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TOWARDS SUSTAINABLE CITIES

A multi-criteria assessment framework for studying urban metabolism

Doctoral dissertation
by
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ABSTRACT

Seventy percent of the global population is expected to live in cities by 2050, occupying more land and generating more emissions. The effect of urban emissions reduces the capacity of natural ecosystems to function effectively while at the same time negatively impacting human health and well-being. Therefore, the sustainable management of urban areas is crucial for the long-term sustainability of the human economy. The management strategies should adopt a new systemic perspective that considers cities as socio-ecological systems characterised by complex human-nature interactions. This perspective is also based on the shift from the traditional "black box" urban metabolism models, accounting for the input of resources and output of wastes and products, to the network models capable of unfolding the internal metabolism of cities. The theoretical part of the work covers two interdisciplinary research fields: Ecological Economics and Industrial Ecology, combined in a network science methodology.

Firstly, the bibliometric analysis of global scientific literature on urban metabolism was performed to identify the temporal developments and new areas for investigating the metabolism of the urban systems. In the empirical part, the environmental accounting and the multiple methods of network science methodology were integrated to estimate the environmental costs, metabolic efficiency and self-sufficiency, and impact of each sector in urban socio-ecological systems. The research corresponds to the 11th and 12th Sustainable Development Goals. It contributes to developing sustainable resource management strategies for Sustainable Cities and Communities by identifying inefficient or unsustainable resource consumption patterns. The first case study focused on estimating total emergy use in the Vienna Region. The results show that "mining" and "agriculture" are not prioritised in terms of investment by the Vienna Government. In addition, the ecological network analysis was applied to analyse the structural and functional attributes of Vienna's urban metabolic system to identify weaknesses in the system's ecological hierarchy and relationships and the sectors behind these weaknesses. The results show that "wholesale and retail" and "energy" sectors are responsible for the low financial support to producers (agriculture and mining) by the tertiary industries. The other study found that the footprint of final products by "agriculture" became larger when an emergy-evaluated version of direct carbon emissions was used.

A multicriteria approach integrating the input-output and the emergy accounting methods could be a valuable tool in investigating socio-ecological interactions, allowing a comprehensive understanding of environmental and socio-economic flows exchanged between industrial sectors and the environment. The integration of environmental accounting with the multiple methods of network science methodology allows for the investigation of internal metabolic processes behind resource consumption and environmental pollution while overcoming shortcomings of single criteria approaches to urban metabolism.

Keywords: input-output analysis, multi-criteria assessment, emergy accounting, ecological network analysis, urban metabolism

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Naples, February 10th, 2021

Oleksandr Galychyn

LIST OF ORIGINAL ARTICLES

This dissertation consists of the following articles:

I. Galychyn, O., Buonocore, E., &Franzese, P. P. (2020). Exploring the global scientific literature on urban metabolism. *Ecological Questions*, *31*(4), 1.

II. Galychyn, O., Fath, B., Shah, I. H., Buonocore, E., & Franzese, P. P. (2022). A multi-criteria framework for assessing urban socio-ecological systems: The emergy nexus of the urban economy and environment. Cleaner Environmental Systems, 5, 100080.

III. Galychyn, O., Fath, B., Buonocore, E., & Franzese, P. (2022). Ecological network analysis of a metabolic urban system based on input–output tables: Model development and case study for the city of Vienna. Cleaner Production Letters, 3, 100019.

IV. Galychyn, O., Fath, B., Wiedenhofer, D., Buonocore, E., & Franzese, P. (2024). An urban emergy footprint: Comparing supply- and use-extended input-output models for the case of Vienna, Austria. Cleaner Production Letters, 6, 100058.

FIGURES

TABLES

ABBREVIATIONS

CF	carbon footprint
CO_2	carbon dioxide
MA	matrix algebra
ENA	ecological network analysis
ES	ecosystem service
EE-IOA	environmentally extended input-output analysis
IE	Industrial Ecology
IOA	input-output analysis
J	joule
LCA	Life Cycle Assessment
MFA	Material Flow Accounting
QEM	Quality Equivalent Method
seJ	solar emergy joule
UM	urban metabolism

CONTENTS

1. INTRODUCTION

> Inability to accept the mystic experience is more than an intellectual handicap. Lack of awareness of the basic unity of organism and environment is a serious and dangerous hallucination. For in a civilization equipped with immense technological power, the sense of alienation between man and nature leads to the use of technology in a hostile spirit—-to the "conquest" of nature instead of intelligent cooperation with nature. (Watts & Pinchbeck, 2013)

1.1. BACKGROUND

During the twentieth century, urbanization has become an urgent issue due to its impact on the health of urban dwellers (i.e., caused by heat island effect, greenhouse gas emissions, energy shortages) and biodiversity and ecosystems services (i.e., habitat loss, reduction of capacity of ecosystems to provide of ecosystem services due to the expansion of urban built-up areas) (Elmqvist et al., 2013; Lapointe et al. 2021). Currently 56, 2% of the world's population lives in urban areas. It's projected to hit 70% population by 2050, producing more emissions (i.e., 50% of the projected increase in GHG emissions associated with urbanization) and contributing to a decline in the production of ecosystem services (i.e., loss of 13% of woodland areas and 10% of biodiversity) and human health impacts (i.e., more than a double increase in a number of premature deaths) (OECD environmental outlook to 2050, 2012).

These pessimistic projection stems from the increase of final energy demand by 50%, owing to the nearly 30% increase in the energy consumption of the industrial sector (agriculture, mining, manufacturing and construction) associated with developing countries between 2018 and 2050, 40% increase in energy consumption of transportation sector, and 39% and 26% increases in energy consumption in household and service sector, respectively. On the other hand, a less profound growth in the energy consumption is projected for developed countries, with 25% associated with the industrial sector, 20% with the transportation sector, and 25% and 20% attributed to households and services, respectively. The service sector in the developing world will also increase by 50% instead of 25% growth in the developed world, overshadowing other sectors in terms of demand for energy investment and emergy based CO2 released in production and transfer of intermediate products. Although the role of the tertiary sector as a significant consumer and polluter in any urban economy is mainly acknowledged (Okamoto; 2013; He & Zhang, 2018; Zheng et al., 2015; Zhu et al., 2019), the way it influences and is influenced by the natural ecosystems and urban ecosystems has been largely overlooked (Zhang, Zheng, & Fath, 2014; Zhai 2018; Zhai, 2019). The service, industrial, transportation, and domestic sectors belong to the socio-economic sub-system, supported by the environment sub-system (Wang et al. 2019).

The growth of the socio-economic sub-system transforms the natural land into the built-up area and causes climate change. Climate change affects the urban economy through health impacts such as diarrhoea, nervousness, and lung tissue damage health ("Climate impacts on human health, US EPA", 2017) as well as a reduction in agricultural production (Venkatramanan et al., 2019). This phenomenon also affects the properties and processes of ecosystems (biological diversity, energy flux, nutrient cycling) (Malhi et al., 2020) and their services which support human health and well-being (Diaz et al., 2019). In the case of ecosystem services, climate change degrades provisioning services, for instance, by lowering precipitation rates and by increasing the magnitude of disturbances such as wildfires which led to shortages of water supply for cities. Rapid urbanisation degrades regulating services, for instance, through deforestation, leading to biodiversity loss and higher concentrations of CO2 in the atmosphere. This global issue also alters the decomposition of soil organic matter, leading to the acceleration of soil carbon losses (Weiskopf et al., 2020). In addition, the alteration of cultural services followed by climate change results in the decline of the tourism sector and an increase in the number of mental and physical health-related cases in any community (Sandifer and Sutton-Grier, 2014; Weiskopf et al., 2020).

These health and environmental costs have led to the urgent need for better knowledge on how cities should be sustainably managed (Myers et al., 2013; Vardoulakis & Kinney, 2019). Urban ecologists (till the 2000s) applied linear thinking to the cities to represent them as a disturbed state of natural ecosystems or modified natural landscapes called urban ecosystems (Burns, 2008; Musango et al., 2017), which assumed a complete absorption of waste by ecosystems. Being a close linear equilibrium model based on the maximum resource efficiency, zero production of wastes, it failed to consider energy and material exchange with the surrounding environmental context, the resilience of such interaction and the complexity of relationships among human components and resources they extract from nature (Carter et al., 2014; McGinnis & Ostrom, 2014). The new system ecology thinking, on the other hand, views cities as open, dynamic socio-ecological systems characterised by the complex resource-based interactions between human activities and the natural ecosystems (Carter et al., 2014; Musango et al., 2017; Saguin, 2019).

The resource-based (i.e., matter and energy) socio-ecological exchange processes between urban economies and natural ecosystems and transformations in urban economies can be represented by urban metabolism (Saguin 2019). However, traditional "black box" urban models account for the input of material and energy resources and the output of final products and wastes, disregarding transformation processes in the urban economy. In addition, the environmental support to the technological operations of urban socio-economic systems was always the main research focus, instead of tracing the transformation of direct natural (organic) into the indirect socio-economic (technical) metabolic flows within the urban socio-ecological system. To minimise the impacts of urbanisation on resource consumption from the environment and emissions absorbed by the environment, socio-ecological transformations of the internal metabolism of urban socio-economic systems should be unfolded to reveal the issues associated with the structure and functions of the urban metabolic system, thereby providing a diagnosis of urban metabolic processes (Zhang et al., 2014; Zhang et al., 2015).

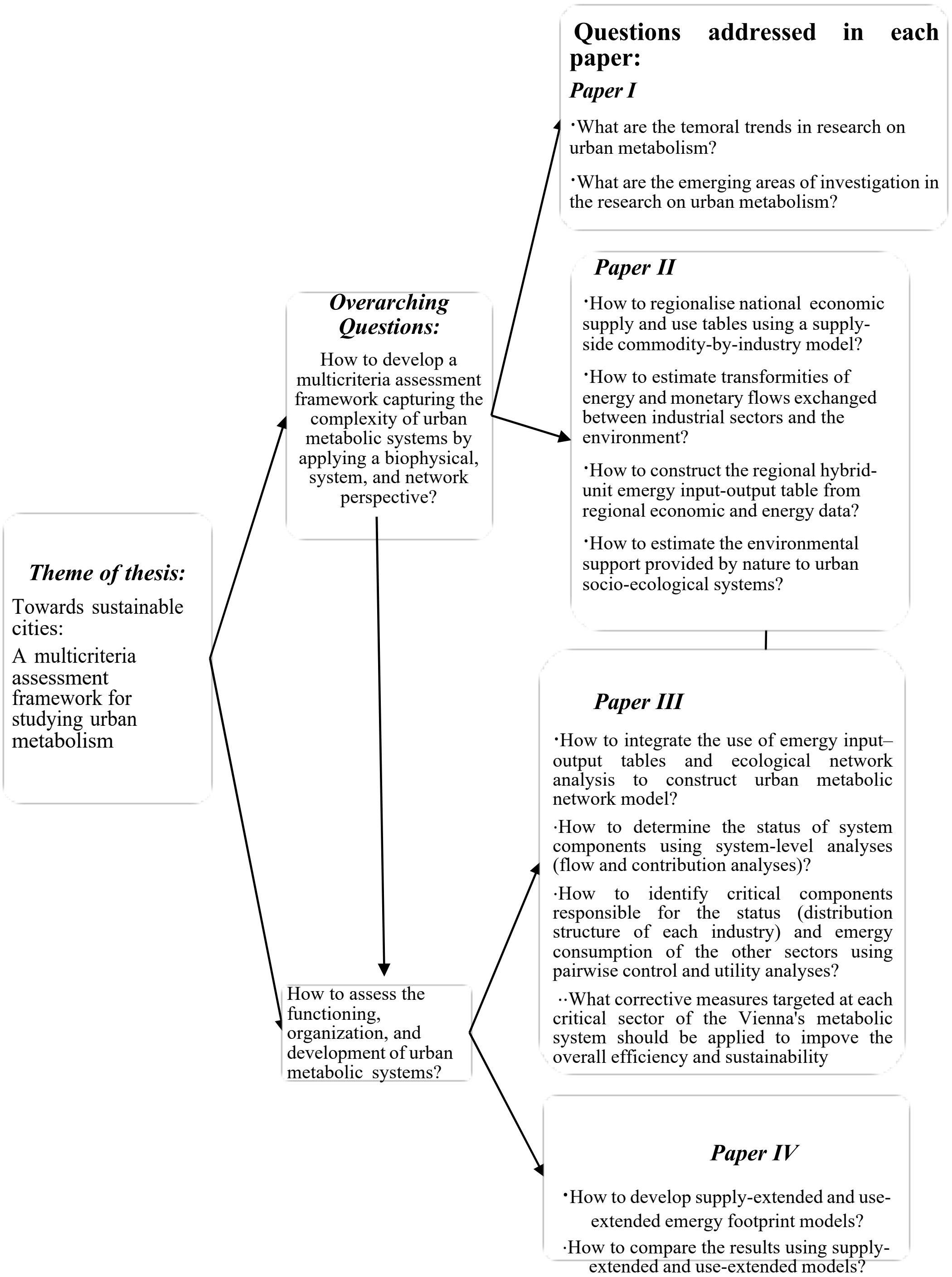
The impacts of urbanisation require integrated management of cities and their resource metabolism for long-term sustainability and economic prosperity (Musango et al., 2017; Saguin,2019). Although some attempts have been made to devise a framework suited for the integrated management of cities (Zhang et al., 2014; Zhai et al., 2018; Zhai et al., 2019), all of them were limited to a single criterion (i.e., energy or water), did not explore the structure of the tertiary sector and the contribution of its components to urban economy, and also failed to comprehensively assess the assistance of the natural metabolic flows to the urban socio-economic sub-system, and to assess the consequences of the combined socio-economic and ecological footprints resulted from the consumption of resources upstream and downstream components (i.e., industries) of the urban socio-economic system. Finding solutions to environmental problems require a complete understanding of the urban system based on the close collaboration of environmental (biologists), economists and sociologists (Zhang et al., 2015; Folke et al., 2021). Therefore, future studies might need to focus on cities′ interdisciplinary and system perspectives to understand the complex interconnected metabolism of socio-economic and ecological sub-systems of urban metabolic systems.

2.2 Aim of the thesis and research questions

The interdisciplinary and system-based approach to cities was employed in my thesis, interconnecting natural and social sciences. The theoretical part of the work is rooted in two interdisciplinary research fields: Ecological Economics and Industrial Ecology, combined in a network science methodology. The main goal of Ecological Economics is that the socio-economic subsystem is embedded in its ecological life-support system, which recognises that human activities are constrained by biophysical limits created by the external environment (i.e., limitations to climate, biodiversity, etc.) and by the impacts of these actions have on it (i.e., climate change, biodiversity loss, etc.). This goal set up a requirement for urban metabolism studies, namely limits to resource utilisation and emissions stemming from the functioning of urban metabolic systems. On the other hand, the Industrial ecology is concerned with the extraction of natural resources, their transformation into products and material or energy flows implied in their exchange among industrial sectors, and the disposal of wastes into the environment. This discipline aims to improve the resource utilisation efficiency of industries by using waste and by-products of one industry as input for the other one. This advocates the importance of transition towards closed-loop systems, where wastes are reused and recycled following circular economy principles. The network science methodology combines these two goals in a single framework to understand the structure and functions of the urban metabolic system, revealing the hierarchy of components in terms of their contribution to the system and system-level influence on them. This highlight attempts to disaggregate the tertiary sector of the urban economy to reveal the system's components (industries) responsible for the unsustainable structural distribution of industries and detrimental functional relationships within the system, the extent of dependence of the components on the system and ultimately, points to the most vulnerable sectors in the system.

These research goals, when dealing with sustainable resource management policies and ecosystem services, need to consider multiple criteria (energy, money, etc.), multiple scales and multiple methods to evaluate environmental support (benefits) provided to the system's components, their contribution to the urban economy, their economic and environmental costs, economic and environmental impacts at different spatial scales of analysis.

Studies that use a single criterion, scale (i.e., individual households or city), as well as single methods, fail to capture the complexity of the urban socio-ecological system by disregarding ether environmental or socio-economic flows, the environmental context in which the investigated system is embedded, and network of metabolic processes in urban socio-economic sub-systems. Therefore, this thesis aims to explore the integrated resource metabolism of the urban economy and its surrounding environment using an interdisciplinary and systems-based approach. The goal is to develop multi-criteria assessment frameworks that capture urban metabolic systems' complexity by applying a biophysical, system, and network perspective. This goal is achieved by integrating the urban metabolism framework and a multi-method approach to environmental accounting. In the empirical part, I assess the environmental support and impacts of industries in Vienna's urban metabolic system and their environmental impacts on it. The dissertation focuses on the research questions listed in FIGURE 1 and addressed in Papers I-IV



Theme of thesis:

Towards sustainable cities:

A multicriteria assessment framework for studying urban metabolism

Overarching Questions:

How to develop a multicriteria assessment framework capturing the complexity of urban metabolic systems by applying a biophysical, system, and network perspective?

How to assess the functioning, organization, and development of urban metabolic systems?

Questions addressed in each paper:

Paper I

- What are the temoral trends in research on urban metabolism?
- What are the emerging areas of investigation in the research on urban metabolism?

Paper II

- How to regionalise national economic supply and use tables using a supply-side commodity-by-industry model?
- How to estimate transformities of energy and monetary flows exchanged between industrial sectors and the environment?
- How to construct the regional hybrid-unit emergy input-output table from regional economic and energy data?
- How to estimate the environmental support provided by nature to urban socio-ecological systems?

Paper III

- How to integrate the use of emergy input–output tables and ecological network analysis to construct urban metabolic network model?
- How to determine the status of system components using system-level analyses (flow and contribution analyses)?
- How to identify critical components responsible for the status (distribution structure of each industry) and emergy consumption of the other sectors using pairwise control and utility analyses?
- ·What corrective measures targeted at each critical sector of the Vienna's metabolic system should be applied to impove the overall efficiency and sustainability

Paper IV

- How to develop supply-extended and use-extended emergy footprint models?
- How to compare the results using supply-extended and use-extended models?

Title of papers

Paper I: The scientific research on urban metabolism: A bibliometric analysis
Paper II: A multi-criteria framework for assessing urban socio-ecological systems: The emergy nexus of the urban economy and environment
Paper III: Ecological network analysis of a metabolic urban system based on input–output tables: Model development and case study for the city of Vienna
Paper IV: An urban emergy footprint: Comparing supply- and use-extended input-output models for the case of Vienna, Austria

FIGURE 1 The main research questions of the thesis connected to the corresponding paper

2. THEORETICAL AND CONCEPTUAL FRAMEWORKS

The Pacific coral reef, as a kind of oasis in a desert, can stand as an object lesson for a man who must now learn that mutualism between autotrophic and heterotrophic components and between producers and consumers in the societal realm, coupled with efficient recycling of materials and use of energy, are the keys to maintaining prosperity in a world of limited resources (Odum, 1977, p. 364)

2.1 Human-environment interactions: a systems perspective

2. Systems thinking approach

The system thinking associated with living or biological systems was firstly coined by Ludwig von Bertalanffy in 1950, who then moved from a generalized system (general system theory) toward a living system based on the unity between man and nature (von Bertalanffy,1955, 1956, 1968). The formulation of the system thinking approach was later added by the theory named "systems ecology", which was formulated through an application of general system theory to ecosystems (Odum, 1964, 1983, 1994). According to this theory, the system is characterised by the number of elements having a specific arrangement and relations between and among them. Consequently, the dynamic of such systems alters their organisation of life and increases their complexity (Montuori, 2011). This theory also defined the system as an open entity, in which its components interact with their environment through feedback mechanisms to maintain its functionality (living state).

The importance was that a holistic view of the system implied that its parts are connected both directly and indirectly, affecting the ability of the system to organise itself and associated attributes such as stability, resilience, growth and complexity (Levin, 2005; Yackinous, 2015). The sub-systems of all complex systems are delimited by their boundaries, which not only separates the sub-systems from sub-systems with different characteristics (i.e., economic or social sphere) or environment (Boriani, 2017) but also delimits the networks of components that form a self-autonomous entity to interact with the external environment through inputs and outputs (Bunge, 1992; Kritz, 2010). It is very subjective and tailored to the objective of the study. The boundaries also define a limit to the system's growth, constraining its expansion by the ability of the external environment to function correctly to support the system in question (Boriani, 2017). The boundaries between the system and its external environment are fuzzy to the point that even Earth can be viewed as a complex nested system in which the human economy interacts with biosphere, atmosphere and lithosphere sub-systems (Donner et al., 2009).

System thinking is a holistic approach based on the interconnection of events and dynamics of their interactions instead of reductionist thinking, which is based on the study of each event or part mechanism individually. The differences between traditional linear thinking and system thinking are shown in FIGURE 2. Linear thinking focuses on direct cause and effect when one event is directly followed by the other. In the system thinking, however, the cause would be feedback loops, and the outcome would be the adaptation to the environment and survival of the system.

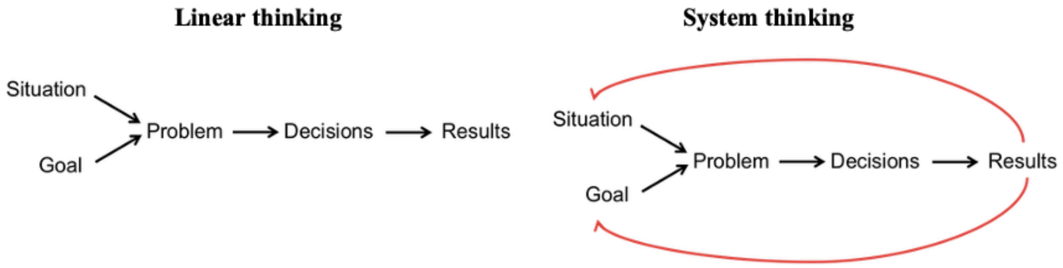


FIGURE 2 Differences between linear thinking and systems thinking

Feedback from each component affects another component, thereby changing the system’s properties. To alleviate these problems, systems' complex nature and behaviour should be assessed entirely, incorporating all the parts that create them. System thinking is suited for alleviating complex issues such as climate change, systems characterised by numerous feedbacks from direct and indirect interactions between system elements and between elements and their environment, and complex systems composed of complex networks characterised by mainly non-linear interactions (Pourbohloul and Kieny, 2011; Preiser et al., 2018).

2.1.2 Thermodynamic features of ecological systems

The metabolism of urban socio-ecological systems is rooted in the thermodynamic properties of ecological systems. It is stemmed from Odum’s study on thermodynamic features of ecological systems, where he explored energy and matter flow exchanged between the ecosystem and the outside environment (Odum, 1996). However, Rudolf Clausius and Nicolas Léonard Sadi Carnot invented the first and second law of thermodynamics, respectively. Later some studies assessed the level of organisation, complexity and development of ecosystems via energy flow exchanges (Odum, 1996; Fath, Patten and Choi, 2001; Jørgensen and Fath, 2004; Ulanowicz, 2004).

The first law of thermodynamics (i.e., conservation of embodied energy) states that energy can neither be created nor destroyed. In a closed system, the total energy is transformed from one form into another without any energy source or sink, i.e., the total amount is conserved throughout the transformation process. Energy forms differ in their ability the produce applied work. High-quality energy products include products such as diesel, charcoal, and electricity. Conversely, primary energy products received directly from nature without transformations such as solar energy, constitute low-grade energy. As a result, 1.60×10^5 J of solar energy is required to produce 1 J of electricity. The energy can only be used once for a transformation. Any conversion process subject to the loss of energy, i.e., heat. Each loss affects transformation efficiency and results in a lower amount of energy available for transformation (Collins et al., 2006; Ayres, 2016). The second law of thermodynamics (entropy law) states that entropy (or disorder) in a closed system continuously increases, so the system will never self-organize (Shannon et al., 1948; Harvey et al., 1990). In short, any natural or technological process in closed systems is accompanied by an increase in entropy, leading to a decrease in the number of useful energy approaches (Ayres, 1998; Kostic, 2014; Kostic, 2020).

Based on their thermodynamic characteristics, ecological systems fall within the category of open systems that exchange energy and matter with their external environment. Another category closed system, only involves energy metabolism (Fath, Patten and Choi, 2001). The isolated systems are subjected to the highest disorder and the lowest amount of useful energy at equilibrium due to the absence of any interaction with the environment. The only example of a closed system is the planet Earth itself since it exchanges solar radiation with outer space. Solar radiation can be considered the sole primary direct input into ecosystems, which plants directly capture and then transfer indirectly through the different trophic levels of a food web. The ecological systems are highly organised systems that receive solar energy and release high-entropy heat outside. Being far from equilibrium, entropy production does not approach a minimum, making this exchange necessary to maintain a non-steady-state (Nicolis and Prigogine, 1977; Fath, Patten and Choi, 2001). Ecosystems and the biosphere, in general, consume about the amount of solar energy in the form of relatively short-wave radiation (visible light) as the amount of heat energy radiates back to space in the form of long-wave radiation (Kiehl; Trenberth, and Kevin, 1997; Silow at al., 2010). This solar energy is converted by plants via photosynthesis into chemical energy and stored in them as biomass, which can be used as a source of food for upper trophic levels, or converted to other forms of high-quality energy such as fuel (Ragauskas et al., 2006; Najjar et al., 2010).

2.1.3 Social-ecological systems and sustainability

Socio-ecological systems are human-driven ecosystems characterised by complex interactions between the human economy and natural ecosystems (Frank et al., 2017). Cities can be considered socio-ecological systems since they constitute complex interactions between the urban economy and the surrounding hinterland. Many natural ecosystem traits also apply to municipalities. For example, cities are embedded into the global socio-ecological system (Haase, 2021). An ecosystem is a biological community that interacts with the physical environment through the energy and material flows supporting trophic structure and biotic diversity (Tansley, 1935; Odum, 1971). Any type of ecosystem, natural or urban, is hierarchical, complex, and adaptive. They can include a large number of components (depending on the level of aggregation), significant dominance of indirect effects (Higashi and Patten, 1989), non-linear functional relations (Smith, 1974), sensitive dependence on initial conditions (Hastings et al., 1993), distributed control (Borrett, 2006), and cross-scale relations and associated regime shifts (Holling, 1986; Folke et al., 2004). Based on thermodynamics, ecosystems are open systems that operate in far-from-equilibrium conditions with irreversible internal processes and are accompanied by entropy production at the expense of exergy (Jørgensen and Fath, 2004; Silow et al., 2010).

The global processes within the biosphere are driven by three sources: the available solar energy, geothermal heat, and dissipation of tidal momentum (Brown et al., 2016). The human economies (socio-technical systems) are directly and indirectly supported by flows of ecosystem services (ES) derived from stocks of natural capital (i.e., living organisms, minerals) that release wastes and emissions to the environment. In Figure 3, the aggregated systems diagram schematising the interplay between environmental processes and global socio-economic systems is shown.

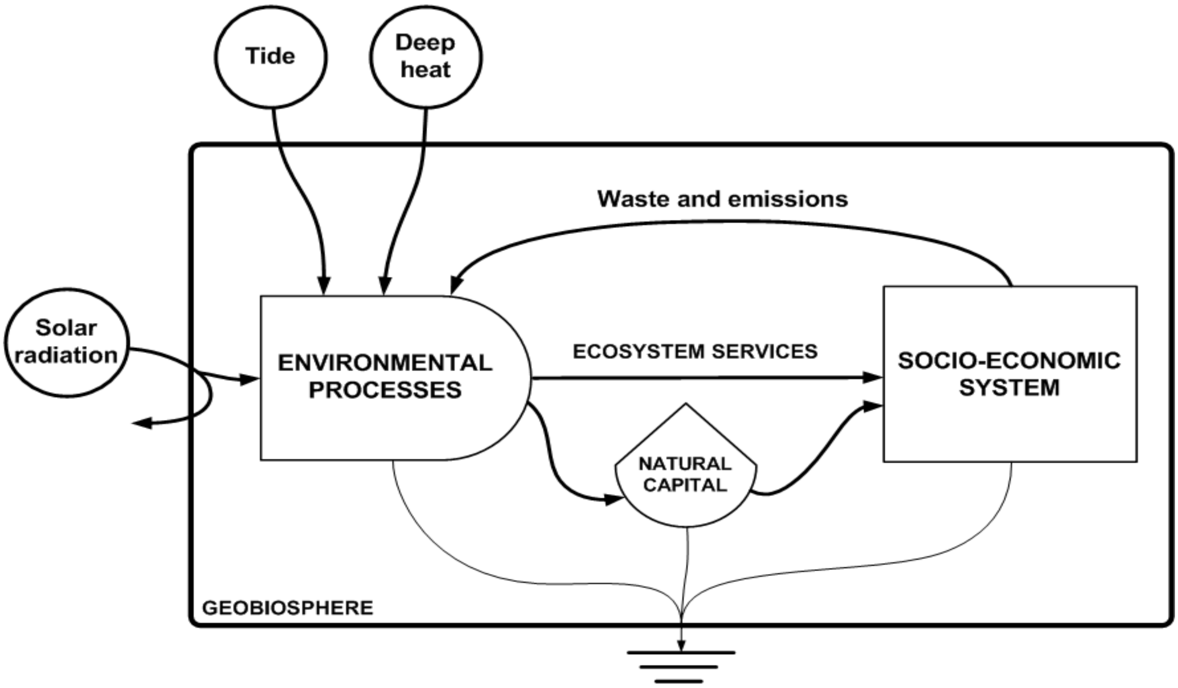


FIGURE 3 Systems diagram showing an aggregated view of the interactions between environmental processes and socio-economic systems at global scale. Adapted from Häyhä and Franzese (2014)

Humans are considered an integral part of ecosystems (Millennium Ecosystem Assessment, 2005; Schoon, 2015). Social-ecological systems are based on the view that humans are a part of nature and do not function independently (Fiscus and Fath, 2018). Ecosystems provide goods and services vital for society's well-being and the future development of socio-economic systems (Heezik and Brymer, 2018). The impacts of human activities alter the ecosystem's structure and functions and reduce its capacity to generate flows of ES (Frank et al., 2017). On the other hand, human activities such as the impact of technology drive co-evolution between the social system and ecological system. The global socio-ecological system is an assembly of loosely interconnected and co-evolving social and ecological systems (Haider, 2021). They interact within the biosphere at different temporal and spatial scales and across the scales (Desjardins, 2019; Folke et al., 2016). Analysis focusing only on ecological systems does not allow the trace of ecosystem capacity issues to provide its services to the source to fix a problem. On the other hand, focusing only on the socio-economic system would mean taking sources of benefits to society and their limitations for granted.

Humans are the dominant force of change on Mother Earth. Global environmental problems such as climate change or biodiversity loss are induced by the accelerated pace of their actions in the biosphere (Folke et al., 2021). The safe-operating space for humanity associated with the acceleration of human activities and their impacts on the biosphere is crucial for the sustainable future of the human economy (Folke et al., 2021). Crossing tipping points will lead to the global shift to a new regime that threatens human health and well-being (i.e., loss of biodiversity and ES). (Folke et al., 2021; Lenton, 2019; Rockström, 2009). Therefore, the sustainable management of human economies should be based on economic and biophysical limits to growth (Niccolucci, 2006; Manfroni et al., 2021; Martin et al., 2016).

2.1.4 Industrial Ecology

Industrial ecology (IE) is commonly defined as a study of systemic- relationships between society, the economy, and the natural environment, where such relationships are represented as material and energy flows. It attempts to archive balance and mutualistic rations between industrial processes and environmental sustainability (El-Haggar, 2007). The socio-economic system focuses not only on the material energy flows but also on the information flows and interactions between system parts, such as public government, society, and industry (Jonker and Harmsen, 2012). IE fills the gap between the human system and ecosystem to attain mutually exclusive future benefits of sustainable development (Awan, 2020).

IE research is mainly concerned with reducing throughput (total supply and the total consumption) of all kinds of materials and fuels, whether they leave a site as products, emissions or waste (Grasso et al., 2009). In detail, it investigates 1) supply of natural resources to production activities in socio-economic systems (upstream processes) (Kalt et al., 2021), 2) impacts of production processes and consumption activities on socio-economic systems and external environment (economy-wide impacts) (Chen and Wu, 2017; Wiedmann et al., 2020; Wieland et al., 2020), and 3) the efficiency of material, waste and energy exchanges within the socio-economic systems (Li et al., 2017).

Industrial ecologists use the systems perspective to quantify the patterns of materials and energy consumption in different societies and to identify system-wide environmental impacts associated with products. This perspective is used to capture not only external processes (inputs of materials and energy and the output of wastes and emissions) multiplicity of flows involved in the production and transfer of products, i.e., include all factors affecting the product during its 'full life cycle ('cradle-to-grave'). All IE approaches, if used separately, provide only partial information about the system: environmentally- extended input-output analysis (EE-IOA), material and energy flow analysis, substance analysis, life-cycle assessment, and system modelling. Therefore, hybrid approaches to analyse more variables affecting the life cycle of a product and associated impact are encouraged (Fry et al., 2021; Wiedman et al., 2020). In IE socio-economic system is embedded into a larger environmental system to analyse the implications of local decisions related to the consumption of a product at a global level and vice versa. Thus, the impact of the production of a product (i.e., biomass) can be traced via supply and conversion chains till the consumption of final products (i.e., pollution from wood combustion) to identify the global impact of human-dominated processes while challenging the industrial-environment resilience and adaptability (Kalt et al., 2021, Wan et al., 2020) and ecological carrying capacity (Song et al., 2019).

The purpose of the IE concept is to be a helpful analogy for facilitating the development of industrial systems toward the principles of the development of ecological systems (Korhonen, 2001). To do this, industrial ecosystems and urban socio-ecological systems (cities) need to reduce their dependence on the external environment for material and energy resources and improve resource utilisation efficiency to move from a linear to a cyclical or closed-loop system. This shift also entails minimising a production process's gross energy and labour costs (Shekarian, 2020). Natural and urban ecosystems as complex systems include many production processes directly and indirectly affected by the interactions with each other through energy and material exchanges, resulting in high footprints. One approach solves this issue by placing the production process in the context of other industrial and natural processes that utilise its waste, reorganizing them into clusters accordingly to archive nearly "zero" emissions. However, IE alone does not incorporate any solution to reduce the impact of consumption activities on production processes and the environment. Thus, integration or combined use with other concepts is required to deal with the impacts of production and consumption activities in urban socio-ecological systems.

The most common approaches used in IE are Life cycle assessment (LCA), Material flow analysis (MFA), environmentally- extended input-output analysis (EE-IOA), and Energy Analysis. a) LCA is a standardised approach to assessing the environmental impacts of a product or process over its entire life cycle (cradle-to-grave) (Algren et al., 2021; Muralikrishna and Manickam, 2017) b) MFA describes the flows of materials from sources to sinks in an industrial system (Duchin and. Levine, 2008; Laner, 2016), c) Environmentally extended input-output analysis (EE-IOA) evaluates the environmental impacts of industrial production processes (producing sectors) or economic consumption activities (consuming sectors) within a socio-economic system (Dias et al., 2014; Kitzes, 2013; Wieland et al., 2020). d) Energy Analysis accounts for direct and indirect commercial energy supporting man-made processes (Franzese et al., 2009).

2.1.5 Network science methodology

> Nature, displayed in its full extent, presents us with an immense tableau, in which all the order of beings are each represented by a chain which sustains a continuous series of objects, so close and so similar that their difference would be difficult to define. This chain is not a simple thread which is only extended in length, it is a large web or rather a network, which, from interval to interval, casts branches to the side in order to unite with the networks of another order (Lecrere de Buffon, 1770).

Network science is the study of network representations of physical, biological, and social phenomena leading to predictive models of these phenomena (National Research Council 2005). Network science has become a powerful tool to describe the structure and dynamics of complex real-world physical, biological, social, and technological systems (Iñiguez, 2020). The need to mathematically describe both components and interactions has promoted the rise of network science as an interdisciplinary effort to quantify the structure and dynamics of complex systems such as ecosystems and urban socio-ecological systems (Zhao, 2012; Sayles, 2019; Kluger, 2020).

The network science concept stems from graph theory, the branch of mathematics concerned with connecting points (vertices/nodes) through edges/lines (Iñiguez, 2020; Mukherjee, 2019). Graph theory was founded in 1736 by Leonhard Euler in the paper on Seven Bridges of Königsberg (Kaliningrad, Russia), published in 1741. He was given a stack to figure out whether it was possible to cross each of the seven bridges only once. To solve this problem, he substituted landmasses with nodes and bridges among them with edges, focusing on simplifying connection information since only connections' existence (or absence) was relevant. This procedure allowed him to arrive at a simplified mathematical representation of the problem and to prove that a mathematical solution to the problem did exist only if the number of all possible pathways between each pair of landmasses (nodes) in the network is equal and the flow is cyclical (start and terminates at the same node). This discovery has led to the development of graph theory (Paoletti, 2011). The flow analysis was improved by the discovery of the way undirected and directed flows affect the nodes in the network, such as the chemical composition of Paraffin (Cayley, 1857; Cayley, 1875). After there have been notable developments in the network theory.

In the last century, the mathematicians Paul Erdo and Alfred Renyi (1959) introduced a random network, which proved a contribution to building a simple toy model of network formation that explains some statistical properties of complex networks, including the food web (Bascompte, 2007). The random network did not correspond to the real networks such as genetic or internet networks because ranking in terms of degree (number of links that connect each node to the other nodes) existed in such systems. Therefore, Barabasi & Albert (1999) introduced the "preferential attachment" problem. In their model, a new node is created at each time step and connected to existing nodes according to the "preferential attachment" principle (Hexmoor, 2015). Preferential attachment means that the more connected a node is, the more likely it will receive new links (Karyotis and Khouzani, 2016). Zoologist G. Evelyn Hutchinson (1957) developed a niche concept in ecology, thereby analysing the functions of an organism in the ecosystem (Melo-Merino et al., 2020). However, it was not until Cohen (1978) that models of food webs grounded on this principle were built (Bascompte, 2007). This mainstream application of network science to ecology had the most development. Cohen (1990) developed the cascade model random graph theory (Erdos and Renyi 1959). The model included only direct feeding relationships between species-based top-down trophic level hierarchy. His model did not address only indirect feeding but also cycling and loops (i.e., cannibalism). Williams and Martinez (2000) proposed the niche model addressing the indirect feeding, introducing trophic overlap between species (sharing of consumers among species with the same trophic position), thereby connecting species into a more complex network of interactions (direct and indirect) (Pascual and Dunne, 2006). This model also proved that network structure is not random but rather follows 'preferential' development (Pascual and Dunne, 2006). Nested-Hierarchy Model (Cattin et al. 2004) addresses limitations of the 'niche model' that prey is supplied to predator at a constant rate, but the model effect on indirect feeding has not been tested (Pascual and Dunne, 2006; Stouffer et al., 2006).

Cattin et al. (2004) constrained the nested-hierarchy model by phylogeny. They studied a larger number of indirect pathways of nutritional flow by including a rule allowing consumers to feed on the species outside their trophic level. In short, all these communities (population) ecology models focus strictly on feeding relations, thus lacking decomposers and detritus (cycling mechanism). Modified niche, in which detritus component into niche model, was built to overcome this problem (Haynes et al., 2007). Fath (2004) also addressed this problem by constructing the cyber-ecosystem model, in which cycling is archived at the expense of exclusion of indirect feeding, i.e., cannibalism. Morris et al. (2005) analysed the trophic relationship among ecosystem components using information indices and constructed realistic (robust and efficient in transferring flows) network models.

The main contribution to the development of network theory in ecology is attributed to Odum's (1959) synecology perspective (1959). That year he introduced a complete electrical circuit diagram of the ecosystem model. The electrical current was the equivalent of the carbon cycle; resistors were the equivalents of various categories of groups of plants and animals, etc. However, it was not until 1973 that mathematical complexity in terms of the number of variables was sufficient for other scientists to build more realistic network models rooted in community assembly algorithms: modified niche (Haynes et al., 2007), cyber-ecosystem model (Fath, 2004), lognormal model (Morris et al., 2005). These newly developed network models provided a basis for analysing the structure and functions of ecological systems (Fath and Patten, 1999; Fath, 2007). Odum's other contribution to the network theory was the established language of system ecology in 1971 to represent energy flow exchanges among the ecosystem's components (Li et al., 2010). The community assembly rules for the network analysis inherited into a modified niche, cyber-ecosystem and lognormal model were rooted in this simplified model of an ecosystem (Fath, 2007).

Network analysis is also used to study system-level indices. One such direction was the robustness (sustainability) assessment of ecosystems through information indices (Ulanowicz, 2000; Ulanowicz, 2009; Ulanowicz, 2011). He introduced ascendency (level of organisation) and network redundancy (level of resistance to changes in the external environment). The trade-off between these two indices he termed 'window of vitality' to measure the level of robustness (sustainability) of ecosystems. Other scientists studied ecological functions to measure the progress of the level of organisation and adaptability towards ecosystem growth and development (Fath, 2017). System storage (Jorgensen & Mejer (1979,1981), throughput (Odum and Pinkerton, 1955), ascendency (Ulanowicz, 1986,1997), the environmental cost of storage and flow (Odum,1988, 1991), dissipation (Chneider and Kay, 1996), cycling (Morowitz, 1968), residence time (Cheslak & Lamarra, 1981), specific dissipation (Prigogine, 1955), the environmental cost of usable energy (exergy) storage (Bastianoni and Marchettini, 1997) were unified using network analysis (Patten, 1995; Fath and Patten, 1999; Fath et al., 2001). This unification allowed us to identify a typical pattern (organisation) of food web development (Fath et al., 2001).

However, the mainstream research on network analysis in ecology focused on internal production processes and economic activities to reveal abnormalities in the trophic and functional relationships among them. Ecologists have used multiple types of network models. For example, ecologists interested in animal behaviour and social structure have mapped the interactions among individuals of a population (Borret et al., 2014). The other ecological networks studied were mutualistic networks and hostparasitoid networks (Ings et al., 2009). The main properties studied through network analysis were indirect effects ratio, network homogenisation, and network mutualism (Fath, 2012). Most of the studies are used to study natural ecosystems (Liu et al., 2019; Muhtar et al., 2020; Nogues et al., 2020; Zhang et al., 2018). Zhang and colleagues (2009) were the first to apply network science to study urban ecosystems. In recent years, however, studies that examine urban ecosystems appeared more frequently (Chen et al., 2020; Xia et al., 2020; Zhu et al., 2019; Zheng et al., 2021). However, the natural and urban ecosystem models remain too aggregated, and surrounding ecosystems are considered only as a source ('black box' ecosystem models). Thus, the complex urban socio-ecological systems operating within local, regional and global ecosystems are yet to be explored.

Another application of networks in ecology can be named spatial networks stems directly from graph theory to generalise the consequences of habitat loss for patch connectivity and its implications for meta-populations (Bascompte, 2007). Till 2001 full pair-wise connectivity matrices have been used to represent connectivity in metapopulation studies (Hanski,1994). The adoption of graphs in ecology and conservation started with Urban & Keitt 2001, who developed a graph-theoretic methodology to explore the connectivity of habitat patch networks using electric circuit theory (Moilanen, 2011). Fortuna, Gomez Rodrıguez, & Bascompte, 2006 looked at the relationships between landscape structure and robustness of landscape connectivity based on the patch removal simulations. Until recently, this field was mainly resilience and robustness due to the human disturbances of patches (Saura, Bodin, & Fortin, 2014; Prima et al., 2018), moving from spatial predictions-based network characteristics (i.e., centrality, closeness, clustering) to the combined approach, which uses network properties and the internode matrix composition and node attributes to make predictions (Doherty & Driscoll, 2018; Prima, 2019).

However, recently this approach has been integrated into the mainstream application of network science to study CO2 absorbed or sequestrated capacity transferred during land use and cover changes (Zhang et al., 2016; Xia et al., 2019). Despite identifying problematic land use patches and carbon-based relations, spatial orientation can provide only a vague direction (Xia et al., 2018), and too aggregated patches can limit the quality of the results obtained, mainly resulting in the higher indirect effects and mutualism in the network (Baird et al. 2009). Therefore, the models should be further improved to address these limitations. This dissertation will integrate environmental accounting with the mainstream network science approach to studying internal metabolic processes in urban socio-ecological systems.

2.2 The unconventional economic paradigm: Ecological Economics

The new paradigm may be called a holistic world view, seeing the world as an integrated whole rather than a dissociated collection of parts. It may also be called an ecological view, if the term "ecological" is used in a much broader and deeper sense than usual. Deep ecological awareness recognizes the fundamental interdependence of all phenomena and the fact that, as individuals and societies we are all embedded in (and ultimately dependent on) the cyclical process of nature (Capra and Pauli, 1995).

3. Limits to growth: reconsidering the scale of economy

Human activities have always been biophysically connected to the ecological systems through the flows of materials and energy. Rapid population growth accompanied by the dominance of neoclassical economics resulted in the rapid increase in extraction of raw materials directly from the natural environment and in the release of emissions and wastes generated by urban and national economies. These activities alter ecosystem structure and functions and undermine its capacity to generate ecosystem services (ES) for socio-economic systems, negatively affecting the biosphere, human economy, and human well-being worldwide.

During the period of classical political economy, Adam Smith was the first to mention the importance of the population and the limited natural resources as developmental factors of human economies in 1776 (Bogović and Licul, 2018). He mentioned the rent of land, skilled labour wages, and capital as components of value-added products and the national wealth. In addition, he stressed that labour and land are the highest inputs to capital creation and the contributors to national income (Smith, 1776). Marxist theory of exploitation conveyed the same idea about human labour and land. Furthermore, Marx has laid a foundation for an urban metabolism (UM) method (model) within IE developed by Wolman (1965) by describing metabolism materials (cattle manure) exchanged between humans and nature (Burkett, 2006).

Malthus (1798) had argued that cultivated land, when reaching maximum productivity, would not be able to support the population growing exponentially, leading to the balance between population and land (Bogović and Licul, 2018). David Ricardo (1772-1823) has developed an economic-ecological model characterised by complex agriculture activity- the environment interactions. He showed that the accumulation of capital would stop when the size of a population exceeds the capacity of agricultural land to sustain it (Bogović and Licul, 2018; Ji and Luo, 2020). John Stuart Mill (1806-1873) extended the idea of the state of stagnation as the destination of economic growth by changing the meaning of economic growth itself from capital accumulation to the equal distribution of capital among humans. In this way, he investigated the inner working of the global socio-economic system to maximise human wealth and reach a stationary state in economic production. He describes the stationary state in a simple term below:

> The best state for human nature is that in which, while no one is poor, no one desires to be richer, nor has any reason to fear being thrust back by the efforts of others to push themselves forward.

The constraint in population size was an essential factor in archiving the dynamic stable state with zero economic growth:

> There is room in the world, no doubt, and even in old countries, for a great increase of population, supposing the arts of life to go on improving, and capital to increase. But even if innocuous, I confess I see very little reason for desiring it. The density of population necessary to enable mankind to obtain, in the greatest degree, all the advantages both of co-operation and of social intercourse, has, in all the most populous countries, been attained.

Later during the 19th century, the importance of technology choice for material and energy exchanges between humans and nature was recognised. Adam Smith and other classical economists undermined the importance of technology in favour of labour, which is reflected in the absence of technology in determining the value-added of the product and national wealth. Another vital transition occurred after 1848 with the emergence of monetary utility on top of the physical utility of a product. This was when the paradigm shift in economic thinking started by introducing the exchange value of a product measured in monetary terms. Therefore, the value of products was determined by the use-value (value of production) and exchange among consumers (value of transfer), thereby considering the consumption of the product as total value. The capital was extended to incorporate transfer alongside the purchased labour, changing its meaning to the income generated by consumption activities. Thus, the value of capital became greater than the value of land (Mehrotra, 1991).

Neoclassical economics emphasised labour, capital, and technology as factors of production necessary for economic growth. This field was focused on the socio-economic system alone, not taking the environment into account. However, the Growth theory developed by Solow (1956) postulates that capital accumulation and labour and technology allow economic growth to continue indefinitely, with technology being the main driving factor. The other neoclassical economic, namely John Hicks, Franco Modigliani, and James Tobin, continued developing his concept. Its rise continued until 1970, when stagnation of economies and inflation of prices due to the oil crisis has resulted in the loss of its validity (Villaverde, 2019).

Moreover, evidence of extensive social costs from pollution undermined the price theory of neoclassical economics. Environmental problems such as pollution were considered externalities. Therefore, pollution was converted into money and included in calculating the cost of a production process to achieve optimal allocation of resources or distribution of wealth (Pareto efficiency) (Centemeri, · 2009; Spash, 2021).

The ecosystem in a neoclassical economy was viewed as a subset of the economy. The shortage of natural capital could be substituted by artificial capital, indicating the need for Ecological Economics. The failure of Neoclassical economics to consider biophysical principles for economic production was widely criticised (Ayres and Ayres, 1978; Christensen, 1989; Costanza, 1980; Georgescu-Roegen, 1971; Hall and Bradley, 1990; Odum, 1971).

Kenneth Boulding (1966) argued that the transition from a linear ‘cowboy economy’ with unlimited resources (i.e., national economy) toward a circular ‘spaceship’ economy with scarce resources (i.e., Earth). He applies a reductionistic and system perspective when shifting between local and planetary boundaries. While at the local level, the capacity of the global external environment to deliver materials and energy and to assimilate wastes seems unmeasurable, at the global level, the absence of it pushes people to improve resource utilisation efficiency and employ circular economy strategies.

Malthus (1798) believed that the human desire for wealth would prevent society from collapsing. In addition, Adam Smith also believed that individual desire for wealth is beneficial for a country. Unlike Garrett, Hardin (1968) thought that it is a human desire for wealth that will lead to the collapse of the human economy. He thought that individuals having access to a common pool of resources would deplete them without care for others to the point of hunger and famine. Using externality (pollution), he illustrated a reverse example of the ‘tragedy of commons’ using externality (pollution). He used the example of a rational man for which the discharge cost is less than its purification, pushing him to add more negative resources to the shared resource pool. By doing it, this man goes against his interest since he is a part of the environment. He chooses to pollute for household savings. He also selected an example of the owner of a factory on the bank of a stream to illustrate that when private property boundaries are not delimited, individuals will choose to pollute more for their gain without care for a more extensive public service provided to the population in which their plots are embedded. Thus, unlimited economic and population growth will lead to the simultaneous collapse of society and degradation of the environment, i.e., the socio-ecological system will seize to exist.

The steady-state economy proposed by Herman Daly in 1970 contributed the most to the establishment of Ecological Economics (Røpke, 2004). Elaborating on the ideas of John Stuart Mill (1861) in the aspect that the development of society continues in a steady-state economy, Boulding's spaceship economy (1966) in terms of circular economy and resource efficiency, and low entropy energy exchange in the economy (Georgescu-Roegen, 1971). He considered that energy and material input into the economy should remain lower than the depletion of natural resources because some aspects of the former provide unique and irreplaceable functions while releasing energy and material output lower than the environment's assimilative capacity. Thus, the economy in a steady state does not exceed environmental constraints, thereby representing the state of sustainable economic development:

> "Boundary-oriented stability tends to minimise future regrets rather than maximise present satisfaction (Daly, 1973, pp. 63)."

For sustainable development of the human economy, the 'strong and weak sustainability' should be also considered (Ayres, 2001; Pelenc and Ballet, 2015). Weak sustainability stands for the low importance of natural capital compared to man-made capital due to both means being interchangeable when evaluated in monetary units. Conversely, strong sustainability states that natural capital cannot be replaced with manufactured capital, but both capitals are complementary when considered in biophysical units (energy, matter). Therefore, it imposes responsibility on humans to exploit renewable resources at a level that allows them to be replenished over time and to exploit non-renewable resources at a rate that will enable their use by future generations (i.e., resource utilisation efficiency) (Ekins et al., 2003; Davies, 2013; Usubiaga-Liano and Ekins, 2021).

Neoclassical economics is grounded on weak sustainability and assumes that limits to growth can be avoided by replacing resources with capital if enough substitution units and technological improvements have been archived (Ayres et al., 2004; Lefstad, 2021). In addition, it assumes that tipping points cannot limit economic growth (Murphy et al., 2021). Ecological economics, instead, is based on strong sustainability, and it recognises the superiority of any ecosystem (local, national or global) over any social and economic systems ((Costanza, 2008; Ang and Passel, 2012; Hediger, 2008; Rees, 2002; Buriti, 2019). Environment controls and limits economic activities in exchange for waste and emissions, which, by harming the environment, further constrains economic activities (Vivien, 2008; Blampied, 2021; Klitgaard, 2020). This framework employs methods such as embodied energy analysis, material flow accounting, and emergy accounting to assess natural (i.e., solar energy), human-driven (i.e., agrichemicals), labour costs and associated indicators (Hayna and Franzese, 2014).

In 1988, the International Society for Ecological Economics (ISEE) was formed, and the discipline was institutionalised. The field incorporates three interrelated goals: sustainable scale, fair distribution, and efficient allocation (Daly,1992; Malghan, 2010). Ecological Economics focuses on the limited availability of ecosystem goods and services vital for human life provided by healthy ecosystems. During the last decade, accounting for nature's contribution to the internal metabolic processes (industrial processes) in urban socio-economic systems has been a widely studied issue (see Chapter 2.3).

2.2.2 Thermodynamics in economics

Georgescu-Roegen was the first to apply thermodynamics to economics in 1971. He argued that the goal of the economic system should be to archive and maintain low entropy energy exchange. The economy is an open subsystem operating within the larger closed environmental system (Earth). Each economic activity receives a low entropy energy flow from the environment (low disorder), which undergoes transformation inside economic system, and then released back to the environment in the form of high entropy energy flow. This means that industrial processes in the economy dissipate free energy (usable energy) into bound energy (waste energy) and usable materials into degraded materials. Energy sources are depleted to change natural resources (crude oil) into state usable by economic activities. The economic system's entropy does not decrease but conserves usable energy remaining after the human economy and environment release high entropy. (Clark et al., 1988; Annila and Salthe, 2009). This material and energy exchange between the human economy and the environment is depicted below (FIGURE 4).

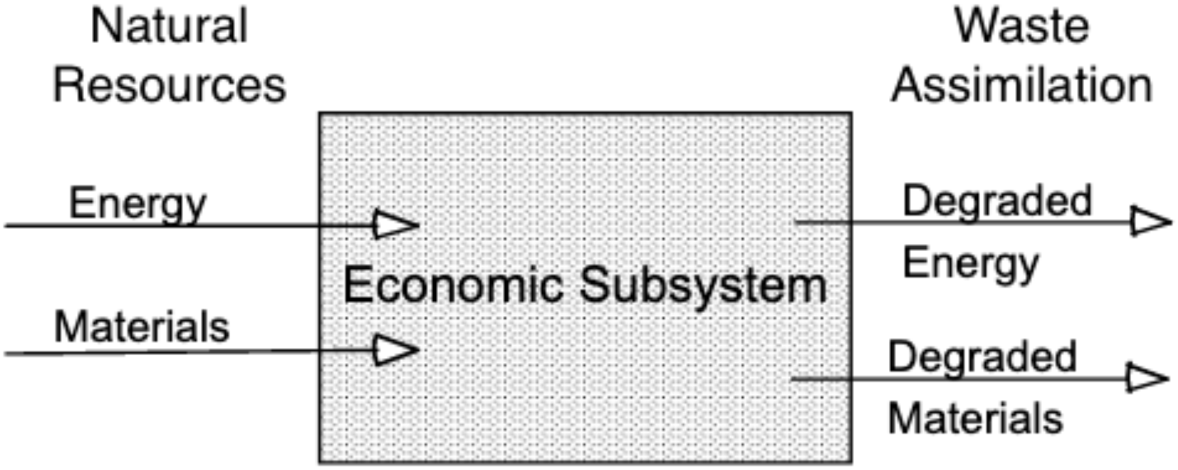


FIGURE 4. Material and energy exchange between human economy and environment

Therefore, even though energy and matter change from natural to man-made form (products and services, emissions, waste heat), they do not disappear and can be harvested but not created. Without natural input, any production and consumption processes in the economy cannot exist (Costanza, 2012; Ibrahim, 2017; Ruth, 2011).

Any production process within the economy releases high entropy into the surroundings even if the end-product has low entropy (low-entropy copper metal refined from high-entropy ore). Nevertheless, the entropy of natural resources grows while they are being used up in production, transfer and consumption processes within the system resulting in high-entropy waste, i.e., greenhouse gas emissions (Ogushi, 2006; Kaberger and Mansson, 2001; Ruth, 2011).

Kaberger and Mansson (2001) highlighted the limited availability of exergy and itsthe fundamental role as an input to any economic activity. The higher the exergy efficiency, the less energy losses and internal irreversible economic processes, reflecting the sustainable functioning of the system. This highlights the importance of high exergy utilisation efficiency of economic processes and low throughput in archiving a steady state of the economy (Honkasalo, 1998; Kaberger and Mansson, 2001).

Many studies analysed interactions between the economy and environment using material and physical stocks and flows. Georgescu-Roegen (1971) introduced the flow-fund model based on two types of inputs into production processes: stock-flow resources (non-renewable energy and materials) and fund-service resources (labour, capital and land). He highlighted these different categories' complementary use and depletion potential to sustain human economies. Berg et al. (2015) included monetary counterflows inside the human economy paid in exchange for a supply of the physical stock flows with aim to better represent financial processes and their impact on economic sectors. Lately, interactions between the ecosystem, the financial system and the macroeconomy have been explored by developing a stock-flow-fund ecological macroeconomic model (Dafermos et al., 2017). This implies the need to examine the economic and environmental systems' inner workings to reach a perfect balance between the stability of economies and the sustainability of environmental systems.

Among the two primary accessible energy sources (mineral deposits and the flow of solar radiation), solar energy holds the highest potential for the human economy despite not have been directly accessible to humans (Popescu, 2012). Since a mineral deposit is a finite source of free energy severely affected by human exploitation, more rational use of this source is required. If the extensive exploitation of this source continues, it will result in scarcity of this source and damage the future economic process (Couix, 2019). The most abundant renewable energy source, namely solar radiation, is still limited even though it will last for a few more billion years. If non-renewable resources are depleted, humanity will turn to solar radiation and new technologies most likely be developed to harvest and convert it to directly usable energy (i.e., electricity). It could be used up faster than its natural regeneration rate if humanity exhausts non-renewable resources stocks. Thus, resource use limits should be respected for the long-term sustainability of socio-ecological systems.

2.3 Urban metabolism

2.3.1 The concepts, definitions, and classifications

Urban metabolism (UM) is currently developing a research field addressing the flows of materials, energy, resources, food, and people in cities, providing a coherent framework to study human-environment interactions. Since the early 1960s, the issue of the complex relationship between society and nature was widely debated in global scientific literature, highlighting the dependence of cities on their life-support systems in terms of materials (i.e., glass, straw) inputs (i.e., natural energy) to maintain their metabolism (Hanya and Ambe, 1976; Newcombe, 1978; Duvigneaud and Denayeyer-De Smet,1977; Stanhill, 1977).

The city is an open system heavily dependent on exchanging resources with larger ecological systems to produce footprints and emissions (Basu, 2019; Tan et al., 2019; Tan et al., 2021). Thus, the urban economy, similarly to the human economy, depends on a continuous inflow of ecosystem goods and services for its metabolic activity, releasing in the process wastes and emissions.

The definition of UM derives from the metaphor of organism in biology, in which organism uses material and energy inflows from the environment to convert them through chemical reactions into nutrients required for growth and maintenance (Foster, 1999). Karl Marx (1867) was to propose and described 'social metabolism'. He defined social metabolism as human-nature interaction through the labour process in a village, thereby applying system thinking to show that human activities depend on humans' contribution: human labour, nature: materials (cattle manure), energy, and conditions (quality of the soil). Thus, he conceptualised metabolism as socio-ecological dynamics.

Later the two schools of UM were established: one school focused on socio-economic metabolism without any environmental context in which cities are embedded (Wolman, 1965), and the other school took forward the socio-ecological metabolism with a dominant role of nature in human activities (Zucchetto, 1975; Kennedy et al., 2010). The second school did not define UM but studied the ecological dimension of the urban environmental system characterised by exchanges of natural and socio-economic flows. The first school viewed UM as a material and energy flow exchange within cities, resulting in waste and emissions. Adept of the mainstream school Kennedy (2007) combined the material flow metabolism with energy metabolism in a single definition of UM and provided a consistent explanation for UM.

Later Zhang (2015) socio-economic (technological) and natural (organic) metabolic processes in the definition of UM, thereby identifying UM as a distinct type of socio-ecological metabolism. His definition included cities' dependence on ecosystems in terms of flows and internationalised ecosystems in UM. The definition of urban metabolism introduced by Musango and colleagues (2017) disregarded this recent development. Instead, similarly to Zucchetto (1975), focused on the combination of socio-economic and natural processes into socio-ecological processes in cities. The principal definitions used to describe UM are presented below (TABLE 1).

TABLE 1 Evolution of urban metabolism concept

Definition of urban metabolism	**Reference**
Metabolism of city involves countless input-output transactions… The input side of chart will show the requirements in tons per day of water, food and fuels of various kinds. The output side will show the metabolic	Wolman,1965

products of that input in terms of sewage, solid refuse, and air pollutants.	
… it may further our understanding of the energy basis of human systems.	Zucchetto, 1975
The whole integrated collection of physical processes that convert raw materials and energy, plus labour, into finished products and wastes...	Ayres, 1994
Households, as a kind of economic system, interact with environment to survive. In this process, households get resources from and give emissions back to environment. This integral pattern of natural resource flowing into and out of households is called household metabolism.	Liu et al., 2005
The sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste	Kennedy, 2007
We will treat urban metabolism as the gathering of all of the city's socioeconomic (technological) and natural (organic) metabolic processes	Zhang, 2015
Collection of complex sociotechnical and socio-ecological processes by which flows of materials, energy, people, and information shape the city, service the needs of its populace, and impact the surrounding hinterland	Musango et al., 2017

Ayres (1994) launched the third school, UM. He defined UM as a combination of industrial processes which transform materials, energy, and human labour into usable products and wastes. Although always used by Odum's school, human labour has not been incorporated previously into UM definition. This definition was similar to the mainstream school because it included only technological processes within socio-economic systems. However, this direction provided an insight into the sustainability of urban metabolic processes. Liu et al. (2005) developed a household metabolism concept, in which households interact with the environment to get resources and release wastes. His idea is reductionistic and does not provide a comprehensive picture of the metabolism of urban economies. This shows that the concept of UM is still developing. However, only the second school (Zhang, 2015) captures complex human-environmental interactions to assess the contribution of natural metabolic processes to the urban socio-ecological system. Ferrao and Fernandes (2013) developed a socio-ecological framework for UM, which reflect the definition expressed by Zhang (2015) (FIGURE 5).

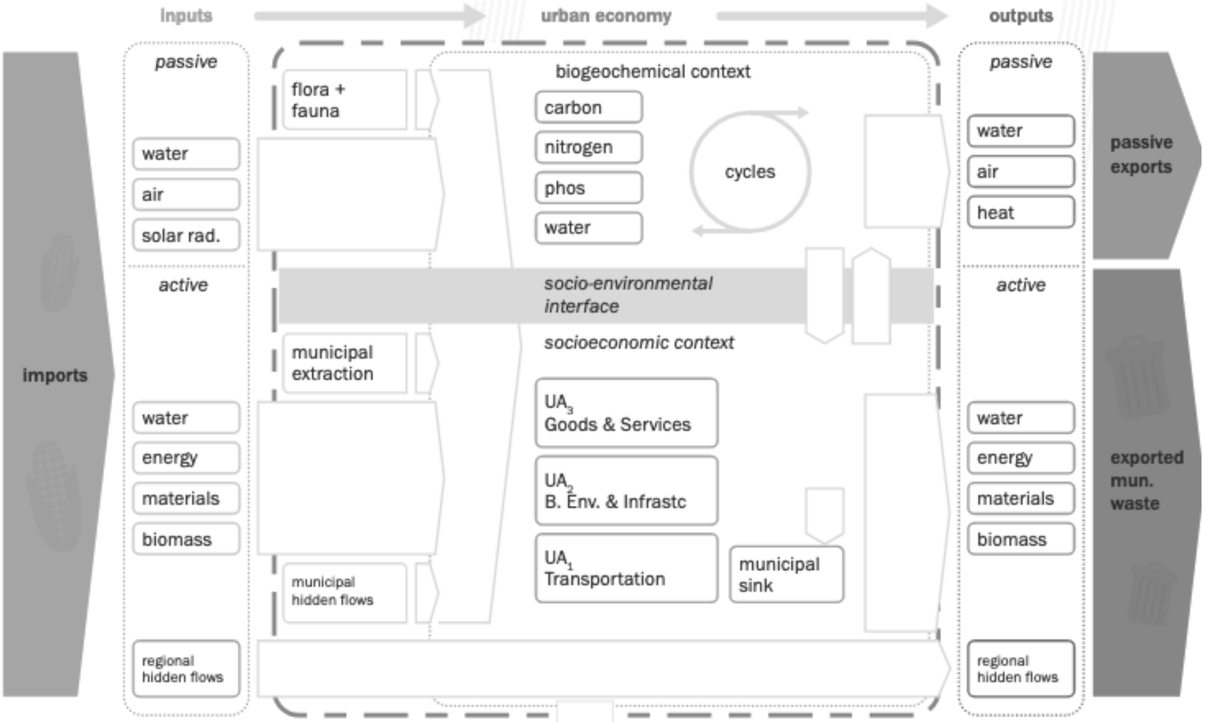


FIGURE 5 Urban socio-ecological metabolism framework. Source: Ferrao & Fernandez (2013:40).

2.3.2 Developments in models to study urban metabolism

In 1965, Wolman published in Scientific American a seminal article in which he developed an input-output model for a hypothetical American city of one million inhabitants. In his study, he downscaled national data to determine the daily quantities (tons) of water, food and motor fuel needed to sustain one million city residents and the daily amounts of waste (tons) of sewage, solid refuse and air pollutants discharged by the same population. He has aimed to resolve the pollution problem by looking into the input and output side of consumption activities, which led him to develop the UM concept (Derrible et al., 2021; Kennedy et al., 2007). Although his model accounted only for material flows exchanged between the city and countryside while omitting energy flows (i.e., electricity) and other materials (infrastructure materials and other durable goods), it was the first model in IE to reflect upstream and downstream impacts of consumption activities in cities (Decker et al., 2000; Kennedy, 2010).

The liner accounting model follows the "take-make-dispose" stages of the production process, resulting in stress imposed on local resource supplies and associated with a substantial environmental impact (see Chapter 2.1.4). Considering planetary resource constraints, in pursuing long-term viability and sustainability, cities rely on shifting from linear metabolisms to circular metabolisms (Musango et al., 2017). Therefore, linear metabolism results high impact on human health (i.e., greenhouse gas emissions), biodiversity loss, and reduction of capacity of ecosystems to provide ES (Didenko et al., 2018; Michelini et al., 2017; Wright et al., 2019). Haberl (2001) developed an extended energy metabolism model for societies and urban systems. He modified the analytical framework of MFA to include nutritional energy flows required to support societal metabolism. In his study, he combined commercial energy with nutritional energy flows through the energy conversion chain to account the for total energy needed to sustain the energy metabolism of society (Haberi, 2001) and to measure the environmental impact of the land-use change biomass harvest on the energy (CO_2) flows in ecosystems (Zhang, 2013). His approach was later applied to the network accounting model to study energy security and utilisation efficiency of urban industries (Zhai et al., 2018; Zhai et al., 2019)

Another vital contribution to the accounting of urban metabolic flows was made by Girardet (1990). He developed a circular accounting model for UM using the nature-inspired cyclical or closed-loop production system prevalent in the IE field (Wachsmuth, 2012). The circular accounting model follows the "reduce-reuse-recycle" stages of the production process, where wastes (or by-products) of metabolic processes in the city are used as the raw materials for it (i.e., industrial symbiosis) (Lucertini, 2020). Emulating a food chain where one organism's waste is another's sustenance allows decreasing environmental impacts and improves cities' resource utilisation efficiency and self-sufficiency (see Chapter 2.1.4). This model did not include the larger environmental systems in which the urban ecosystem is embedded, treating a natural system as an external source. Moreover, the circular model is a "black box" in which internal aspects of the city are ignored (Musango et al., 2017).

This model does not allow for identifying internal metabolic processes behind large non-renewable resource consumption (or their declining availability) and the associated environmental pollution (Fath et al., 2014). Such models can provide only an overview of urban metabolic efficiency and the degree of sustainability (Zhang, 2015). These shortcomings trigger the continuous self-organisation process of urban ecosystems, leading to the long-term mismanagement of raw materials, associated higher environmental costs (i.e., energy, materials), pollution, and considerable damage to economic activities.

Finally, Zhang et al. (2009) introduced a network accounting model to explore UM. They used ecological network analysis (ENA) to explore UM and develop a network accounting model. The application of ENA to UM allowed us to uncover internal metabolic processes and represent trophic interactions between consumers and resources (food web). The model was used to compare four Chinese cities (Beijing, Tianjin, Shanghai and Chongqing) based on the distribution of benefits and costs between each pair of industrial sectors and the metabolic transfer efficiencies among them in each city. The study found that transfer efficiency increases along with the increase in the number of transfers between each pair of nodes due to the rise in the cycling of energy, materials, and money. In addition, Zhang et al. (2009) found that mutualistic symbiotic relationships dominated in Beijing due level of cooperation between sectors in the management of the metabolic system being the highest. The advantage of network accounting models compared to 'black box' urban models is that they provide more direct support for diagnosing problems and suggesting measures to solve the issues, such as how to increase the efficiency of flows of energy and materials, how to increase the quality of life, and how to sustain development (Zhang, 2015). This model has been successfully applied to address energy security, resource use efficiency, industrial solid waste reduction, and sustainability of cities (Cui et al., 2021; Guan et al., 2019; Fath et al., 2014; Zhang et al., 2019).

Since 2009 there has not been any notable development in accounting models to study UM. Still, the number of publications on UM topic is increasing, highlighting the further development in this field in the future (Galychyn et al., 2020).

2.3.3 Disaggregation and multi-scale impact of urban metabolism

There is an ongoing debate on disaggregating (further uncovering) urban metabolic systems to capture the multi-scale impacts of urban ecosystems and single industries within cities. Analysis at multiple spatial scales has become increasingly important because cities, as the main concentrations of human environmental impacts, play an essential role in sustainable development at scales ranging from local to global (Zhang, 2015).

Kissinger & Stossel (2019) performed a multi-scale analysis city's material metabolism using the city of Tel Aviv (Israel) as a case study. This study identified problems in direct and indirect consumption of materials in Tel Aviv and the associated impact of waste disposal on national and global scales. However, advancing sustainability requires performing a comparative analysis of the implications of existing and proposed measures on the UM. The other issue is that this study is grounded on a linear accounting model for UM, jeopardising the sustainability of the urban socio-ecological system (see Chapter 2.3.2). The further research analysed the implications of existing urban and national policy measures for Tel Aviv's UM on local, regional and global scales in the context of changes in urban population growth and consumption patterns to reduce the magnitude of urban metabolic processes and improve the urban sustainability (Kissinger and Stossel, 2021). This study allowed us to uncover the source of materials on which a city depends beyond its boundaries, the most affected scales from urban emissions (i.e., GHG from electricity generation in the city), and the impact of imports from other scales on emissions emitted during local consumption activities (i.e., GHG from transportation fuel consumption). However, this linear accounting model is also a 'black box' urban model (see Chapter 2.3.2). Numerous studies apply a multi-scale 'black box' urban model (Clift & Druckman, 2016; Heinonen et al., 2020). However, in 2015 some studies explored UM using an input-output model, which only partly uncovered the 'black box' analysing direct environmental (CO_2) exchanged among sectors of urban economies (Chen et al., 2016a; Chen et al., 2016b; Fry et al., 2018; Wiedmann et al., 2016). Recently Fry and colleagues (2021) extended an impacts input-output based urban model from local to regional and national scales, which allowed them to analyse the direct impact of urban consumption activities across scales. The model failed to account for indirect impacts of urban metabolic processes and did not directly diagnose problems (directly identify critical sectors in production and consumption patterns) but provided a basis for identifying and analysing the complicated processes that may lead to this critical situation in some sectors (Fath, 2014; Zhang, Zheng, & Fath, 2014). In TABLE 2, different approaches to the study impacts of UM at various scales are summarised.

TABLE 2 Approaches to the study impacts of urban metabolism at different scales

Scale	**Accounting model**	**Approach**	**Methodology**
Nested	Linear	'black box'	Material flow analysis (MFA)
Nested	Network	'grey box'	Input-output analysis (IOA)

Urban	Network	‘network’	Ecological network Analysis (ENA)

Despite all these efforts to improve the ‘black box’ and ‘grey box’ urban model, there has been barely any advance in the accounting model to study UM after 2009. Most developments have been performed using the input-output model (Wu and Chen, 2017; Zhang et al., 2014; Zhang et al., 2016), which is an incomplete network model based on the mainstream school of UM originated from the IE field (Wolman, 1965; Haberi, 2001) the most novel ones applied to the national scale such as the advance of Haberi’s energy metabolism approach based on energy conversion and use in the national economy (Guevara, 2017) (see Chapter 2.3.2). The other issue was that environmental support provided by natural ecosystems to the urban economy was excluded from UM studies, thereby focusing on the user-side perspective of UM (Wang, 2020; Xia et al., 2020; Xu et al., 2021). The studies that employed the network accounting model have not solved this problem, thereby excluding work of nature done to produce energy and material flows used in the urban economy. However, the network accounting model was improved to assess each industrial sector's integral influence and dependence on the whole urban metabolic system to determine the sectors that jeopardise the energy security of Guangdong Province (Zhai, 2018; Zhai, 2019).

Moreover, the efficiency of acceptance and transfer of energy by each sector in the urban metabolic system were identified, providing insight on the improvement of the level of organisation to improve the system’s efficiency. However, this advancement has not been applied to the urban scale and only identified critical sectors in production and consumption patterns in cities disregarding the contributing sectors to the crucial situation of identified sectors. In TABLE 3, recent improvements in the network accounting model are briefly summarised.

TABLE 3 Advancements in network accounting model during last decade

Scale	Field	Method	Recent advancements
Urban	Environmental Accounting	Emergy Synthesis (ES)	Has been addressed since 2009
Urban/ National	Industrial Ecology	Input-output analysis (IOA)	Energy conversion and use in national economy (human health)
Urban	Network Science Methodology		Energy security of city assessed based on total influence and dependence of each sector (human well-being).

Ecological
network
Analysis (ENA)

Estimation of efficiency of
acceptance and transfer energy
by each sector in the urban
metabolic system allowed to
improve system's efficiency
(urban ecosystem health)

It's clear that future studies should explore the metabolism of the urban socio-ecological system since natural ecosystems' health and nature's contribution to the urban economy is disregarded among studies that employ the network accounting model. Assessing the multi-scale impacts of urban metabolic processes should not precede the improvement in the network accounting model. FIGURE 6 illustrates the concept of scale and the associated accounting model and methods that can contribute to a fuller understanding of UM.

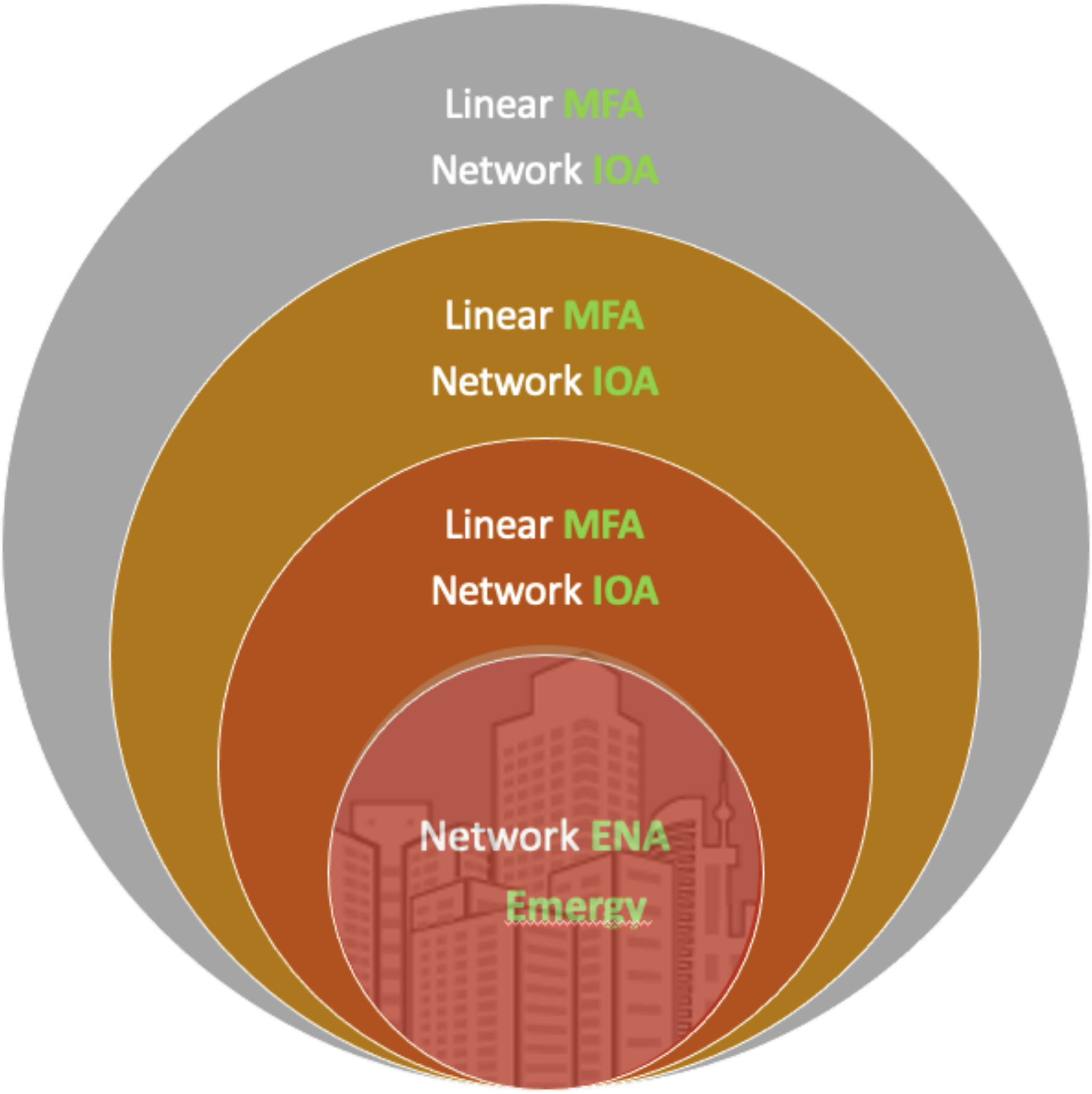


FIGURE 6 The multiple scales, accounting model and methods to study urban metabolism.

Including environmental support provided by natural ecosystems and improving methods to identify the sources of problems that manifest in critical situations in other sectors and input and output sides constitute the novel direction aimed to advance research on network accounting models. These improvements in the network accounting models can decrease the impacts of the urban system on the natural ecosystem that sustains it (Zhang, 2015) and promote more sustainable and efficient development of urban metabolic systems.

2.4 Integrating Environmental Accounting and Network Science Methodology to study urban metabolism

The world's population is entering a new urban era in which the planet's ecology is increasingly influenced by human activities, with cities as important centres of demand for ecosystem services (ES). With the projected doubling of urban populations, there will be an accelerating demand for these services in the future (Elmqvist, 2015). Humans play an essential role in cultivating and enhancing ES to maximise their delivery to urban economies (Comberti et al., 2015). The sustainability of urban ecosystems depends on the maintenance of healthy ecosystem functions providing humans with a host of valuable ecosystem services (ES), including food provisioning, water purification, CO_2 sequestration, climate regulation, and natural protection (Costanza et al., 1997; Daily, 1997; Barbier et al., 2011) vital for the human economy and well-being(Russo et al., 2014). ES are differentiated by the natural input (i.e., solar radiation, rain) and human-driven inputs (i.e., electricity and other energy products, fertilisers, machinery) required to support them. The cost of services supported by human-driven inputs (provisioning services) is higher compared to different categories of ES due to the fixed amount of non-renewable resources on Earth (i.e., coal deposits) (Shafiee and Topal, 2009; Utama et al., 2014). The environmental costs refer to the total (direct and indirect) amount of matter and energy invested in the upstream processes to make the actual flows available to the final users (Häyhä and Franzese, 2014). The natural and human-driven inputs are supplied to the urban system to be used in a) production of goods and services within the urban economy, b) to support final users (population), and c) to generate emissions and waste (Russo et al., 2014).

The integration of the environmental accounting under the theoretical frame of urban metabolism (UM) can help analyse how cities use raw and processed resources supplied from larger environmental systems to maintain and reproduce structures and functions of the urban environment (Russo et al., 2014). Here, adopting the network accounting model to study UM directly identifies problems in production and consumption activities manifesting in upstream environmental costs (i.e., high environmental costs of human-driven inputs) and huge downstream environmental impacts (Fath et al., 2014; Zhang, 2015). In addition, the downstream system boundaries of urban economy in 'black box' urban models are not clearly defined (Schmid, 2020). Such models group together intermediate outputs of production processes within an urban economy (a) and requirements of final consumers (b) into the 'output' category disregarding their 'life cycle stage in the urban economy, specifically transportation and distribution of goods and services to final consumers.

Environmental accounting methods allow the assessment of both environmental costs and impacts generated while exploring UM, whereas Network Science methodology allows for improved direct assessment method of IE, namely Input-Output Analysis (IOA), to perform ENA to analyse total (direct and indirect) socio-economic and ecological flows exchanged among sectors of urban economy and between urban economy and environment. FIGURE 7 shows an attempt to conceptualise an integrated view of urban socio-ecological system functioning concerning urban metabolic processes. Three main windows of attention can be identified regarding UM generation and use: 1) environmental costs (assessed using emergy accounting), 2) distribution of trophic levels and cost-benefit relationships among sectors of urban assessed in physical and monetary terms), and 3) generated environmental impacts (evaluated using EE-IOA).

A comprehensive approach to UM should capture the complexity of city networks while accounting for the use of raw and processed resources for building and maintaining urban structures and functions, the production, transfer and consumption of goods and services, thus integrating network theory and biophysical environmental accounting frameworks through the application of a broad multicriteria framework.

Several disciplines and methodological approaches have been employed to study nature's contribution to economic activities in cities and the environmental impact of these activities.

Instead of focusing on partial information about the metabolism of urban socio-ecological systems using single-criterion analysis or method, integration of biophysical accounting and network science approaches, further improved by a detailed investigation of environmental impacts of in production (upstream) and consumption (downstream) parts of urban economy, improved will ensure a broader understanding the environmental cost and benefits hidden in ecological and socio-economic flows exchanged among industries and the environment. This cannot be archived without further disaggregation of urban systems and exploration of multi-scale scale impacts affecting production processes and economic activities in cities. To archive this objective interdisciplinary cooperation, including ecologists (emergy analysts and network scientists), economists, urban planners, biologists, and geographers to deal with different issues arising from further improvement and testing of this multicriteria approach. The comprehensive assessment of the state (condition) of socio-economic metabolic processes in cities in terms of sustained cost and received benefits is crucial for the long-term sustainability of urban economies and their environmental life-support systems.

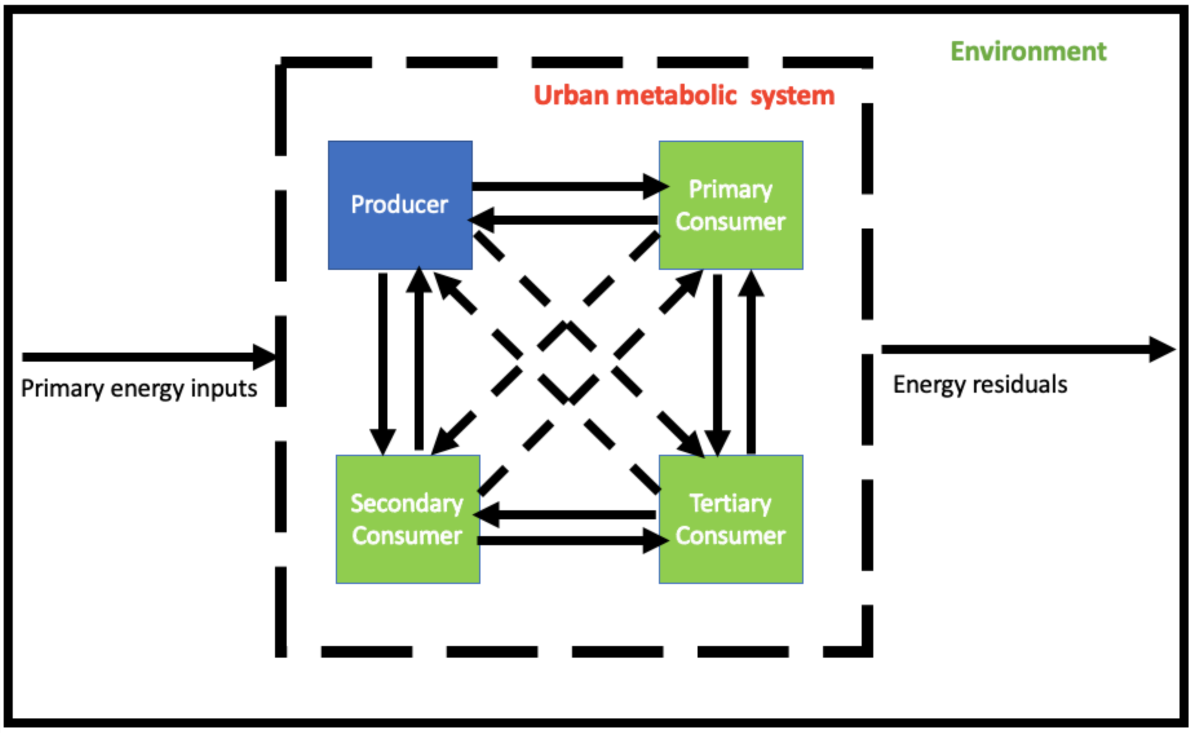


FIGURE 7 Multicriteria framework showing costs, cost-benefit relationships, and impact as the three main dimensions of urban metabolic processes involved in the production, transfer and consumption of goods and services

3 METHODOLOGY

3.1. Integrated Environmental Assessment of urban metabolism

Environmental accounting is an essential tool for understanding the matter and energy flows at the entry point into any system (natural, socio-economic, or socio-ecological) and at the point of exit from any system. This tool alone can provide information about economic and environmental costs sustained by users (or donors) to support socio-economic or ecological systems in providing actual flows to final users (Buonocore et al., 2014; Hayna and Franzese, 2014).

Environmental accounting can be used to provide an overview of environmental costs and environmental performance (resource efficiency) of the urban metabolic system (amount of natural, human-dominated inputs, and human labour required to produce a unit of good or service) when applied to UM (Zhang, 2015; Huang et al., 2018). The environmental costs (see Chapter 2.4) The environmental costs and resource efficiency of the urban system can be estimated using direct and indirect commercial energy (fossil and nuclear energy flow, as well as renewable energy flow under human control), materials (biomass, metals, construction materials), water, CO_2, and flows of land cover (Ulgiati et al., 2006; Viglia et al., 2018).

Environmental accounting methods can be divided into two categories. The first category assesses direct and indirect resource use to produce 1 unit of product or service. These approaches consider the material, energy and monetary inputs into upstream production processes of the urban economy. The second category deals with the investigated. Upstream methods account provide insight into the magnitude of direct and indirect (implied) environmental burden, self-sufficiency and the dependence of systems on imported resources, and the sustainability of a given system (large economic yield versus low environmental stress).

Downstream methods focus on the output side of the system (released wastes and emissions to air, water, land), thereby providing insight into the problems upstream (i.e., excessive use of non-renewable resources, a large share of imported resources) or to point out to performance (resource efficiency) issue in the system if the low level of resource use results in the considerable environmental impacts.

In Environmental Accounting, an inventory of the input flows in terms of mass or energy is used to calculate the total environmental input into the system and the environmental performance. Such inventory includes ecological (natural and human-dominated inputs) and socio-economic inputs (human labour and services), providing a compressive picture of socio-economic and ecological supports from the different spatial and temporal scales.

In our study, we integrated environmental accounting with the network science methodology resulting in the complex ecological and socio-economic exchanges among industrial sectors of the urban economy. Therefore, the environmental support in this study was assessed based on the total cost of energy consumed by each component of an urban economy. Where represents the sum of the environmental cost of consumption of energy supporting each sector i:

$$T_i = f_{ij} + Z_i$$

Where Z_i is the environmental cost of natural energy inputs and f_{ij} *is* environmental cost of the amount of energy sold from each sector j to each sector i in energy units

Resource and self-sufficiency in this study are defined as a pairwise and system-level dependence of each industrial sector in the urban economy. System-level dependence stands for the capacity of each sector to receive energy and money from all other sectors in the system to improve its ability to drive the development of all other sectors. The availability of local energy sources, land for production facilities (i.e., agriculture) and population density play the central role when the shortage of products to support a specific sector's production is dealt with through imported products from other provinces. In this case, the industry needs contribution from different sectors to improve its resource and self-sufficiency to contribute to the development of other sectors. Pairwise-level dependence stands for the reliance of a specific industry on imported natural resources (i.e., wood biomass), energy products or economic services from any sector to replenish its production to meet the demand of this specific sector and other sectors. In addition, benefits or costs derived from an interaction with a particular industry also reflect pairwise-level dependence. When the relationship between each pair of components is mutually beneficial, the self-sufficiency of the sectors increases, and vice versa. The sector receiving more benefits improves its self-sufficiency.

To sum it all up, the resource and self-sufficiency of each sector are estimated based on direct and indirect contributions to -and -from each sector of the urban economy, control and dependence relationships among each sector of the urban economy, and benefits and costs implied in these exchanges. Thus, the resource and self-sufficiency of each industry can be measured if all inputs and outputs from the compartments (sectors) of the urban economy are known:

$$f_{ij} + Z_i = f_{ji} + Y_i$$

Where Z_i and Y_i are emergy embodied in natural energy inputs and outputs, respectively.

Ultimately, combining these methodologies allows us to reveal components facing problems (low rank-based contribution exchange and consumption) and the components responsible for the issues in the target components. The direct environmental support to the urban economy was estimated through the multi-criteria framework, which integrates emergy synthesis and IOA, used to analyse the interdependence of industries in the urban economy. On the other hand, the indirect environmental support was estimated using ecological network analysis (ENA)- a network science method used to analyse the structure and functions of ecological systems.

Conversion factor measures environmental cost (direct and indirect amount of money, energy, or environmental resources) required to produce 1 unit of ith input to the system. The lower value indicates that the system is more efficient in processing the total environmental resources to maintain 1 unit of ith input. Concerning the production process, this means the total E to a single process ('black box' urban model) is divided by the sum of f_i reflects the performance of the investigated process:

$$e_p = g + f_i \, e_i / \sum_{i=1}^{n} f_i$$

Where E is the sum of all environmental costs associated with the production process, $\sum_{i=1}^{n} f_i$-is the total raw amount of product expressed as an amount of money or energy content, e_i is the direct and indirect amount of money, energy, or environmental resources required to produce 1 unit of ith input, g- solar energy inputs into production processes, e_p is the total environmental cost needed to make 1 unit of product used as input into the production process. The upstream method of environmental accounting implemented in this work will be described in the next sub-chapters.

3.1.1. Emergy Synthesis

Emergy Synthesis (Brown and Ulgiati, 2004, Odum, 1988, Odum, 1996) is an environmental accounting method that accounts for the direct and indirect solar energy costs of ecological and socio-economic inputs into the production system (or process) based on the principles of thermodynamics. This method is based on backward linkages in the system of interest, with solar radiation being considered a starting point because of their no backward linkages to solar energy. According to this method, the total environmental support provided from the global scale of the biosphere to the UM consist of environmental costs of ecological inputs (free environmental and human-dominated inputs) and socio-economic inputs (labour and services) (Herendeen, 2004; Russo et al., 2014; Viglia et al., 2018). In other words, total environmental support to the urban economy includes the work of the environment to make a product and for the human economy to process it.

The emergy method links both the socio-economic and ecological systems (Dong et al., 2008; Saladini et al., 2018; Pan et al., 2021) through the work of nature and society (Brown and UlgiatI, 2014; Zhang et al., 2016). However, the primary benefit of applying emergy analysis to socio-ecological systems such as industrial parks or cities comes from using the same unit of measurement to compare socio-economic and ecological systems (i.e., solar energy) (Liu et al., 2019; Sha, Melin,&Hurme, 2013). Transformity is the ratio of the total solar energy input required to make 1 unit of available final energy (exergy). Transformity is considered an energy quality factor, with the higher transformity reflecting the higher value (quality) of energy due to the ability of the concentrated energy forms to do more work (Brown and Ulgiati, 2004; Midžić, Štorga, & Marjanović, 2014). On the other hand, low transformity reflects lower costs required to process environmental flows to generate 1 unit of an energy product or economic service. This conversion ratio could also be called specific emergy when each input's raw amount is expressed as matter amount (seJ/g).

The emergy is estimated from available energy(exergy) or the amount of money and transformity.

$$\text{emergy (sej)} = \text{transformity (sej/J)} \times \text{available energy (J)}$$

$$\text{emergy(sej)} = \text{transformity (sej/\$)} \times \text{available amount of money (\$)}$$

The sum of emergy implied and ecological (i.e., energy) and socio-economic inputs (i.e., money) reflect the total environmental support provided to the urban socio-ecological system (Asamoah et al., 2017; Liu et al., 2021; Viglia et al., 2018).

3.1.2. Emergy accounting based on matrix algebra

The matrix algebra (MA) is a family of methods for measuring energy quality (transformity) in ecological and economic systems based on solving simultaneous linear equations. These methods estimate transformations (quality equivalent units) in complex ecological and economic network data (energy and monetary input-output tables).

The first of this family of methods, called the Quality Equivalent Method (QEM), was developed in Patterson in 1983 in parallel to the Emergy methods introduced by Odum. The quality equivalent units (δ) – are the units that measure the quality of each energy form in the socio-ecological system by applying the specific coefficients determined by solving a series of linear equations. Each linear equation represents the energy (energy conversion chain) or economic processes (distribution of producer outputs throughout the economy). Therefore, QEM fulfils the same function as transformity in the emergy accounting method and can be defined as a transformity of energy and monetary systems. Unlike the QEM emergy method only consider backward linkages and is inapplicable to the forward links.

Consequently, QEM assesses the complete economic and energy transformation process, consisting of upstream and downstream operations.

Moreover, QEM does not rely on Emergy algebra methods and instead applies statistical criteria to allocate the emergy inputs to multiple process outputs. This method is assumption-free and removes the requirement to apply decision rules to avoid double counting.

Furthermore, both the emergy and some methods of matrix algebra, namely the matrix inversion approach developed by Costanza, use solar energy as a numeraire, indicating that it's the only primary direct input into ecosystems (Franzese 2009). Lastly, QEM is free of constraints based on the a priori assumption that all processes should have an emergy-based unity efficiency. In natural complex socio-ecological systems, emergy-based process efficiencies are rarely the same because of the existence of residuals of each process. The method allows equal and unequal process emergy efficiencies by solving simultaneous equations.

The main challenge in applying those methods is inapplicability to the underdetermined systems (processes less than quantities). The other problems appear in the process of practical implementation of those methods: non-square matrices, joint production (co-products), negative transformities, matrix singularity (non-invertible matrix), equal process efficiencies (emergy inputs of industrial sectors are identical to their emergy outputs), choice of numeraire and non-unique solution vector of transformities and mathematical elegancy (Patterson 2012; Patterson 2014).

The integration of two MA methods: the matrix method with reflexive practice, allows to estimate transformities of industrial sectors from energy and economic systems and to overcome methodological problems associated with those two approaches. The matrix method is a MA method that allows for estimating transformities from physical and monetary input-output data (Hannon et al., 1986; Patterson, 2012; Patterson, 2014). Moreover, the reflexive method helps convert energy or value-added economic matrix into an emergy-evaluated matrix that guarantees the positive vector of transformities without prior knowledge. Lastly, the reflexive method allowed to overcome a problem associated with the artificial aggregation of columns or rows of matrix to make the matrix square (number of commodities equal to the number of industries.

The emergy-evaluated version of energy and monetary matrices (R) was determined (Patterson, 2014).

$$\mathrm{R} = \mathrm{W}^{\mathrm{T}} \times \mathrm{p}$$

Where W^{T} - transposed version of monetary (or energy) valued-added matrix W (process x quantity), P- diagonalised matrix of solar energy transformities (quantity x quantity). Then, the extended 'outputs matrix' S (p x m) can be constructed, where the p-number of the positive elements (outputs) in matrix W. The values of this matrix are obtained through an allocation as a proportion of all inputs (−) of a relevant process to each process output (+). The construction of the extended 'inputs matrix' T (n x m), where n –number of negative elements (inputs) in matrix X. The values of this matrix are obtained through an allocation as a proportion of all outputs (+) of a relevant process to each process input (−).

The subsequent step is associated with constructing the aggregated 'outputs matrix' U. U matrix is (n × m) of commodity inputs to produce each of the process n outputs. Matrix U is constructed by summing all the sub-process rows in T with the same output (+). Later, we built an aggregated 'inputs matrix' V. V is a matrix (m × g) of output processes directly resulting from each g input. Matrix U is constructed by summing all sub-process rows in S with the same input (−). As a result, we derive aggregated inputs (forward linkages, V) and aggregated outputs (backward links, U) matrices, respectively. Such aggregation procedure always results in constructing a single version of square matrix U and V. Consequently, using both derived square matrices U and V, one unique solution transformity vector (p) in numerical magnitude can be obtained.

It is important to note that the reflexive method allows the use of inconsistent equations by incorporating residuals into the system of linear equations. This is because real ecological (i.e., energy, water) and economic systems usually have unequal process emergy efficiencies. Using an inconsistent system of equations, dissipation losses are excluded from the procedure associated with estimating transformities. Therefore, matrix U and V can be purged from residuals before being incorporated into the matrix inversion equation. An example of the application of such an approach is specified in Patterson (2012). This vector can be applied to ecological and economic systems (Patterson, 2012). Unfortunately, in using this approach, energy residuals were non separated from other energy products, thereby not allowing only consistent linear equations. The reason was that the data on monetary losses of industries were not available. Therefore, zero value for 'waste heat' was assumed, implying the absence of distinction between dissipation and production (Patterson, 2012). The subsequent studies could address this gap by exploring the ways to estimate the economic losses of industries and purge matrices U from by-products (i.e., waste heat from coal-fired power plants). In energy input-output analysis, embodied energy is assumed to be fully conserved without any dissipation and losses, namely, the energy embodied in the output of each production process and consumption activity is equal to the energy embodied in its intermediate inputs and its direct energy inputs (Guevara and Domingos, 2017). Approaches of matrix algebra that allow the system of inconsistent equations to be assessed to estimate transformities (i.e., reflexive method) constitute the crucial future direction of research. The preceding step would acknowledge that ecological and economic systems cannot be described using the determined system of equations since they are more complex.

In this context, the sewage and waste sector play an essential role since the data incorporated in the collection and waste management of waste and water treatment reflect the amount of residual collected, recycled, and disposed to landfill. Moreover, the production of combustibles wastes, the counterpart of capital formation in monetary accounts, constitutes a part of the final demand category. Therefore, disaggregating the final demand category to extract the data on the production of municipal and industrial waste and then subtracting the data on treated and recycled waste from the waste management sector, the energy residuals and monetary costs for their additional treatment can be obtained (number of negative resources produced plus the number of negative resources treated). A more straightforward approach would be to use the value-added matrix (consumption matrix, V subtracted from production matrix, U) (Heun, 2018). This matrix consists of positive elements representing energy or economic outputs (production of energy products or economic goods and services by each industry) and negative elements representing energy or monetary inputs (consumption of energy products or economic goods and services by each sector). Then, by summing over each column, it is possible to arrive at the total value added by each industry. For the value-added monetary matrix, the column sum is always positive instead of the value-added energy matrix, where energy and tertiary industries can have negative values (produce less usable energy than they consume). The column sum of each energy and economic value-added matrix entry represents the residual vector. By adding this vector to the system of consistent equations, we can separate the actual energy and monetary transactions among sectors and dissipated energy to see how much environmental support is associated with each industrial sector's consumption. The matrix V (use matrix) reflects the consumption without energy and monetary losses when purged from residuals. These tables (U and V) can then be used to construct an emergy input-output table and estimate the total environmental support provided to each industrial sector in the urban economy.

The matrix inversion method can be significantly improved by using a pre-conditioning procedure via the reflexive method. This procedure aims to formulate the Kernel matrix Z that can be inserted in the matrix inversion equation to produce a guaranteed positive vector of transformities. The vector of transformities in the matrix inversion method is determined through the multiplication of primary inputs (solar energy inputs) by total direct and indirect energy or economic requirements of industrial sectors (economic activities):

$$\mathrm{p = g(U - V)^{-1}}$$

Where "U" is the energy supply matrix (m × n), "V" is the energy use matrix (m × n), "g" is the numeraire vector (1 × n) of solar energy inputs to an industrial sector, and "p" is the transformity vector (1 × m).

The formula above is based on commodity technology assumption. According to Hannon et colleagues (1986), the post-multiplication of above by g-1(total output by industry in energy or monetary units) yields:

$$\mathrm{p = g \times g^{-1}(C - B)^{-1}}$$

Where $g \times \mathrm{g}^{-1}$ is direct solar energy requirements matrix (direct amount of solar energy per 1 unit of the total output of an industrial sector (emergy of monetary), $(C - B)^{-1}$is embodied energy (or monetary) requirements matrix (direct and indirect amount of energy (or money) required to produce 1 unit of a commodity).

Both formulas technically are the same and can be used interchangeably. However, post-multiplication by g^{-1} reveals that direct emergy intensity translates into transformity vector (embodied solar energy per 1J or €) through total requirements matrix yields solar energy embodied into 1 unit of energy or monetary product. The primary direct solar energy input into ecosystems (solar radiation) enters the supply chain of each commodity (forward linkages) to estimate direct (outside of the city) and indirect (in town) solar energy used in transformations to produce 1 unit of the product of energy and non-energy industry, respectively. This approach has been widely used in energy input-output analysis (Miller and Blair, 2009) to estimate ecological prices in complex environmental and economic systems (Bullard and Herendeen, 1975; Costanza and Neill, 1984; Hannon et al., 1986). Therefore, the correct use of matrix algebra and computation of emergy based on its definition as embodied solar energy per unit of available energy or money is confirmed.

By substituting $(U - V)^{-1}$ for Z^{-1}, the vector of transformities p (1 × n) could be obtained:

$$p = g \times Z^{-1}$$

Where inverse of Kernel matrix "Z" is equal to $(U - V)^{-1}$. The reflexive method can adjust the matrices "U" and "V" but not change their purpose (backward and forward linkages, respectively). Thus, these matrices are interchangeable.

The subsequent steps follow the mufti-criteria assessment framework developed through the integration of a hybrid-unit input-output model with the emergy accounting method: regional monetary and energy input-output tables were multiplied by their respective vectors of transformities (P) and summed up to calculate the total emergy consumed by the urban metabolic system and construct the emergy input-output table, and to develop a hybrid-unit emergy input-output model.

3.2 Network Science Methodology to study urban metabolism

Network Science Methodology to study urban metabolism builds on the input-output analysis (IOA) of the urban metabolic system, a method of IE that explores direct exchanges of matter, energy, and environmental resources among sectors of an urban economy. Flows of embodied water, energy, wastes and emissions (greenhouse gases), natural resources among producing and consuming industries (including final users) are quantified to assess the (economic or physical) cost of total direct input of goods and services into each production process (or consumption activity) within the economy for its production of goods and services (output) measured as the cost required to satisfy the demand of other industries within the economy. Thus, by conceptualising the socio-economic system as a food web of complex feeding relationships in nature, where the predator (i.e., herbivore) receives the energy and matter embodied in energy flow from the prey (i.e., primary producer) by eating the prey, the energy and matter implied in such exchange among industries in the urban economy can be revealed. This methodology provides a basis for understanding and improving the overall efficiency and sustainability of the urban metabolic system.

3.2.1 Input-output analysis to study urban metabolism

An Input-Output Analysis (IOA)- method of industrial ecology (IE) explores the interdependence of energy and non-energy industries in the urban economy (Miller and Blair, 2009). The input-output analysis (IOA) -is an approach developed by professor Wassily Leontief in late 1966 to analyse the interdependence of industries in the national economy. Essentially, this method was a common tool used in Economics and IE (Duchin, 1992). However, the full potential of this method to explore embodied flows exchanged among production processes, and consumption activities was realised through the integration of the systems ecology perspective and economic IOA for accounting of ecological (water, energy, natural resources) elements embodied in intermediate consumption (Zhang et al. 2014a; Chen, 2013; Chen et al. 2019).

Today, it is widely used to study the exchanges of monetary and energy products among industries on local, regional, national and even international scales. The approach describes industries that *consume* products and services of other sectors (input) to *produce* their good or service (output):

$$\mathrm{XA} + \mathrm{V} = \mathrm{XA} + \mathrm{Y}.$$

Where each a_{ij} of n× n input requirements matrix A represents the monetary input of sector I purchased directly by sector j (along with columns) to produce 1 unit of monetary output of sector j, X- total industrial input (in monetary or energy units), and Y--is an n×1 vector of final consumption (total sales from processing sector i to the end-user f in monetary or energy units), V-value added (earnings generated by the production of goods and services, and XA is an intermediate consumption (sales from processing sector i to purchasing sector j) usually designated as Zi.

The left part of the equation (input side) indicates the purchase of various products by consuming sectors and the final user (domestic industry). In contrast, the right one (output side) shows the composition of consuming sectors' inputs required to produce their outputs. The MA methods stem from IOA.

IOA provides the details on direct exchanges among industries in the urban economy, including final demand. Unless multiplied by specific conversion factors, namely embodied ecological intensity, all flows in monetary or energy terms reflect direct exchanges among intermediate sectors and final demand. The final demand also constitutes embodied quantity in both the embodied energy and emergy-based estimations. This category can be derived from an equilibrium equations of ecological elements, a combination of IOA (Hannon et al., 1986; Patterson, 2012; Patterson, 2014) with tools of systems ecology (Zhang et al., 2014; Zhang, Zheng, & Fath, 2014; Li et al., 2018; Liu et al., 2013):

$$pG_i + pZ_{ji} = pZ_{ij} + pF_j$$

Where pG_i is emergy embodied in natural energy inputs, Zij- is emergy embodied in intermediate flow from each sector j to each sector i, "f" is the transformity vector (1 × m). Fj is an n×1 vector of final consumption (total sales from processing sector *i* to the consumer *f*).

The hybrid-unit input-output approach builds on the balance equation's output side (right parts). When passing from conservation of embodied energy to the balance equation in emergy units, the balance holds since MA does not follow emergy algebra rules to deal with problems arising from accounting for co-products and feedback in a network (Li et al., 2010; Patterson, 2012; Patterson, 2014).

Hybrid-unit input-output model is used to analyse the interdependence of energy and non-energy industries in urban economies. This model is composed of two linked models: a model of the energy industries (producers) in physical units (emergy units); and a model of the rest of the economy (consumers) in monetary units (Bullard and Herendeen, 1975; Guevara et al., 2017), and it also conforms to the conservation of embodied energy. A simplified version of the model is presented below:

$$g = \alpha_\theta \times h + \alpha_\tau \times f$$

Where "g" is the total emergy consumed by each industrial sector, and the 'renewable energy sector', "h" and "f" are respectively the sub-vectors of final demand for products of energy industries (in seJ) and non-energy industries in €. "α_θ" and "α_τ" are respectively the sum of direct and indirect emergy purchases required to produce a 1 seJ of output, and the sum of direct and indirect emergy purchases needed to produce a 1 € of output.

'Renewable energy' sector was incorporated into the model as the energy industry and the only ecological component of the urban socio-ecological system. The ecological exchanges between this sector and the urban economy reflect the environmental cost of ecological interaction between the environment and urban economy. The economic services provided by each energy sector constitute an indirect contribution to the urban economy. Ultimately, this method estimates the total environmental support provided to each compartment of the urban-socio-ecological system and the whole system. However, network science methodology needs to be applied to account for the ecological cost of all indirect interactions in the urban metabolic system and to uncover the structure and functions of the urban metabolic system to directly diagnose the problem to identify the reason behind these problems to improve the overall resource efficiency of the system.

3.2.2 Ecological network Analysis

Ecological network analysis (ENA) is a systems-oriented methodology to analyse within system interactions used to identify holistic properties that are otherwise not evident from the direct observations (Fath et al., 2007). Patten (1978) developed this method based on Leontief's IOA (1966) and the synecology perspective proposed by Odum (1959).

When we include ecological systems in which socio-economic systems studied using IOA are embedded, we turn to ENA, a method that studies socio-ecological systems (Fath and Patten, 1999; Fath et al., 2007). At the heart of ENA lies Environ concept (Pattern, 1978; Fath, 2001). Environs are afferent and efferent networks leading to and away from open systems that are components of systems at higher scales (Fath, 2001). Each system element consists of two system-bounded environs: one acts on the defining component, and the other is acted upon by the element (Patten, 1978). Input environs reflect backward linkages traceable backward linkages from systems' outputs to systems' inputs, while the output environs reflect forward links from the system's inputs to the system's outputs. In simple terms, this arrangement reflects that in the ecosystem (city, country, etc.), all components exchange energy and matter flow among themselves and the surrounding environment. This also conforms to the perspective of IE, wherein the wastes and by-products of one industry within the city become an input for the other ("zero-emission" concept). Thus, this approach applies system thinking and socio-ecological system perspective to UM, making zero-emission it possible to analyse the structure and functions of urban metabolic systems.

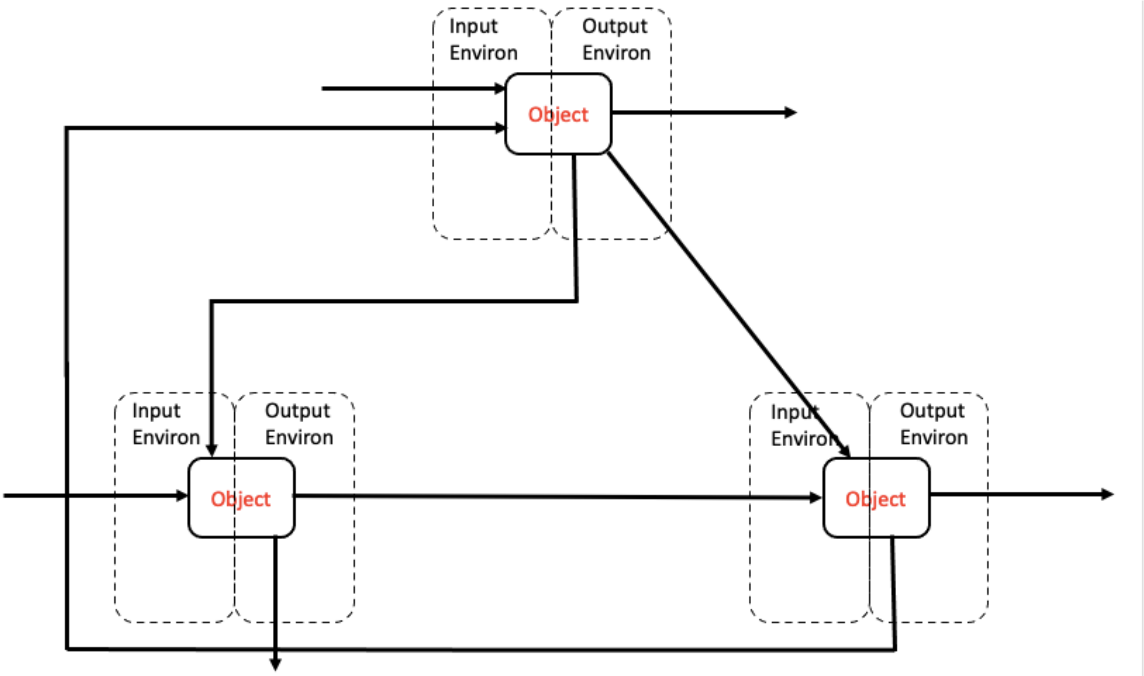


FIGURE 8 Illustration of environ model showing energy (or matter) input-output linkages among metabolic system's components and with a larger environment. Adapted from Fath and Patten (1999)

This method is used to build a flow (or flow-storage) model of the system from input-output data to account for embodied (direct and indirect) ecological flows among components of the urban metabolic system to reveal its structure and functions (Zhang et al. 2014b). The system's structure can be analysed using Structural Analysis. Structural analysis is used to analyse the pattern and connectivity of network models (Fath and Borrett 2006). These two properties of network models are explored by identifying all possible pathways between each pair of components in the network (Fath and Borrett 2006; Fath 2012). The System function is reflected in the number of mass-energy transactions between components (Fath and Patten, 1999). The transaction in socio-economic models has the dimensions of mass or energy per unit area and unit time (M/L^2T). The throughflow analysis determines flows along direct and indirect paths to measure the total medium (energy, money, material, environmental resources) consumed by each urban economy component (industrial sector).

Storage Analysis is used to identify the contribution to storage (components) along direct and indirect paths. Together, Throughflow and Storage Analysis constitute the flow-storage model based on which component influences the system's behaviour, and properties (i.e., indirect effects) can be determined. The Control and Utility Analysis are approaches that can identify the influencer based on the nature of the direct and indirect relationships between components. Control Analysis measures direct and indirect dependence and control between each pair of elements (Fath and Borrett, 2006; Li et al., 2012). Utility Analysis is used to assess direct and total (direct and indirect) benefits and costs between any pair of components in the system (Fath 2012; Zhang 2014a). In the core of the ENA are direct transactions (trophic interactions) of medium (i.e., matter, energy, money) between originating and terminating node (i.e., j → k and k → i in the three-component model). The indirect effect is relational, i.e., based on the relationship rather than a direct transaction (i.e., j → k→i in the three-compartment model). In complex systems like cities, ecosystems, socio-ecological systems, indirect pathways and associated flows (and storage) increase infinitely. These indirect relations in a more complex network can be represented using the infinite power series associated with an increase in the number of pathways until all indirect interactions in the system are accounted for:

$$B = A^0 + A^1 + A^2 + A^3 \ldots + A^m + \ldots = (I - A)^{-1}$$

Where A^0 is the originating and terminating node coincide (zero connection). The values of this matrix are equivalent to the identity matrix (I) (Fath, 2012). $A^1$is a direct connection between each pair of sectors along the direct path. A^2, A^3 *and* A^m are indirect connections along various lengths of m ($m \geq 2$), B total number of connections along various lengths in the network.

Using the infinite power series associated with the non-dimensional quantity of interest (throughflow, storage, contribution, control or utility) allows determining the status of the components in the system based on contribution exchange among them and their consumption. Ultimately, pairwise control and utility analyses can identify the elements responsible for components' statuses and emergy (energy and monetary) consumption.

3.2.3 Environmentally extended Input-Output Analysis

Environmentally extended input-output analysis (EE-IOA) is a method grounded on IOA, in which the production and exchange of goods and services within an economy are supplemented with the information containing the associated environmental inputs or outputs to evaluate the relationship between economic activities and upstream and downstream environmental impacts (Kitzes, 2013; Wieland et al., 2020; Usubiaga-Liaño et al., 2021).

In 1970, Leontief published an article in which he assessed the amount of pollution associated with given levels of production and consumption (Leontief, 1970). He developed a simple, economical and physical input-output table of a hypothetical economy represented by two productive sectors (Agriculture and Manufacturing) and one type of final demand (Households). Firstly, he constructed an input-output table in physical units (bushels of wheat for the outputs of Agriculture and yards of cloth for the outputs of Manufacture) (Schaffartzik et al., 2014). Then, the monetary input-output table was obtained from economic input-output data using 2$ per 1 bushel for wheat (price for agricultural products) and 5 $ per 1 yard for cloth (price for manufacturing products) (Schaffartzik et al., 2014). Finally, he extended the monetary input-output table with the 'air pollution' generation vector to include negative externalities ('non-market' transactions) to understand the effect of technological change on the production of pollutants and the cost of their elimination for productive sectors and households (Leontief, 1970).

Analysis similarly to LCA is based on a 'full life-cycle perspective', focused on environmental impacts associated with all the stages of a product's life in the economy, which is from raw material extraction through materials processing, manufacture distribution, and use of finished products (Muralikrishna and Manickam, 2017; Schmid, 2020). However, this approach also evaluates the environmental impacts of economic activities (production processes and consumption activities) during the entire lifecycle of each product used in the economy (Patterson et al., 2017; Schmid, 2020). Therefore, the boundaries of this approach correspond to the borders of local, regional or national economies, not leaving out any product groups and economic activities within economies (Schmid, 2020). This analysis assesses mainly the impacts of commercial energy consumption (Wieland, 2020; Owen et al., 2017), GHG emissions (Fry et al., 2021; Wiedmann et al., 2020), water (Islam et al., 2021; Ridoutt et al., 2018). However, the most developed during the last decade was in design energy extension (Wieland, 2020; Owen et al., 2017).

There are mainly two different approaches to measure impacts induced by consumption and emissions by economic activities and associated products: production-based (or 'territorial') accounting (PBA) and consumption-based accounting (CBA) (Chen et al., 2018; Schmid, 2020). Production-Based Accounting (PBA) attributes the emissions to the industries where goods and services are produced, regardless of the destination of these commodities for consumption purposes (Afionis et al., 2016; Steininger et al., 2018). It holds producers responsible for energy consumed (CO2 emitted) during the production of goods and services (Schmid, 2020). Specifically, PBA focuses on activities responsible for direct CO2 emissions (energy consumption) such as energy, manufacturing, mining, use of fuels by households, transport, industry and waste incineration (Harris et al., 2020). For instance, emissions from energy production are attributed to the energy sector instead of energy consumed by tertiary industries (i.e., transportation and storage).

On the contrary, consumption-based accounting (CBA)attributes GHG emissions as all the emissions that occurred during the production and transfer of goods and services to the final demand categories (i.e., household consumption, government consumption, capital formation) irrespective of their actual source (Ottelin et al., 2019; Schmid, 2020; Zhai et al., 2021). Thus, the consumption-based accounting" approach can be used to trace products from final consumption to source and quantify the primary footprint (i., e biomass, energy) at the source (Owen et al., 2017; Kalt et al., 2021). There are significant differences between PBA and CBA. PBA-based accounting captures CO2 emitted within cities, including direct emissions from fuel use, electricity by production processes, and emissions from consumption and export of goods and services produced in the town (Schmid, 2020). CBA-based accounting exceeds city boundaries and includes indirect emissions induced by the import of goods and services (i.e., purchased goods and services from outside of the city, investments, emissions from extraction and transportation of natural gas to town) (Harris et al., 2020; Schmid, 2020; Lenk et al., 2021). The physical extension in production-based and consumption-based accounting can represent primary environmental inputs or direct demand of households for evaluating the total environmental footprint of final products or final demand categories (Kitzes, 2013; Wieland et al., 2020; Usubiaga-Liaño et al., 2021). The upstream-based sources of energy consumption (or GHG emissions) of industrial sectors (i.e., energy extraction) represent supply extension.

Conversely, use-extension represents the downstream-based sources of energy consumption (GHG emissions) of industrial sectors (i.e., final energy demand for products). These two models can investigate the socio-economic and ecological costs of direct CO2 emitted during the production of goods and services by production activities (energy, manufacturing) and consumption activities (transport) and from direct energy use consumption activities of final users along the complete energy conversion chain. Ultimately, the total environmental costs associated with producers' upstream and downstream CO2 impacts can be effectively assessed and compared with traditional carbon footprint (CF) to provide insight into the effect of the inclusion of environmental work and the extension of upstream boundaries on CO2 emitted during energy production and use.

4 PAPERS

The dissertation consists of four papers exploring how to develop a multi-criteria assessment framework for integrated ecological and economic assessment of internal metabolic processes in cities. Paper 1 identifies research areas that require investigation and associated models and methods for studying urban metabolism (UM). Paper II-IV deal with one case study: Vienna municipality (Austria). Paper-II introduced a multicriteria framework integrating environmental accounting and network perspective (model) to estimate the environmental support provided to urban socio-economic systems. Paper III combines a multicriteria framework with network science methodology to study the structure and functions of urban metabolic systems. Paper II-IV focuses on integrated biophysical and economic estimation of carbon footprint (CF) of goods, services, and economic activities in cities, considering their entire life cycle through footprint analysis.

4.1 Paper I

Paper-I summarises recent developments and research gaps on urban metabolism (UM). The main definitions and applications of urban metabolism (UM) are reviewed. Moreover, the main developments of perspectives (accounting models) to study urban metabolism (UM) are reviewed are discussed in chronological order. The main contribution of Paper I is the identification of future research direction on urban metabolism (UM) and perspectives (models) and methods that can be used to address these directions. In the case of the future areas of research, the shift of main focus from environmental issues to environmental accounting and socio-economic aspects was captured. In the case of the models, we found that the network model and ENA will play an essential role in future urban metabolism (UM) research. The paper concludes that a multi-criteria assessment framework can support the investigation of complex relationships between natural and socio-economic systems within cities.

4.2 Paper II

Paper-II developed a multicriteria framework for integrated ecological and economic assessment of internal metabolic processes in cities. The paper faces the question of how to integrate a hybrid-unit input-output model with the emergy accounting method to estimate the environmental support provided to urban socio-economic systems. To archive this objective, the supply-side commodity-by-industry input-output and location quotient (LQ) approach based on value-added and final energy consumption were used to obtain the regional shares of monetary and energy production (location quotients), respectively. Then, these shares were applied to disaggregate Vienna's monetary and energy balance data. Consequently, Leontief's "commodity by industry model" integrated the regional energy use data with regional supply data". The matrix algebra (MA) methods were used to estimate the transformities of industrial sectors. Regional monetary and energy input-output tables were multiplied by their respective transformity values and summed to build the emergy input-output table. This table was used to estimate the total environmental support provided to each component of Vienna's socio-ecological system to identify sectors targeted for economic development to improve the share of renewable and save resources. In conclusion, it was maintained that a multi-criteria assessment framework capable of investigating the urban metabolism (UM) of cities and regional contexts through the identification of sustainable pathways rooted in material circularity and resource efficiency is beneficial for the design of policies in line with the "integrated wealth assessment" and "circular economy" principles.

4.3 Paper III

In the paper, emergy input-output was combined with ecological network analysis (ENA) to assess the total consumption and contribution exchange among the sectors (status) and functional relationships along all possible metabolic paths of ecological and socio-economic flows exchanging in an urban economy and between the urban economy and its environment. In this way, the critical components responsible for the other sectors' status and total emergy (socio-economic and ecological) consumption are identified using pairwise control and utility analyses. The results showed that "wholesale and retail trade, repair of motor vehicles" and "electricity, gas, water supply, sewerage, waste, and remediation services" are responsible for the low financial support of producers ("agriculture, forestry and fishing" and "mining and quarrying") by the tertiary industries, reflecting a shortage of agricultural and mining products to meet consumer demand. Some problems within tertiary industries were preventing them from supporting producers were identified. Some consumers had the highest monetary dependence on the other sectors, indicating the lack of self-sufficiency in monetary use and an inability of these sectors to deliver investments effectively to producing sectors. Other sectors rely on imports ("electricity, gas, water supply, sewerage, waste, and remediation services" and "transportation and storage") to improve their production capacity, leading to the low delivering abilities of these sectors. The results also showed that pairwise competitive indirect relationships dominated the system. The combination of the multi-criteria approach with ENA constitutes an indispensable tool for studying the total ecological and socio-economic costs of all indirect interindustry exchanges among production and consumption activities in urban metabolic systems, thereby providing support for city managers and policymakers to guide resource consumption towards an efficient and sustainable urban metabolic system.

4.4 Paper IV

In Paper IV, Environmental accounting was integrated with Footprint Analysis to investigate carbon footprints (CF) in upstream (production activities) and downstream parts (consumption activities) of the energy conversion chain in terms of direct producer and consumer responsibility for CO_2 emissions. The environmental costs of carbon footprint (CF) at the entry point into the urban economy (energy extraction) and at the final stage of the energy conversion chain (energy use) were used to assess the responsibility of producers and consumers, respectively. Then, environmental costs of carbon footprint (CF) of final products, carbon footprints of final demand categories by source industries, and carbon footprints from energy consumption by source sectors were compared to their actual cost to assess the difference stemming from applying donor side versus user side approach to carbon footprint (CF) assessment.

The outcomes of the study showed that carbon signature changes when CF is evaluated in emergy (environmental cost) terms: a) products of extractive industries and services demonstrated a larger emergy-evaluated footprint than manufacturing products, and b) energy and mining industries do not exceed services as opposed to "manufacturing" and "agriculture" when emergy and carbon footprints by source sectors are compared. Therefore, these sectors are not key sectors for meeting the final demand by Vienna consumers (b).

In the case of final demand categories, the outcomes also showed that final demand categories have a low sensitivity to the extension design applied to estimate emergy footprints due to the direct energy use of biofuels by final demand categories (i.e., households) being far less pronounced compared to the final consumption by production (industries). Despite the only noticeable difference in the category of Exports, this category is almost identical using use extension design compared to the supply-extended design. For this category, the

export of agricultural and energy products stands out with this slight difference. The differences in these two products are mainly due to the small amount of direct emergy export of biofuels allocated directly to the final demand category of exports in the extended use model.

An approach integrating Environmental Accounting and Footprint Analysis allowed extending upstream boundary spatially to incorporate a global environmental support system (biosphere), in which urban socio-economic sub-system is embedded. The temporal boundary was also enlarged to cover all solar energy inputs originally captured in ecological processes during the earth's entire history, which translates into direct and indirect solar energy consumed in the socio-economic (monetary) and ecological (energy) exchanges among the sectors of Vienna's urban economy. Moreover, an integration also allowed the incorporation of economic (labour and services) and ecological categories (renewable energy inputs such as solar radiation) into the carbon-evaluated IO model. We used to estimate carbon footprints induced by final products, source sectors, and final demand categories by source sectors.

However, the conceptual differences imply that emergy-evaluated supply-extension puts more weight on the economic dimension (labour and services) and thus reflects environmental support for economic activities of energy industries as a prerequisite behind emergy use. In comparison, emergy-evaluated use-extension puts more weight on the physical dimension and thus reflects environmental support to the direct energy consumption by final demand categories (households, government, capital formation and exports) as a prerequisite to any emergy use. Therefore, both the supply and use extensions provide partial information on environmental support provided to source industry or final product and complementary information on activities responsible for emergy footprint (ether energy or tertiary industries).

Despite some limitations of this approach related to the assumption of economy-wide average energy prices and the inability of standard production-based accounting (PBA) to accommodate the monetary imports category of final demand (services invested from the national economy), it could provide a more comprehensive assessment of product footprints of primary energy sources and final energy carriers (entire energy conversion chain) from a direct producer responsibility perspective. When this step is archived, emergy extensions can be assembled from the multi-scale nested MRIO tables to estimate the global environmental support to local impacts manifesting at the international level.

The understanding total environmental cost of direct carbon footprint (CF) stemming from the production and use activities in the economy will assist policymakers in assessing the implication of their decisions for the whole urban economy and its global life-support system based on biophysical constraints of economic activities and their consumption efficiencies.

RESULTS AND DISCUSSION

PAPER I

5.1 Exploring the global scientific literature on urban metabolism.

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Exploring the global scientific literature on urban metabolism

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Abstract. Urban ecosystems can be conceptualized like living organisms supported by material and energy flows that allow the generation of ecosystem structures and functions and the production of goods and services. Urban metabolism accounts for the flows of materials, energy, resources, food, and people in cities, providing a framework for the study of the interactions between natural and socio-economic systems. In this paper, the global scientific literature on urban metabolism was explored to identify knowledge gaps and emerging research areas over the last decades. A bibliometric network analysis was implemented to generate maps based on network data of scientific publications displaying relationships among scientific journals, researchers, countries, and keywords. The total number of publications on urban metabolism from 1990 to 2019 resulted in 498 documents. USA and China resulted the first countries publishing on urban metabolism while among the journals, the Journal of Industrial Ecology and Journal of Cleaner Production resulted the first in the ranking. The co-occurrence network map of keywords showed that, over the last decade, the main focus of research on urban metabolism has shifted from environmental issues to environmental accounting and socio-economic aspects. Considering the importance of urban systems for the achievement of local and global sustainability goals, it is likely that the scientific literature on urban metabolism will continue growing over the next years. Being cities characterized by complex relationships between natural and socio-economic systems, it is desirable that future studies will explore the multidimensional features of urban metabolism through multi-criteria assessment frameworks.

Keywords: Urban metabolism, VOSviewer, bibliometrics, social network analysis.

1. Introduction

Urban ecosystems can be conceptualized like living organisms supplied by material and energy flows supporting ecosystem structures and functions, and the production of goods and services (Nikodinoska et al., 2018; Russo et al., 2014). Urban metabolism accounts for the flows of materials, energy, resources, food, and people in cities, providing a framework for the study of the interactions between natural and human systems. The sustainable management of cities is based on the sustainable exploitation of natural capital stocks delivering a large set of ecosystem services vital for human economy and well-being (Häyhä and Franzese, 2014). The interplay of environment, economy, and resources taking place within urban ecosystems can be explored and monitored over time using different environmental accounting methods (Franzese et al., 2008). These methods can help understanding how cities use raw and processed resources supplied from larger environmental systems.

According to Kennedy et al. (2007), urban metabolism can be defined as "the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste".

It consists of a model that describes and quantifies the main input and output flows (e.g., materials and energy) processed by a city system. In this way, urban metabolism also represents a powerful analysis, planning, and management tool for accelerating the transition to a circular economy (Levoso et al., 2020).

1.1. Linear accounting models

The metabolism of many cities worldwide has been investigated by several researchers developing different models of urban metabolism focusing on the assessment of different variables. Wolman (1965) in his pioneering article "The metabolism of cities" applied material flow analysis by conceptualizing the operation of an urban system based on the analogy between urban metabolism and living systems. Haberl (2001) developed an energetic metabolism model of societies and urban systems. Odum (1996) developed an emergy-based accounting framework including natural flows, human labor, and economic services measured in solar energy equivalents. Other energy-based urban metabolism models were based on exergy, which represents the amount of useful work that can be performed by exploiting an energy flow (Zhang, 2013). Another input-output accounting method to explore urban metabolism was based on ecological footprint (Dakhia and Berezowska-Azzag, 2010).

1.2. Circular accounting models

Ulgiati et al. (2011) proposed Life Cycle Assessment (LCA) to investigate the metabolism of socio-economic systems. Rugani and Benedetto (2012) stressed that the LCA is more focused on downstream impacts and does not account for human labor and ecosystem services. Other studies tried to face these limitations by integrating LCA with Emergy accounting (Buonocore et al., 2019; Reza et al., 2014; Skaf et al., 2019; Ulgiati et al., 2010; Viglia et al., 2013).

Girardet (1990) proposed a cyclical urban metabolic model to overcome the limitations of the linear carbon metabolism approach not capable of accounting for the negative feedback of human impacts on natural ecosystems and their ability to provide ecosystem services such as, for instance, carbon sequestration. Thus, an ecosystem perspective was adopted to reduce the dependence of cities on natural ecosystems by increasing their internal cycling. The extension of this perspective was then employed both from a management (Huang et al, 2007) and from a metabolic activity viewpoint (Zhang et al., 2006). More recently, Goldstein et al. (2013) coupled urban metabolism and LCA applying an integrated model to the five cities of Beijing, Cape Town, Hong Kong, London, and Toronto, allowing a more comprehensive assessment of recycling processes within cities and environmental impacts beyond their boundary.

1.3. Network accounting models

Zhang et al. (2009) proposed the ecological network analysis as a tool to explore urban metabolism and used the emergy method to account for different types of natural and huma-driven flows (materials, energy, and money flows) exchanged within the urban metabolic system.

Li et al. (2010) developed an ecological network model of societal metabolic system displaying the internal environmental effects due to the exploitation of natural resource flows in China. Liu et al. (2010) performed an extended exergy analysis of the urban metabolic system of the Chinese city of Beijing. Chen et al. (2010) emphasized the theoretical capability of the emergy and exergy approaches to add eco-flows within an urban metabolic system, despite the difficulties in their practical adaptability.

More recently, some studies advocated the return to the input-output analysis due to its usefulness in portraying the emissions of socio-economic systems at different scales. In this regard, Li et al. (2018) used ecological input-output analysis to analyze the utility of the direct and indirect carbon flows in urban metabolic system. Sovacool and Brown (2009) focused on the analysis of carbon-related metabolic processes to account for the impact of urban metabolism on global climate change. Other studies focused on the social and economic sources of carbon emissions while ignoring the carbon sequestration from natural compartments (Kennedy et al., 2010; Ye et al., 2011). The ecological network analysis as a tool to study urban carbon metabolism was applied by Chen and Chen (2012) to study carbon emissions in the city of Vienna (Austria). Previous studies mostly investigated the vertical direction of carbon emissions and carbon sequestration, namely flows from land to atmosphere and vice versa (Zhang et al., 2016).

Many studies, among which Zhao et al. (2014), Lu et al. (2015), and Lu and Chen (2015), accounted for the socio-economic carbon sinks while ignoring the impact of land-use and cover changes on the carbon emissions and sequestration (Zhang et al., 2016). The ecological network analysis allowed to connect the vertical carbon flux (Zhang et al. 2016) with the horizontal emissions among economic sectors and a single "environment" compartment. Li et al. (2018) used ecological network analysis to account for monetary input-output flows and convert them to embodied carbon dioxide flows among sectors. The spatial analysis of urban carbon metabolic network based on land use and cover change (LUCC) performed by Xia et al. (2016) allowed to connect the natural and artificial components of an urban ecosystem based on their roles in the city's carbon metabolism. This approach can support the sustainable management of the spatial pattern of urban carbon metabolism and an adaptation to the low-carbon spatial design scenarios (Zhang et al. 2016). Consequently, Chen et al. (2010) suggested that the information indices of network analysis (ascendency and overhead) should be integrated into the assessment methodology of urban metabolic systems to evaluate the sustainability of urban development in terms of system efficiency and stabilizability. The different approaches to the study of urban metabolism are summarized in Table 1.

In this paper, we review the global scientific literature on urban metabolism to identify knowledge gaps and emerging research areas over the last decades. A bibliometric analysis was conducted to generate maps based on network data of scientific publications displaying relationships among scientific journals, researchers, and countries. Finally, a keywords analysis was performed to review the co-occurrence of different terms connected to the research on urban metabolism.

2. Materials and Methods

2.1. Data Collection

The keyword "urban metabolism" was used as a search input to explore the global scientific literature on the topic. The time frame was set to include all available publication years in the Web of Science Core Collection (WSCC) database set from 1990 to 2019. All data was saved as "Tab-delimited (Mac)" files which contained "Full Record" and "Full Record and Cited References" content. The "Full Record" and "Full Record and Cited References" content were respectively used for co-authorship and co-occurrence analyses (e.g., network maps of authors, countries, and keywords) and citations analysis (e.g., network map of scientific journals).

2.2. Bibliometric Network Analysis

Bibliometric network analysis is an effective tool combining bibliometrics and social network analysis (SNA) to investigate specific fields of science (Reuters, 2008; Zou et al., 2018). SNA and maps based on network data allow for the application of systems thinking in bibliometric science. In particular, such analysis allows for the construction of network maps based on the relationships among countries, journals, organizations, authors, and keywords related to the investigated topic (Chen et al., 2016; Buonocore et al., 2018; Pauna et al., 2018, 2019; Skaf et al., 2020).

VOSviewer (version 1.6.12) software was used to perform the bibliometric analysis. This software allows for the creation, visualization, and exploration of maps based on bibliometric network data. The output results are displayed in clusters to allow for a clear visualization of the existing connections among the bibliometric data. Table 2 summarizes the main technical terms used by the software.

Table 1. Approaches to the study of urban metabolism.

Approaches	Advantages	Disadvantages
Linear	Allows to decrease resource dependency by decreasing the consumption of the imported resources while substituting them by local resource supplies.	Stress imposed on local resources leads to the high dependency on imported ones. In other words, the city brings a low contribution to economy while causing a huge environmental impact.
Circular	Accounting for recycling and reuse of wastes allows to reduce the dependence on the imported resources, thereby decreasing their demand and an overall environmental impact of a socio-economic system.	The unknown internal sources of environmental impacts and constraints (or their absence) on resource use in cities that trigger the continuous self-organization process of urban ecosystems may lead to the long-term mismanagement.
Network	Allows to optimize the structural properties (e.g., cycling) to retain the resources on pathways and adjust the relationships among the economic sectors and external environment towards mutualism to minimize the harm (pollution and competition) between the sectors.	The ecosystem is considered as a "single compartment" that interact with a socio-economic system's compartments and direct and indirect effects between social and ecological compartments are unknown. The urban socio-ecological carbon flux model was able to open the "black box".

Co-authorship, co-occurrence, and citation analyses (Table 3) were conducted to create network maps showing: (1) the co-authorship among researchers and countries, (2) cited scientific journals, and (3) the co-occurrence of keywords. Each network map that resulted from the analyses contains nodes with size determined by "total link strength", and lines connecting the nodes with thickness based on "link strength" (Table 2).

The amount of clusters visualized in the network maps is determined by the resolution parameter. The higher its value, the higher the level of details. This value can be set to visualize an appropriate number of clusters in the maps (Van Eck and Waltman, 2019). In this study, the resolution was set to 1 for all the analyses.

3. Results and discussion

The total number of publications on "urban metabolism" from 1990 to 2019 resulted in 498 documents. Figure 1 shows the trends based on the number of publications and cumulative citations. Both trends show an exponential growth since 2009. This outcome can be due to the effects of the Europe 2020 strategy enacted in legislation in 2009 and calling for smart, sustainable, and inclusive growth.

Applying the social network analysis to this set of publications, five network maps were generated (Figures 2-6). For each network map, the five items with the highest weight in terms of total link strength and citations were reported in Tables 4-7.

3.1. Co-authorship authors network

The co-authorship authors analysis is based on documents with a maximum of 25 authors per document, resulting in 1165 authors. Moreover, only author with a minimum of 5 documents published on the topic were selected, resulting in a total number of 24 authors. The final network map shows only 12 authors grouped into 4 main clusters and characterized by a higher level of connection (Fig. 2). The top 5 authors ranked by number of documents are shown in Table 4. Yan Zhang, with 32 documents and 861 citations, resulted the main author contributing to the growth of the research on urban metabolism using the ecological

Table 2. Main terms in VOSviewer software (Van Eck and Waltman, 2019).

Term	Description
Items	Objects of interest (e.g., publications, researchers, keywords, authors).
Link	Connection or relation between two items (e.g., co-occurrence of keywords).
Link Strength	Attribute of each link, expressed by a positive numerical value. In the case of co-authorship links, the higher the value, the higher the number of publications the two researchers have co-authored.
Network	Set of items connected by their links.
Cluster	Sets of items included in a map. One item can only belong to one cluster.
Weight attribute: Number of Links	The number of links of an item with other items.
Weight attribute: Total Link Strength	The cumulative strength of the links of an item with other items.

Table 3. Description of VOSviewer analyses used in this study.

Type of Analysis	Description
Co-authorship	In co-authorship networks, researchers, research institution, or countries are linked to each other based on the number of publications they have authored jointly.
Co-occurrence	The number of co-occurrences of two keywords is the number of publications in which both keywords occur together in the title, abstract or keyword list.
Citation	In citation networks, two items are linked if at least one cites the other.

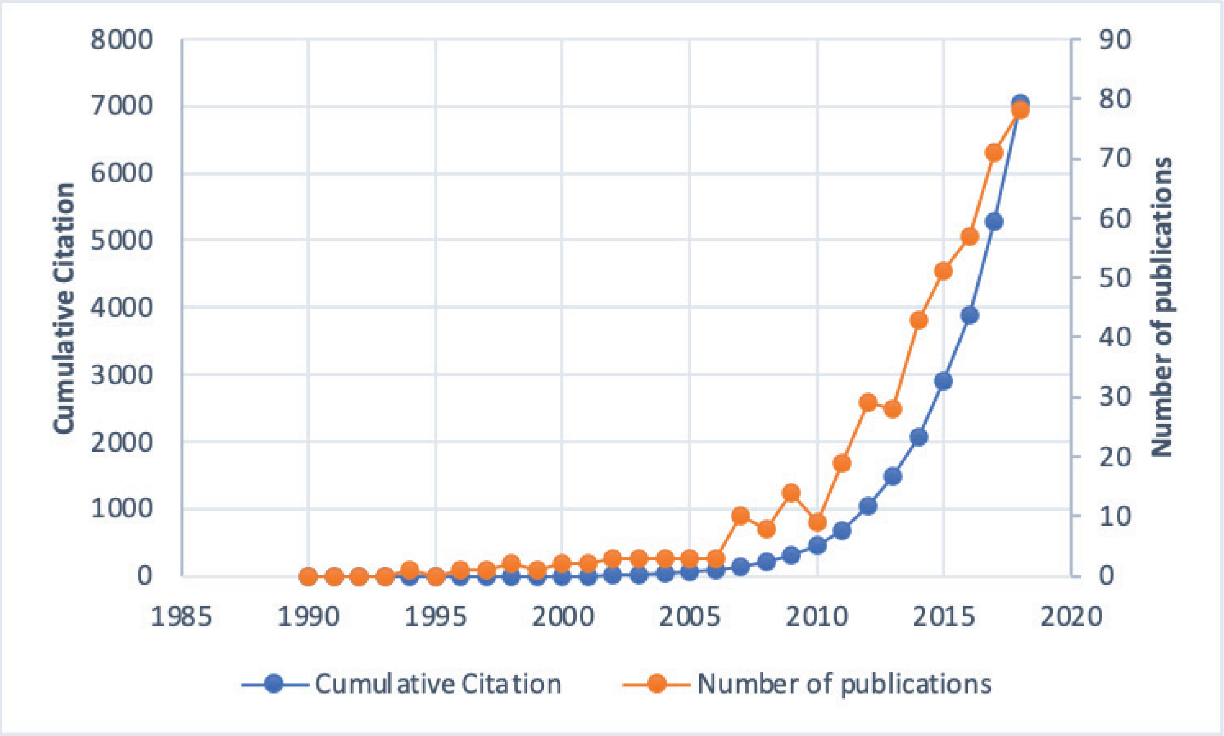

Figure 1. Temporal trends of documents published from 1990 to 2019.

Table 4. Top 5 authors ranked by number of documents.

Author	Specialization	Total link strength	Link	Documents	Citations
Zhang, Yan	Industrial Ecology	61	9	32	816
Chen, Bin	Industrial ecology, Systems Ecology	25	7	23	391
Yang, Zhifeng	Urban Ecology, Water Management	50	10	19	622
Liu, Gengyuan	Urban Ecology, Systems Ecology	38	10	12	239
Fath, Brian D.	Systems Ecology, Ecosystem Ecology	29	9	12	280

network analysis methodology. Four out of five authors are Chinese, highlighting the considerable attention that the Chinese scientific community pays on the subject. The major focus on this research subject is most probably due to the critical environmental conditions characterizing Chinese cities, determining the need for facing and solving these environmental problems towards more sustainable cities.

The results in Table 4 also reveal that the topic of urban metabolism is mostly investigated by authors specialized in “industrial ecology” and “system ecology”, confirming the need for investigating urban metabolism thorough the study of the complex metabolic linkages among industrial, urban, and natural systems by means of a unified framework.

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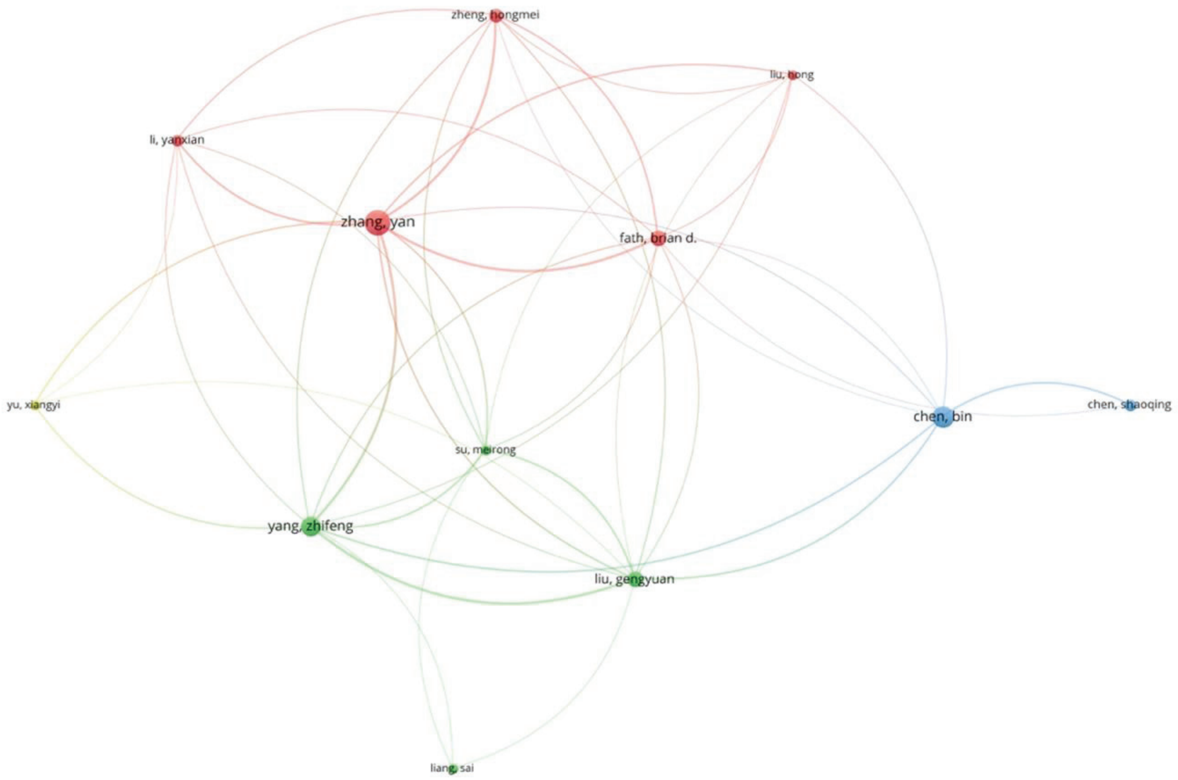

Figure 2. Network map of authors based on number of documents.

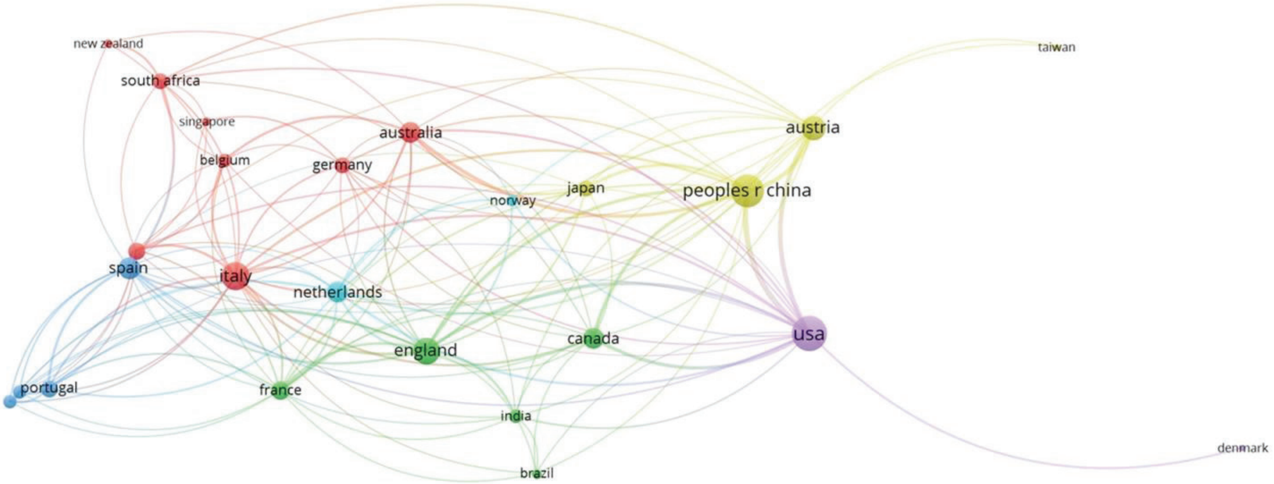

Figure 3. Co-authorship countries network map based on total link strength.

Table 5. Top 5 countries ranked by total link strength

Country	Total Link Strength	Links	Documents	Citations
USA	83	19	112	2,287
Peoples Republic of China	77	14	130	2,088
Italy	53	21	37	436
England	48	18	38	795
Austria	43	15	25	641

3.2. Co-authorship countries network

The analysis resulted in 60 countries publishing on urban metabolism. Documents co-authored by more than 25 countries were excluded. Out of the total number of countries, only 26 countries met the threshold of minimum 5 documents. The network map shows 6 main different clusters (Fig. 3). It is interesting to note that most clusters include different countries belonging to different geographic areas. For instance, the cluster in red color includes countries located in Europe, Asia, South Africa, New Zealand, and Australia. These results highlight the existence of a very diversified global network of researchers committed on urban metabolism studies.

The top 5 countries based on the total link strength are shown in the Table 5. USA ranks the first by the number of citations and total link strength, while China ranks the first by the number of documents. In addition, it is interesting to note that Italy ranked first by the number of links but has a relatively small number of documents, confirming that this country is an emerging international player in the field of urban metabolism.

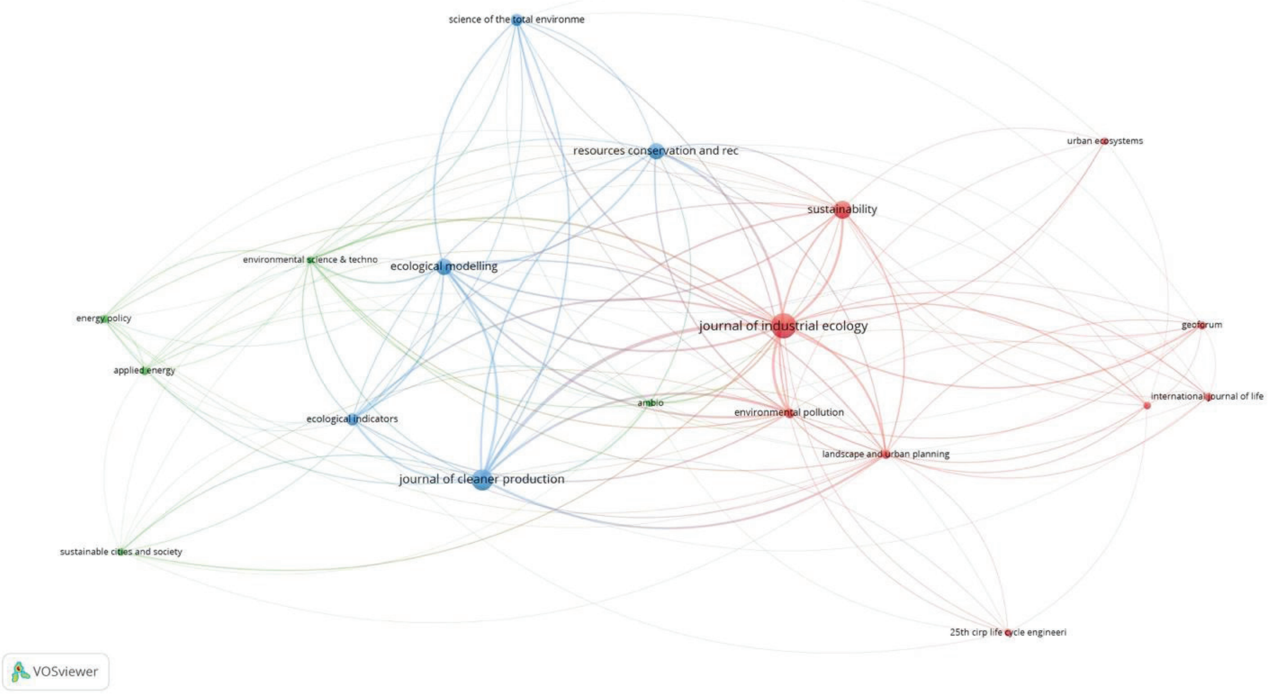

Figure 4. Network map of citations analysis of journals based on total link strength

3.3. Citation analysis of journals

The citation analysis resulted in a network map including 19 items out of 171 journals publishing on urban metabolism that met the threshold of having at least 5 publications on the topic. The network map shows 3 main clusters (Fig. 4). The top 5 journals ranked by total link strength are shown in Table 6. The Journal of Industrial Ecology and Journal of Cleaner Production are the first ranked in terms of total link strength and number of documents. Despite its relatively recent foundation in 1996, the Journal of Industrial Ecology is ranked first, showing the high commitment of its scientific community on the topic of urban metabolism.

3.4. Co-occurrence keywords network

The analysis of keywords resulted in 1940 items. Applying a threshold of a minimum number of 5 occurrences, a total number of 167 keywords was generated. The network map shows 7 main clusters (Fig. 5). The top 5 keywords are ranked in Table 7 based on the total link strength.

The network map in Figure 5 shows that "cities" and "energy" have a close relationship to urban metabolism, confirming the importance of the energy issue and of city structures and functions in relation to urban metabolism studies. The keyword "sustainability" highlights the relevance of cities for the achievement of local and global sustainability goals. In fact, considering that about 55% of the world's population lives in urban settlements (UN, 2018), understanding the metabolism of urban systems is crucial for the achievement of the 2030 Agenda for Sustainable Development Goals. It is also noteworthy that China is included among the top 5 keywords related to urban metabolism. In the last decades, China has experienced rapid urbanization and industrialization processes leading to critical environmental problems such as resources depletion, atmospheric pollution, and waste generation (Tian et al., 2017). In this context, finding solutions for sustainable urban development has become a notable research interest in the Chinese scientific community and urban metabolism has been used as an effective approach for analyzing the structure and functioning of urban systems. In addition, Fig. 5 also shows that the topics of "industrial ecology" and "ecological network analysis" play an important role in the context of urban metabolism studies.

The main keyword related to urban metabolism are also shown in the overlay map (Fig. 6) providing a temporal perspective for the interpretation of the co-occurrence network map of keywords. The map is based on the average year of publication of documents they occur in, on a color gradient from blue (older publications), to green (publications equally distributed across the timespan), to yellow (more recent publications). The distribution of the keywords along a temporal gradient allowed to understand the evolution of the scientific research on "urban metabo-

Table 6. Top 5 journals ranked by total link strength

Journal	Total link strength	Links	Documents	Citations
Journal of Industrial Ecology	396	18	51	1638
Journal of Cleaner Production	309	15	38	447
Ecological Modelling	223	16	23	593
Environmental Pollution	217	18	8	545
Resources Conservation and Recycling	150	15	23	346

Table 7. Top 5 keywords based on the total link strength.

Keywords	Occurrences	Total link strength	Link
Cities	178	1104	160
Energy	111	742	150
Sustainability	90	600	144
Metabolism	65	396	122
China	57	378	115

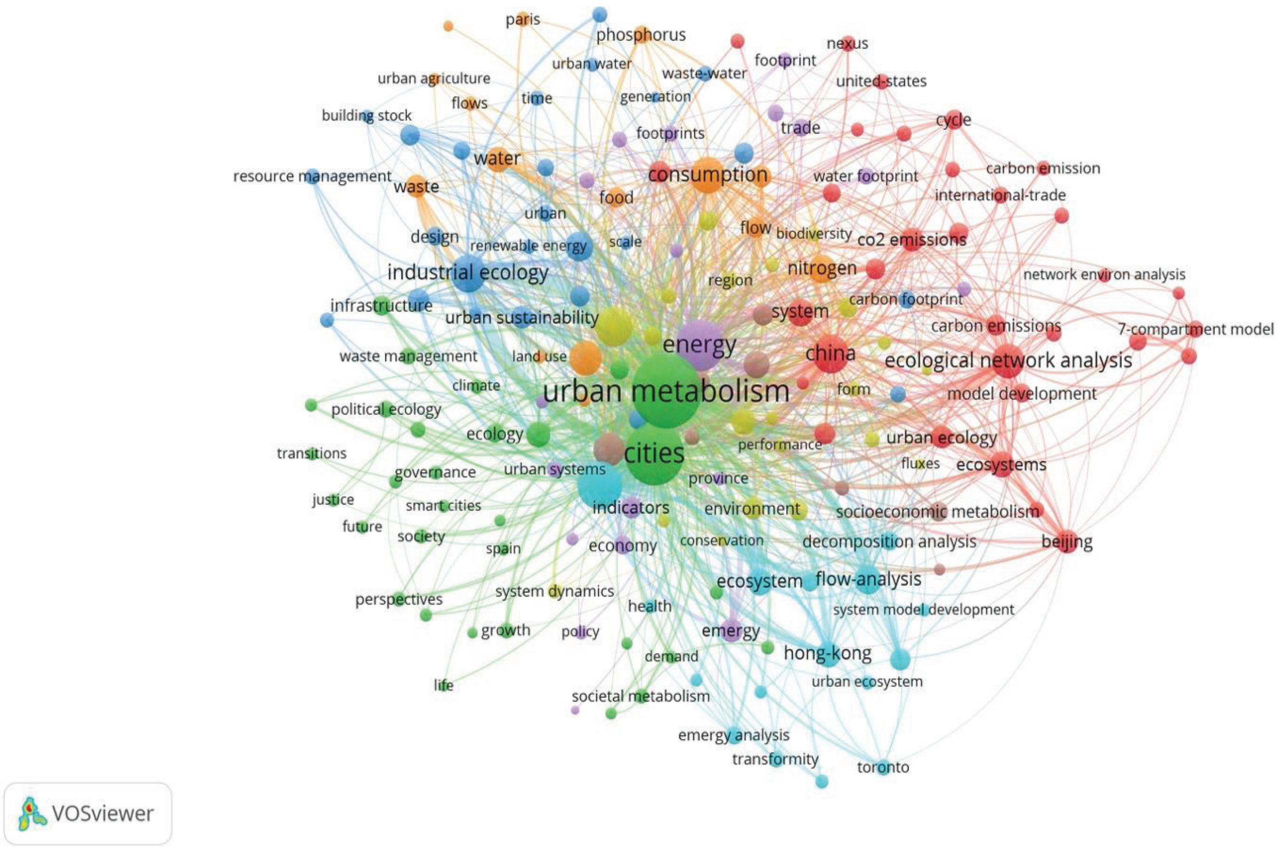

Figure 5. Network map of keywords co-occurrence based on total link strength

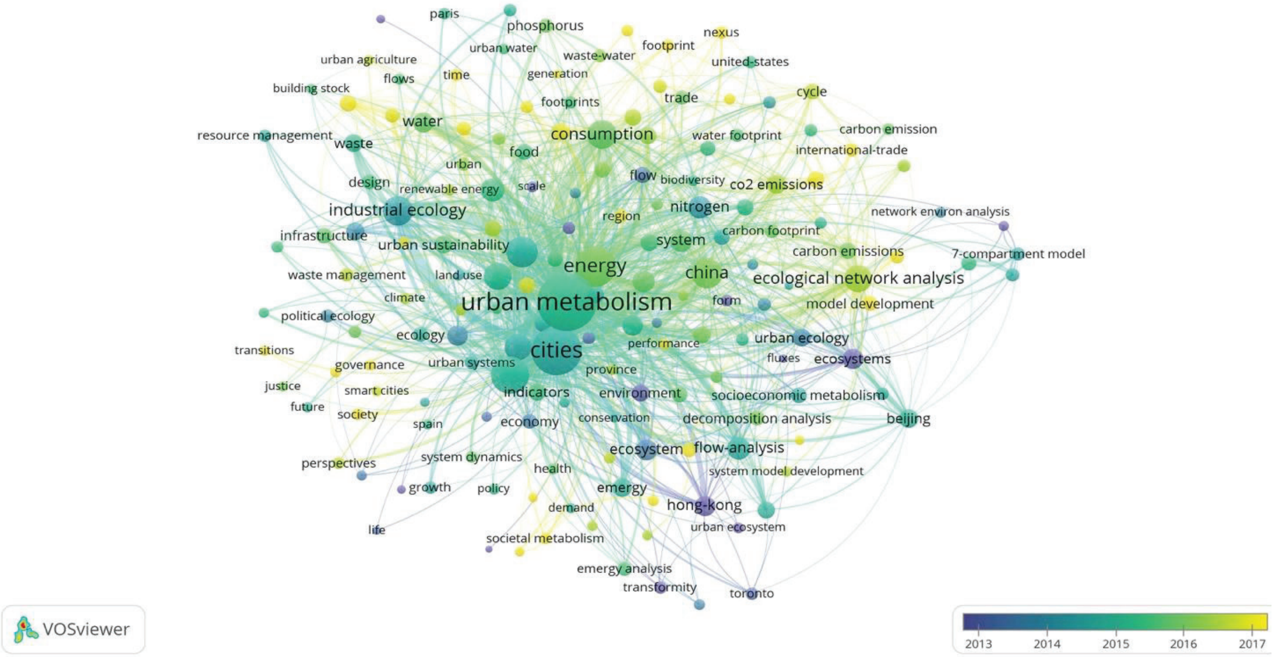

Figure 6. Overlay visualization of the co-occurrence network map of keywords

lism", identifying the most recent topics and main research pathways. The overlay visualization map shows a shift from older studies more focused on environmental aspects (e.g., "ecosystems", "environment", "nitrogen") to a recent focus on the importance of environmental accounting tools (e.g., "water footprint", "emergy analysis") and socio-economic aspects (e.g., "international trade", "governance") showing the awareness on the importance of studying environmental, social, and economic aspects of the sustainability of urban systems.

4. Conclusions

In this study, the global scientific literature on urban metabolism was explored through bibliometric network analysis. The results of this study provided an overview on the main aspects characterizing the topic of urban metabolism and allowed the investigation of the relationships occurring among authors, journals, countries, and keywords. The temporal analysis of publications showed that the scientific research on urban metabolism has experienced an exponential growth over the last ten years. The temporal development of the scientific research on urban metabolism was also investigated, capturing a main shift of focus from environmental issues to environmental accounting and socio-economic aspects.

Considering the importance of urban systems for the achievement of local and global sustainability goals, it is expected that the scientific literature on urban metabolism will continue increasing over the next years. Being cities characterized by complex relationships between natural and socio-economic systems, it is desirable that future studies will explore the multidimensional features of urban metabolism through the development and application of multi-criteria assessment frameworks.

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PAPER II

5.2 A multi-criteria framework for assessing urban socio-ecological systems: The emergy nexus of the urban economy and environment

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A multi-criteria framework for assessing urban socio-ecological systems: The emergy nexus of the urban economy and environment

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ABSTRACT

The social and ecological impacts of urbanization require integrated management of cities and their resource metabolism for long-term sustainability and economic prosperity. Traditionally, network models are used to study internal metabolic processes in cities, complementing the traditional "black box" urban models to account for the input of material and energy resources and the output of final products and wastes. This study introduces a multi-criteria assessment framework by integrating a unique hybrid-unit input-output model with the emergy accounting method to estimate the environmental support provided to urban socio-economic systems, applied here to the case of Vienna, Austria. By focusing on the internal organisation and functioning of urban socio-economic systems, the proposed framework strengthens the understanding of ecological and socio-economic flows exchanged among industries and the environment. The results suggest that resources can be saved by applying supply-side and demand-side interventions and improving share of renewables. The multi-criteria assessment framework developed in this study allows to investigate the urban metabolism of cities and regional contexts through the identification of sustainable pathways rooted in material circularity and resource efficiency, supporting the design of policies in line with the "integrated wealth assessment" and "circular economy" principles.

1. Introduction

In the last century, urbanisation has caused an increase in the demand for ecosystem services while altering the ecological structures and functions (Frank et al., 2017). The current trajectory indicates that nearly 68% of the global population will be inhabiting cities by 2050, showcasing further damage to socio-economic and life-support systems (Ritchie and Roser, 2018). These social and ecological alterations have helped recognise the need for sustainable urban management, and their surrounding areas, for safeguarding the long-term sustainability of urban ecosystems (Kalantari et al., 2019). Such management strategies could, similarly to the marine, coastal, and watershed studies, consider cities as a complex techno-economic system comprising complex human-nature interactions (Frank et al., 2017; Herrero-Jáuregui et al., 2018). Contrary to the traditional "black box" urban models, this multi-faceted integrated approach accounts for the input of material and energy resources and the output of final products [i.e., generated gross domestic product (GDP) and supported population] and waste, thus creating network models capable of unfolding the intricate urban metabolism (Zhang et al., 2009; Musango et al., 2017).

Most of the research before 2006 was dedicated to the metabolism of urban systems with less emphasis on ecological considerations (Bodini and Bondavalli, 2002; Chen, 2003; Bailey et al., 2004). Most of these studies focused on a single-criterion analysis representing the whole system from an ecological perspective instead of an integrated (multi-criteria) socio-ecological perspective. To address this limitation, a conceptual model for metabolic processes in an urban socio-ecological system was developed by Zhang et al. (2006). Zhang et al. (2009) developed a network model for the urban economy and environment a few years later. However, this model was highly aggregated, and the

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analysis of ecological and socio-economic flows among economic sectors (i.e., compartments) was also overlooked. Chen et al. (2010) introduced a more comprehensive model characterised by ecological flows among industries. Later, Liu and Zhang (2012) used a disaggregated network model based on a physical input-output table comprising 45 economic sectors. Nevertheless, their model did not account for free environmental inputs, human labour, and economic services, thus, leaving out consumption patterns crucial for the urban economy and metabolism.

More recently, studies by Zhang and colleagues (2014) and Li et al. (2018) have focused on material consumption patterns for improved estimation of material intensity factors. Using the matrix inversion formula, both studies determined the embodied material intensity of each economic sector per $ of economic service. The first study employed a disaggregated physical input-output table of Beijing comprising 32 sectors (Zhang et al., 2014a), while the second used a more aggregated 13-sector data for Guandong province (Li et al., 2018). However, both studies did not investigate the total material use by each industry and environment or their contribution to the urban economy. Other recent studies still do not account for the indirect economic contribution (i.e., services) to each component of the urban socio-ecological system (Zhang et al., 2018; Xia et al., 2019) and the carbon flows/supply from the environment to different sectors of urban economy (Chen et al., 2020). According to the literature review, most studies continue to rely on a single-criterion analysis while disregarding the usefulness of multi-criteria analysis (Chen and Chen, 2012; Zhu et al., 2019; Chen et al., 2020). Although a recent study by Morris et al. (2020) has investigated the impacts of energy, agriculture, construction, and natural compartment on the overall emergy cycling, the emergy use patterns in a whole urban socio-ecological system are yet to be identified.

In this context, this study could lead to an improved understanding of sustainable urban metabolism by introducing a framework that identifies inefficient or unsustainable emergy use patterns in an urban socio-ecological system while providing a basis for developing sustainable resource management strategies at the regional scale. Therefore, the main research question is as follows: How to develop a multi-criteria assessment framework capturing the complexity of urban metabolic systems by applying biophysical, systems, and network perspectives? To find solutions, we have proposed a multicriteria assessment framework that integrates hybrid-unit input-output and the emergy accounting methodologies to enhance our understanding of environmental and socio-economic flows exchanged between industrial sectors and the environment and characterise the internal organisation and functioning of urban socio-ecological systems.

This study adds scientific contribution to previous research in several critical ways regarding downscaling monetary and energy supply and use data, implementing a two-step approach linking sequentially downscaling based on the supply-side approach with the builing of input-output systems based the demand-side model, introducing hybrid-unit emergy input-output model for urban scale, and combining of matrix inversion and reflexive methods to derive non-negative transformities from under-determined systems of equations.

The application of downscaling approach developed by Liu and Vilain (2004) was extended to national monetary and energy supply and energy use tables. Such application allowed authors to combine supply and use data via demand-side Leontief's model based on industrial technology assumption to build regional energy and monetary input-output tables (Miller and Blair, 2009). Ultimately, joint monetary (energy) production (co-products) was accommodated into the input-output table, thereby avoiding negative monetary (energy) transactions among the industrial sectors and unequal process energy (monetary) efficiencies stemming from joint production (Patterson, 2014). In addition, authors could downscale data on production and consumption of commodities by sectors to obtain more reliable results as compared to downscaling of national industrial input-output data, namely energy (monetary) value-added matrix (energy and monetary losses by industry) and the total amount of valuable products by sector (industrial output). Furthermore, by using this procedure, we ensured that the resulting regional energy input-output table conforms to the first law of thermodynamics (Heun et al., 2018).

The other novelty of this work is that supply-side Ghosh's commodity-by-industry models and demand-side Leontief's input-output models were used sequentially in the same study, considering the strengths of both models. Ghosh's model was used to build regional monetary (energy) supply and use tables, and Leontief's model created a monetary (energy) input-output system from these tables. Here, first-time industry-based technology and supply-side commodity-by-industry model (supply-side make-use model) were applied together in a single study, which Mesnard (2004) explained in terms of the closed economic circuit (industries closed in a loop to be interpreted economically). Then, the resulting regional monetary and energy supply and use tables were combined into economic and energy input-output tables, respectively since energy use and supply tables are only compatible with industry-based technology and demand-side Leontief's input-output model (Heun et al., 2018). The other reason was that the hybrid-unit emergy input-output model could only be constructed if monetary and energy input-output tables were built using the same technology (Guevara and Domingos, 2017; United Nations 2018). Therefore, the introduction of a two-step approach combining the regionalisation procedure (downscaling approach) using the supply-side method (first step) and the construction of input-output systems using the demand-side model (second step).

The third novelty of this work is that the exact multi-factor (hybrid-unit) energy input-output model developed by Guevara and Domingos (2017) was integrated with the emergy accounting approach to account for socio-economic (monetary) and ecological (emergy) consumption by the energy production process and non-energy (tertiary) industries separately. More importantly, both the economic value of services and the energy value of products provided by the energy industries were incorporated into the analysis (Guevara and Domingos 2017), thereby incorporating the total upstream cost of energy products and economic services exchanged among energy (extraction and production processes) and non-energy industries (the tertiary part of Vienna's economy). The entire environmental support (emergy and monetary criteria) of energy industries to tertiary sectors, and vice versa, has not been explored before in the context of the hybrid-unit energy input-output system (Bullard and Herendeen, 1975; Lindner, S., & Guan, 2014; Shepard and Pratson, 2020). In other words, total emergy used to satisfy the final demand of energy and non-energy industries are separated. Also, both monetary and energy flows are arranged by the processes of energy use and conversion (Guevara and Domingos 2017). This model allows us to separate and then account for two emergy efficiency indicators (A^r and L^E), thereby allowing us to understand how environmental support affects primary-to-secondary energy conversion efficiency (i.e., the total amount of environmental support to primary energy needed by one energy industry to produce the amount of environmental support to secondary energy by another energy industry to satisfy the consumption of tertiary industries) and direct emergy consumption efficiency (amount of direct emergy demand by each tertiary industries to produce their monetary output). Ultimately, this model contributes to understanding emergy used in primary (LE) and secondary energy production processes (Ar) in the urban economy. In short, this model provides a more detailed representation of energy use in the economy and supports the identification of urban production and consumption processes characterised by low levels of emergy consumption. In this study hybrid-unit, input-output model was also applied for the first time to the urban scale. Previous studies have estimated total energy consumption by energy and non-energy production processes and proposed recommendations to improve the energy efficiency of supply chains and reduce emissions for national economies such as Portugal (Guevara and Rodrigues, 2016), Canada (Bagheri et al., 2018) and Japan (Ueda, 2022).

The fourth novel aspect of this study is that these problems are associated with negative transformities and artificial aggregation by rows and/or columns (impossible to arrive at matrix product to deal with different dimensions in starting outputs-inputs matrix), and the issue associated with prior knowledge of transformities have been overcome through the integration reflexive (backward and forward linkages matrices), and matrix inversion approaches (Patterson, 2014). This was archived using the first seven-step of the reflexive approach to ‘output matrix’ U and ‘input matrix V’ to transform and combine them into the Kernel matrix Z, output-input matrix with positive values along diagonals (+) and negative value (−) along non-diagonals, to insert into matrix inversion equation to produce a positive value of transformities. Here, the first-time underdetermined systems of equations (number of commodities considerably exceeds the number of industries) based on backward and forward linkages were extended, aggregated, and combined into a single matrix (Z). We found the aggregated transformities of production processes and consumption activities at the urban scale by following this procedure. The higher the value of transformity indicates the high emergy inefficiency of the production process or consumption activity (Patterson, 2012).

Moreover, this procedure allowed us to overcome the problems of artificial aggregation by rows and/or columns of an inconsistent system of equations (over-determined or under-determined systems) associated with the matrix inversion approach (Patterson, 2012, 2014) and the inapplicability of reflexive approach to the estimation of transformities from an under-determined system of equations (Patterson, 2014). Lastly, the problem associated with the prior knowledge of transformities for the transformation of quantity × process matrix to a process × process matrix through the market share assumption in physical systems (i.e., energy system) was solved through the application of vector of solar energy inputs into each production process and consumption activity (initial data for matrix inversion). This combined approach solves methodological problems associated with both reflexive and matrix inversion approaches and provides insight into unequal emergy process efficiencies in any socio-ecological system. These aspects constitute the novelty of this work.

We tested this new framework on the case study of Vienna. This case study has been chosen due to its overlapping urban and provincial boundaries. Vienna, the Northeast region of Austria, is the smallest (the area is 414.9 km^2) and the most productive province in the country (Statistik Austria 2020). This region generates about one-quarter of the national GDP, about 96 billion euros (€). Vienna’s population is about 1.9 million as of 2018, growing at an annual rate of over 10% (Municipal Department 23 – Economic Afairs, Labour and Statistics, 2018), with the highest urbanisation rate in the country (Statistik Austria 2020). Fig. 1 presents a detailed map of Vienna.

Vienna continues to expand its services-based economy towards knowledge-intensive business services. Most industries in Vienna have shown stable growth in recent decades except for agriculture, manufacturing, and energy industries. The fluctuations in gross value added of agricultural and manufacturing sectors could be partly attributed to the variations in the employment market, resulting in a trade-off between jobs in the manufacturing and service sectors. With production facilities and agricultural fields located outside the Vienna region, the reduced number of jobs could be explained by their low concentration (localisation) in this region despite having their main/head offices inside Vienna. More recently, however, a rise in industrial sectors has substituted the services-based industry, especially after introducing the “smart production policy” in Vienna (Vienna, 2020). This was also illustrated by the location quotient (LQ) values for 2015, a ratio of shares of income (or final energy consumption) in each sector of the regional economy to the income (or final energy consumption) in each sector of the national economy (Munroe, D.K., Biles, J.J., 2005). This ratio indicated a higher concentration of the Vienna province’s production facilities and agricultural fields. Tables S–A and S–B’s supporting information file “S2”[1] provides the value-added and final energy consumption-based LQ of each industrial sector. The sectoral representation, based on LQ, highlights the rising agricultural and manufacturing activities in the Vienna region.

In July 2014, the Federal Energy Efficiency adopted an implementation strategy for enhancing energy efficiency through the “Smart City Vienna Framework” (Vienna City Administration, 2015). This energy efficiency and renewable energy policies were aligned with the decrease of the final energy demand in Austria as a countermeasure to the economic development and rising urbanisation. Later, the “Energy Framework 2030” promulgated in May 2018 has further strengthened the Smart City Vienna Framework and its implementation plan (Vienna City Administration, 2019). In addition, the “Urban Energy Efficiency Programme 2030” based on this strategy was adopted during the same year (Vienna City Administration, 2019). Implementing multiple strategies has resulted in an increased share of renewables by 6.6% from 2014 to 2018. However, energy efficiency has not improved (i.e., only 0.5% improvement). During the same period, the energy consumption of the manufacturing, agriculture, and transportation sectors increased by 1%, while the energy demand of households and services decreased by 1% (Vienna City Administration, 2015; 2019). This could be attributed to the steady rise of Vienna’s industrialisation from 2015 at the expense of services and households and the accompanying changes in the job market. This highlights that several efforts have been made for sustainable urban development and resource sustainability. Nonetheless, analysing the success or potential impact of these efforts in Vienna warrants a comprehensive investigation of the urban socio-economic systems and related metabolism.

The rest of the article is organised as follows: Section 2 explains the methodological framework used in this study. Section 3 discusses the results of this work. Finally, the paper concludes in Section 5 and highlights important implications, limitations, and future recommendations based on this work.

2. Methods and data

This section introduces the overall methodology used to develop a multi-criteria assessment framework used in this study.

2.1. Regional input-output table

As a first step, the regional monetary table was constructed using national monetary use and supply data (AUSTRIA, 2015a). The second step integrated the regional consumption table with the regional monetary use table to build a regional monetary input-output table.

The national monetary use table was regionalised using a supply-side, commodity by industry input-output model, also known as the “Ghosh model”, a widely used model (Miller and Blair 2009). A supply-side commodity by industry input-output model follows the original demand-side commodity logic by industry input-output model. The difference between the supply-side and demand-side input-output model lies in the input coefficients used (Miller and Blair 2009). The Ghosh model is based on the direct-output coefficients matrix, calculated by Equation (1) (Liu and Vilain 2004).

$$\beta = U^{-1}Q \tag{1}$$

Where the m × n matrix “β” represents the national share of commodity, *i* sold to industry *j*. This matrix was obtained by dividing the corresponding row of the national monetary use matrix (U) by the

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[1] Authors are willing to share their entire dataset in Excel format with those who wish to replicate the results of this research.

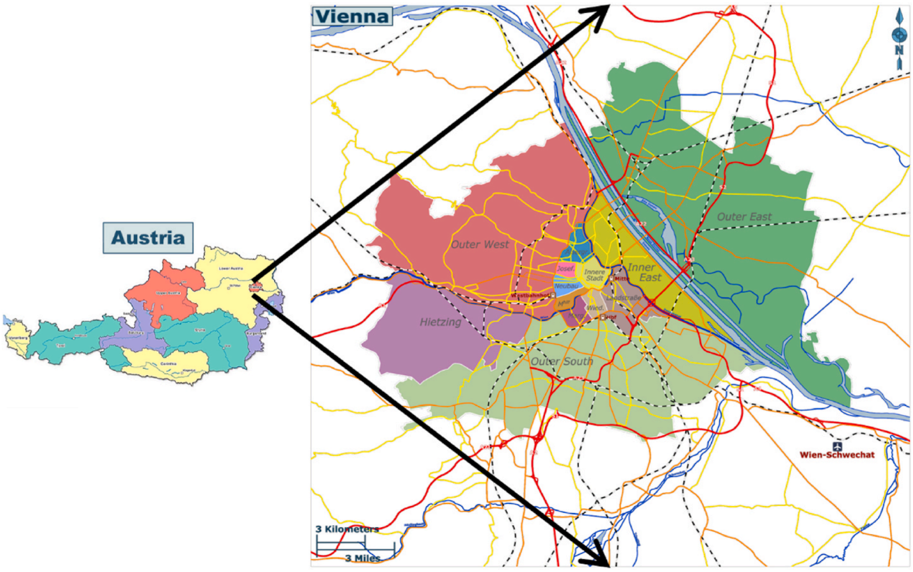

Fig. 1. Map of Vienna based on Wauteurz (2020).

corresponding row of gross commodity output (Q). This matrix denotes a national supply-side commodity by industry model. Then, a national supply commodity by industry model was regionalised to estimate the share commodity inflows to the Vienna region using a simple location quotient (LQ) technique (Liu and Vilain 2004) based on value-added data (earnings generated by the production of goods and services). Finally, the balancing procedure was carried out to adjust the row sum of "β" to be equal to 1 to assign all inflows to individual industrial sectors. If the industry is not present in the region or the LQ < 1, all the commodities sold to this sector are assumed to be sold to the other sectors (Liu and Vilain 2004). For the industry not presented in the Vienna Region, it reflects the following assumption: if an industry such as mining is not present in Vienna Region, the inflows of any commodity that it uses as an input (i.e., natural gas) are assumed to be used by other industries that are both present in the Vienna Region and use the commodity as an input (i.e., natural gas assigned to manufacturing sector because the chemical industry is a sub-sector associated with manufacturing sector).

The national monetary supply was regionalised based on the approach applied to the national use table to build the regional monetary input-output table. The regional monetary supply table was developed using the supply-side model and industry technology as given by Equation (2) (Miller and Blair 2009):

$$D = \frac{S}{Q} \tag{2}$$

Where "D" is the share of each commodity j's total output produced by each industry *i*, Q is the 1 × m vector of commodity gross outputs and "S" is the national supply matrix. The "D" matrix is the core of an industry technology assumption (Guo et al., 2002).

In the second step, we omitted a supply-side input-output model due to poor economic interpretation of economic agents (Mesnard 2004). Hybrid-unit emergy input-output system of the urban economy and environment cannot be constructed if monetary and energy tables describe different technologies (Guevara and Domingos, 2017; United Nations 2018). Moreover, energy use and supply tables appear to be suitable for analysing energy conversion chains (Heun et al., 2018). Therefore, the industrial technology was selected to build a regional monetary input-output table as given by Equation (3):

$$Z = A_i X \tag{3}$$

Where Z is an n × n matrix of intermediate consumption (sales from processing sector i to producer j). The final demand was obtained using the Leontief input-output model as given by Equation (4):

$$F = X - Z \tag{4}$$

Where "F" is an n × 1 vector of final consumption (total sales from processing sector *i* to the consumer *f*). The data contained in "Z", "F", and "X" constitute the regional monetary input-output table.

2.2. Regional energy input-output table

The actual total supply (S) and use data (Q) from the regional energy balances (AUSTRIA 2015b), physical energy flow accounts manual (Physical Energy Flow Accounts - Example Austria - ppt download. Slideplayer.com, 2020), and the structure of national physical energy flow accounts was used to build regional energy use and supply tables (AUSTRIA 2015c). Consequently, the provincial energy use table was integrated with the regional energy supply table using Leontief's "demand-side commodity by industry model".

As data for primary and derived products (electrical energy and heat) was available, the total supply (S) was calculated using Equation (5) for derived or primary products (the primary production of natural inputs was zero):

$$S = U_T + m \tag{5}$$

Where "U_T" represents the primary or secondary production (transformation output) and "m" shows the number of imported energy products. The full use of products (Q) was obtained from Equation (6):

$$Q = Z + F + G + H \tag{6}$$

Where "Z" is the regional sectorial intermediate consumption., "F" is the consumption of households, "G" is the gross capital formation (production of combustible wastes) and "H" represents the exports (Physical Energy Flow Accounts - Example Austria - ppt download. Slideplayer.com, 2020). Since total energy supply should be balanced with the total energy demand, total final energy consumption (Fe) was verified using Equation (7).

$$Fe = Q - Z \tag{7}$$

The regional shares of industrial production and consumption "U_T" were also found using an "a simple location quotient" based on final energy consumption (Miller and Blair 2009; Liu and Vilain 2004). The value-added data was multiplied by the intensity of final energy consumption per million € to compute the final energy consumption of industrial sectors (Vienna City Administration, 2015; Otsuka 2016). The vector of location quotients (regional shares) was used to produce the regionalised versions of matrix "β" and "D". Consequently, "β" and "D" matrices were multiplied by "Q" to build supply and use tables, respectively.

In monetary and energy supply and use tables, the total commodity "Q "and industry "X" outputs must conform to the supply-demand balance (balance for the production units). We used the value-added matrix (W) to check monetary and energy balances. Energy carriers' balances across products and industries must conform to the conservation condition (Heun et al., 2018). In the use and supply table, value-added should be equal to the final demand to comply with the energy conservation rule. Therefore, the value-added matrix (W) was calculated by Equation (8):

$$W = V^T - U \tag{8}$$

Where "V^T" is the transposed supply matrix (commodity by industry), and "U" is the commodity by industry use matrix.

The commodity output proportions matrix (D) was derived from the regional energy supply table using Equation (2).

Since exchanges between commodities were not considered in this study, the D matrix was multiplied by B to obtain the direct-input coefficients matrix "A". Lastly, the final energy consumption was calculated. The monetary and energy input-output tables were necessary since both tables contain the direct and indirect flows exchanged between industrial sectors and the environment.

2.3. Development of emergy input-output model

The next step was to translate monetary and energy flows into standard units of "emergy" to determine the flows exchanged between the industrial sectors and the environment. This was achieved by multiplying those flows by their respective transformities (Li et al., 2010). Transformities for energy and monetary flows were calculated separately due to the nature of flows.

Emergy method accounts for the total environmental support to the process that includes the work of the environment to make a product and for the human economy to process it. The ratio of the available energy previously used up both directly and indirectly in transformations to make energy or monetary product or service to the actual energy content or monetary value of this product or service provides a measure of the environmental cost of the product. This ratio, called transformity expressed in solar equivalent joules (seJ) required to make 1J of a different product or service. The higher transformity represents the higher efficiency and effectiveness of energy transformations in ecological and economic systems. The emergy is derived from available energy (exergy) or the amount of money and transformity; see Equations (9) and (10).

$$\text{emergy (sej)} = \text{transformity (sej/J)} \times \text{available energy (J)} \tag{9}$$

$$\text{emergy(sej)} = \text{transformity (sej/\$)} \times \text{available monetary flow (\$)} \tag{10}$$

Emergy accounts for both the environmental and socio-economic support to the production process. Socio-economic support includes the labour work directly applied to the method and economic services-indirect contribution to the production process such as emergy investment provided from the larger scale of economy. The sum of emergy implied and ecological (i.e., energy) and socio-economic inputs (i.e., money) reflect the total environmental support provided to the urban socioecological system (Asamoah et al., 2017; Liu et al., 2021; Viaglia et al., 2018).

We used matrix algebra to calculate transformities in energy and monetary flow networks. The matrix algebra (MA) is a family of methods for measuring energy quality (transformity) in ecological and economic systems based on solving simultaneous linear equations. These methods estimate transformations (quality equivalent units) in complex ecological and economic network data (energy and monetary input-output tables).

The first of this family of methods, called the Quality Equivalent Method (QEM), was developed in Patterson in 1983 in parallel to the Emergy methods introduced by Odum. The quality equivalent units (δ) – are the units that measure the quality of each energy form in the socio-ecological system by applying the specific coefficients determined by solving a series of linear equations. Each linear equation represents the energy (energy conversion chain) or economic processes (distribution of producer outputs throughout the economy). Therefore, QEM fulfils the same function as transformity in the emergy accounting method and can be defined as a transformity of energy and monetary systems. Unlike the QEM emergy method only consider backward linkages and is inapplicable to the forward links.

Consequently, QEM assesses the complete economic and energy transformation process, consisting of upstream and downstream operations. Moreover, QEM does not rely on Emergy algebra methods and instead applies statistical criteria to allocate the emergy inputs to multiple process outputs. This method is assumption-free and removes the requirement to apply decision rules to avoid double counting.

Furthermore, both the emergy and some methods of matrix algebra, namely the matrix inversion approach developed by Costanza, use solar energy as a numeraire, indicating that it's the only primary direct input into ecosystems (Franzese et al., 2009). Lastly, QEM is free of constraints based on the a priori assumption that all processes should have an emergy-based unity efficiency. In natural complex socio-ecological systems, emergy-based process efficiencies are rarely the same because of the existence of residuals of each process. The method allows equal and unequal process emergy efficiencies by solving simultaneous equations.

The main existing challenge in applying those methods is inapplicability to the underdetermined systems (processes less than quantities). The other problems appear in the process of practical implementation of those methods: non-square matrices, joint production (co-products), negative transformities, matrix singularity (non-invertible matrix), equal process efficiencies (emergy inputs of industrial sectors are similar to their emergy outputs), choice of numeraire and non-unique solution vector of transformities and mathematical elegancy (Patterson 2012, 2014). This section developed approaches to tackle most of those problems (except for non-square matrices). The matrix method was integrated with a reflexive method to estimate transformities of industrial sectors from energy and economic systems and overcome methodological problems associated with those two approaches. The matrix method is an extension of energy input-output analysis to estimate emergy flows among industrial sectors (Hannon et al., 1986; Patterson 2012, 2014). Therefore, this method is compatible with any energy and monetary input-output data (Hannon et al., 1986; Patterson 2014). In addition, the reflexive method is helpful in converting an energy or value-added monetary matrix into an emergy-evaluated matrix that guarantees the positive vector of transformities without prior knowledge of transformities.

The matrix inversion method can be significantly improved by using a pre-conditioning procedure. The reflexive method was used to perform pre-conditioning. We took the solar energy inputs into the regional energy use table as a numeraire because it is the only direct primary input into ecosystems based on the emergy analysis (Hannon et al., 1986; Franzese et al., 2009; Patterson 2014). The first seven steps from the reflexive method were used to transform the energy value-added matrix into a matrix that guarantees a positive vector of transformities (Patterson 2014). This procedure aims to formulate the Kernel matrix Z that can be inserted in the matrix inversion equation to produce a guaranteed positive vector of transformities P. The first steps involve an initial guess of transformities (Patterson 2014). We used the vector of solar energy transfomities to avoid double counting and keep the algorithm intact. As the first step, energy and monetary value-added matrices were determined; see Equation (7) (in original article). Then, the emergy-evaluated version of energy and monetary matrices (R) was chosen, Equation (11) (Patterson, 2014).

$$\mathrm{R} = \mathrm{W}^{T} \times \mathrm{P} \tag{11}$$

where W^{T}-transposed version of matrix W (process x quantity), P- diagonalised matrix of solar energy transformities (quantity x quantity). The next step involves the construction of the extended 'outputs matrix' S (p x m), where the p-number of the positive elements (outputs) in matrix W. The values of this matrix are obtained through an allocation as a proportion of all inputs (−) of a relevant process to each process output (+). The fourth step is based on constructing the extended 'inputs matrix' T (n x m), where n –the number of negative elements (inputs) in matrix X. The values of this matrix are obtained through an allocation as a proportion of all outputs (+) of a relevant process to each process input (−).

The subsequent step is associated with constructing the aggregated 'outputs matrix' H. H matrix is (n × m) of commodity inputs to produce each of the process n outputs. Matrix H is constructed by summing all the sub-process rows in T with the same output (+). The purpose of this step is to arrange outputs (+) on the diagonals of H while inputs (−) are along the non-diagonals to guarantee a positive transformities vector (P). Later, we built an aggregated 'inputs matrix' G. G is a matrix (m × g) of output processes directly resulting from each g input. Matrix G is constructed by summing all sub-process rows in S with the same input (−). The purpose of this step is to arrange inputs (−) on the diagonals of G while outputs (+) are along the non-diagonals to guarantee a positive transformities vector (P).

The last step borrowed from the reflexive method includes the construction of the Kernel matrix (Z), Equation (12).

$$\mathrm{Z} = \mathrm{U} - \mathrm{V} \tag{12}$$

Where U- aggregated 'outputs matrix' (energy supply matrix) and V aggregated 'inputs matrix' (energy use matrix).

As a result, we obtained a perfect matrix to use with the matrix inversion method. The vector of transformities in this method is determined through the multiplication of primary inputs by total direct and indirect energy or economic requirements of industrial sectors; Equation (13):

$$p = g(U - V)^{-1} \tag{13}$$

Where "U" is the energy supply matrix (m × n), "V" is the energy use matrix (m × n), and "g" is the numeraire vector (1 × n) of solar energy inputs to an industrial sector, and "p" is the transformity vector (1 × m). By substituting for Z^{-1} in Equation (9) above, we obtain the vector of transformities P (1 × n) as given by Equation (14):

$$P = g \times Z^{-1} \tag{14}$$

Where "Z" is the Kernel matrix. This operation was performed since the reflexive method can adjust the matrices "U" and "V" but not change their purpose (backward and forward linkages, respectively). As a final step, the regional monetary and energy input-output tables were multiplied by their respective vectors of transformities (P) and summed up to calculate the total emergy flow, construct the emergy input-output table, and develop a hybrid-unit emergy input-output model.

2.4. Hybrid-unit emergy input-output model

The hybrid-unit emergy input-output model was developed using the multi-factor energy input-output model based on the national economic system (Miller and Blair, 2009; Guevara and Domingos 2017; Bagheri et al., 2018). The significant advantage of this model is the segregation of energy and non-energy production and consumption processes within the national economy. By using the exact model, the input-output tables included five energy producers (production, extraction and capture of energy) (SEEA energy): 'environment', 'electricity, gas, water supply, sewerage, waste, and remediation services, 'agriculture, forestry and fishing', 'mining and quarrying', and 'manufacturing'. The multi-factor energy input-output model was adjusted to the regional level using the industry-based regional accounting (Jackson and Schwarm, 2011) and hybrid-unit regional input-output accounting (United Nations, 2018) frameworks. This is provided in Tables S–B in the supporting information file "S2".

The hybrid-unit emergy IO model could be built by combining the emergy input-output table with the monetary input-output table based on the hybrid-unit input-output approach. By following this approach, economic services provided by the energy industries were incorporated into the analysis (Guevara and Domingos, 2017). Moreover, the framework assisted in identifying an emergy use pattern and in estimating the total environmental support provided to the urban socio-ecological system using the case of the Vienna region. Based on Guevara and Domingos (2017), the elements of the hybrid-unit emergy input-output model are presented in Equation (11):

$$\begin{pmatrix} g \\ x \end{pmatrix} \begin{pmatrix} A_{\theta}^{*} & A_{\tau}^{*} \\ A_{\pi}^{*} & A_{\psi}^{*} \end{pmatrix} \begin{pmatrix} h \\ f \end{pmatrix} \tag{15}$$

Where "g" and "x" are respectively the sub-vectors of the total output of energy industries in seJ and non-energy industries in €; "A_{θ}^{*}" is the number of emergy inputs purchased directly to produce 1 seJ of output; "A_{τ}^{*}" is the number of emergy inputs purchased directly to make 1 € of output; "A_{π}^{*}" is the number of monetary inputs purchased directly to produce 1 seJ of output; "A_{ψ}^{*}" is the number of monetary inputs purchased directly to make 1 € of output; "h" and "f" are respectively the sub-vectors of final demand for products of energy industries (in seJ), and non-energy industries in €. Solar emjoule (seJ) is the solar equivalent unit used to measure the total environmental cost of a product or service in the emergy accounting method. In the concluding step, the total emergy use vector (g) was calculated using Equation (12):

$$g = \left(L^{E} + L^{E} \times A_{\tau}^{*} \times A_{\pi}^{*}\right) \times h + \left(L^{E} \times A_{\tau}^{*} \times L_{\psi}\right) \times f \tag{16}$$

Where "L^{E}" and "L_{ψ}" are respectively the sum of direct and indirect emergy purchases required to produce a 1 seJ of output and the sum of direct and indirect monetary purchases needed to produce a 1 € of output.

The vector (g) is the emergy consumed by each industrial sector and the environment. Therefore, by adding the values along the column, total emergy use by each industrial sector and the environment can be calculated to characterise the total emergy exchanged between the urban economy and the environment. By this method, the total environmental support provided to the urban-socio-ecological system could be estimated.

2.5. Data collection and sources

Due to the absence of regional and city-level data, we obtained the data from national supply and use tables contained in the national accounts (AUSTRIA, 2015a). For intermediate monetary consumption and final monetary demand categories, we used Austria's national monetary supply and use data for the year 2015, a complete representation of the national economy. The monetary supply and use table consisted of 65 industries following NACE 2008 classification and 65 products following the CPA classification (AUSTRIA, 2015a). Then, a national monetary supply and use commodity by industry model was downscaled based on value-added data (earnings generated by the production of goods and services) (Vienna City Administration, 2015) to estimate the share commodity inflows to the Vienna region using a simple location quotient (LQ) technique (Liu and Vilain 2004). Here, we aggregated industrial sectors in Austrian supply and use tables to match aggregated gross value-added data by the NACE industry (Statistik AUSTRIA, 2015e). As a result, we obtained monetary supply and use tables, which differentiate between 16 sectors and 64 products.

For energy input-output data, we downscaled physical energy flow accounts (PEFA) (AUSTRIA 2015c). The total regional energy supply and use by-product (total commodity output in TJ) were obtained from the Vienna energy balances (AUSTRIA, 2015b). The regional energy supply and use tables were then, built using the supply-side model (Ghosh "commodity by industry model") to estimate the proportion of commodities used by various industries in Austria. We then used a simple location quotient (LQ) technique (Liu and Vilain 2004; Otsuka 2016) to downscale the national proportions to obtain regional shares of commodities sold to various industries. The downscaling procedure for national energy supply data involved standard procedure, whether Ghosh or Leontief's "commodity by industry model" is chosen (Shao and Miller, 1990). Then, multiplication of regional proportions derived from energy supply and use tables the by total energy supply (or use) from Vienna energy balances (AUSTRIA 2015b) yielded Vienna's regional energy supply and use tables (Miller and Blair 2009).

Renewable energy sources and some energy products used in households were taken from Vienna's regional energy balances (AUSTRIA, 2015b) as it already contains data on the total consumption of households, energy exports, and stocks. To match the data obtained from energy balances with the information on product classification reported in PEFA (39 energy products), we needed to aggerate data by summing the product categories from EB. We took the following natural energy inputs categories and aggregated some of them: hydropower; wind power; solar energy (solar heat, photovoltaic); biogenic primary energy carriers (production of fuelwood, wood waste, black liquor, liquid biofuels and biogases); ambient heat, geothermal energy, reaction heat was taken from the downscaled national physical flow accounts, namely the vector of the final energy demand of households. We also borrowed from the same source energy product categories: gasoline, coal and peat; coke oven gas, blast furnace gas (including converter gas); coke, coal tar, hard coal (patent fuel) briquettes and brown coal briquettes; liquid (NGL); naphtha; fuel oil; refinery gas and liquefied petroleum gas; other oil products (excluding naphtha) and refinery feedstocks; fuelwood, wood pellets and briquettes, wood waste, charcoal, other solid biofuels; bioethanol, biodiesel, and other liquid biofuels; landfill gas, sewage sludge gas, and other biogas; district heat; biogenic waste; non-renewable waste (industrial waste and municipal waste non-renewable). As some energy products were not available on a regional scale (i.e., fossil non-renewable natural energy inputs) and were absent from national physical energy supply and use tables (i.e., nuclear fuel), the number of products was reduced to 25. We, therefore, obtained national physical energy supply and use tables containing 25 energy products and 16 industries, exactly matching the number of sectors included in monetary counterparts.

3. Results and discussion

This section will discuss the results of this analysis using the Vienna region as a case study.

3.1. *Input-output table for Vienna region*

The monetary and energy input-output tables provided support in identifying urban resource flows and assessing the efficiency of urban metabolism. With the help of regional input-output tables, monetary transactions between each pair of components assisted in identifying the weak and strong sectoral connections. Table 1 presents the summary of Vienna's provincial monetary input-output table as of 2015. The complete sectoral details are provided in Tables S–C in the supporting information file "S2".

Based on the regional input-output table (Table 1 and Tables S–C), "mining and quarrying" and "agriculture, forestry, and fishing" are the weakest sectors in the urban economy. Those two sectors and "manufacturing" have shown dependence on imported products. The highest importer was the "manufacturing" sector with 33% of products imported from outside of Vienna region. In addition, all industries, except for "information and communication", "electricity, gas, water supply, sewerage, waste, and remediation services", "professional, scientific, technical, administrative, and support service activities", "financial and insurance activities", could be characterized by negative net incomes (i. e. income-expenditure). The "manufacturing" and "human health and social work activities" sectors had the lowest net incomes i.e., −10237.62 and −1684.4 million €, respectively. These negative values are due to the large import shares in the total outputs of those sectors. Table 2 presents the summary of the energy input-output table for Vienna, as of 2015. The complete sectoral transactions are provided in Tables S–D in the supporting information file "S2".

As shown, "agriculture, forestry, and fishing", "manufacturing" and "electricity, gas, water supply, sewerage, waste, and remediation services" are characterised by the largest share of renewable energy. The "mining and quarrying" sector did not use any renewable energy inputs

Table 1
Summary of the monetary input-output table for the Vienna region, as of 2015.

Sector	Intermediate Consumption	Value Added	Imports	Final Demand	Total output
Agriculture, forestry, and fishing	556.30	168.06	25.00	318.42	749.35
Mining and quarrying	103.00	35.04	22.00	66.65	160.04
Manufacturing	9001.95	7452.29	5848.84	16086.46	22303.08
Electricity, gas, water supply, sewerage, waste, and remediation services	2250.30	432.50	1945.00	1266.65	4627.80
Construction	3472.20	333.04	3372.00	4207.18	7177.24
Wholesale and retail trade, repair of motor vehicles	4527.69	453.71	10185.00	11757.16	15166.40
Transportation and storage	2897.17	1051.04	4406.00	4708.04	8354.21
Accommodation and food service activities	1266.73	514.69	2681.00	3850.59	4462.41
Information and communication	1191.39	952.82	6543.00	5722.57	8687.21
Financial and insurance activities	1506.74	1054.40	5149.00	4896.74	7710.13
Real estate activities	1363.19	462.18	7410.00	7791.29	9235.37
Professional, scientific, technical, administrative, and support service activities	3506.88	2146.35	11657.00	11242.41	17310.23
Public administration and defence, social security	1044.37	434.14	4687.00	5866.11	6165.51
Education	350.14	149.78	5091.00	5413.55	5590.92
Human health and social work activities	1228.96	583.35	5569.00	7253.40	7381.31
Arts, entertainment, and recreation, repair of household goods and other services	700.18	207.04	3335.00	3909.03	4242.23

Where intermediate consumption, value added (income), imports, final demand (expenditure) and total output is in Million Euro (€). The sum of intermediate consumption, imports and value added is equal to the sum of intermediate consumption and final demand for each sector, representing the total economic output of each industrial sector.

Table 2
Summary of the energy input-output table for Vienna region, as of 2015[a].

Sector	Intermediate Consumption	Renewable Energy	Imports	Value Added	Total Output
Agriculture, forestry, and fishing	47.83	1150.31	130.30	24.61	1353.05
Mining and quarrying	79.56	0.00	210.20	132.80	422.56
Manufacturing	6743.86	3161.05	22433.32	496.37	32834.60
Electricity, gas, water supply, sewerage, waste, and remediation services	4710.05	7351.51	15232.57	16355.89	43650.02
Construction	1124.32	0.03	4584.16	0.00	5708.51
Wholesale and retail trade, repair of motor vehicles	3640.92	4.86	7822.04	0.00	11467.82
Transportation and storage	5197.72	6.69	20808.08	0.00	26012.49
Accommodation and food service activities	1973.23	5.30	2735.38	0.00	4713.91
Information and communication	451.81	1.27	692.17	0.00	1145.25
Financial and insurance activities	268.70	0.84	479.65	0.00	749.19
Real estate activities	507.01	0.20	501.85	0.00	1009.06
Professional, scientific, technical, administrative, and support service activities	1237.54	6.55	3534.13	0.00	4778.22
Public administration and defence, social security	4410.87	9.43	4594.68	0.00	9014.98
Education	1009.32	8.79	1036.23	0.00	2054.34
Human health and social work activities	2746.61	0.28	2275.06	0.00	5021.95
Arts, entertainment, and recreation, repair of household goods and other services	1201.66	19.80	1731.69	0.00	2953.15

Where renewable energy, intermediate use, value added, final demand and output is in Terajoules (TJ). The sum of intermediate consumption, renewable energy, imports and value added for each sector represents the total energy output of each industrial sector.

in its production process. The 'construction", "real estate activities", and "human health and social work activities" consumed the least renewable energy to sustain their production activities: 0.03 TJ, 0.20 and 0.28TJ, respectively.

These results highlight the importance of renewable energy in production activities. The renewable and non-renewable energy inputs are captured directly by upstream industries to produce primary energy products (i.e., biofuels). On the other hand, downstream sectors are dominated (services and households) by non-renewable natural energy products. Considering the high total energy consumption of these compartments (i.e., transportation and storage) and energy demand (households), sustainable consumption strategies should be adopted.

As a matter of imports, the "construction" and "transportation and storage" sectors rely on the highest share of imported energy products, 80% and 79% (out of total output), respectively. On the contrary, "human health and social work activities" and "real estate activities" use mostly local energy inputs: 55% and 50%, respectively. Overall, the sectors located on the upstream part of the energy conversion chain have a larger consumption than the downstream sectors. Notably, the "electricity, gas, water supply, sewerage, waste, and remediation services" and "manufacturing" sectors have the largest outputs: 43650.02 TJ and 32834.60TJ, respectively. Moreover, the energy sector is responsible for a significant part of the final demand (households, capital formation and exports): 16355.89TJ. Since this sector is a product of the aggregation of two industries: "electricity, gas, steam and air conditioning supply" and "water supply; sewerage, waste management, remediation activities", the overall output and final demand appear to be considerable.

Finally, Table 2 shows that downstream sectors do not deliver any energy to the final consumers (final demand). That means that the first priority of the regional development strategy should be to decrease the final energy consumption and increase investment in the "manufacturing" sector.

3.2. Transformities of monetary and energy flows

The positive vector of transformities for energy and monetary flows between industrial sectors of the urban economy and the environment was derived. Table 3 presents the transformities from energy and economic network data, respectively, for the Vienna region.

Table 3
Transformities from energy and economic network data.

Sector	Energy network data (sej/J)	Economic network data (sej/€)
Agriculture, forestry, and fishing	8.57E+08	5.39E+10
Mining and quarrying	8.57E+08	2.17E+11
Manufacturing	6.44E+08	3.26E+10
Electricity, gas, water supply, sewerage, waste, and remediation services	8.57E+08	6.26E+11
Construction	2.66E+09	1.15E+10
Wholesale and retail trade, repair of motor vehicles	7.73E+08	1.54E+10
Transportation and storage	2.51E+09	2.37E+10
Accommodation and food service activities	2.66E+09	2.74E+10
Information and communication	2.15E+09	3.53E+09
Financial and insurance activities	2.39E+09	6.59E+09
Real estate activities	1.20E+09	3.12E+10
Professional, scientific, technical, administrative, and support service activities	7.14E+08	8.56E+09
Public administration and defence, social security	2.66E+09	2.91E+10
Education	1.16E+09	2.49E+10
Human health and social work activities	2.38E+09	1.56E+10
Arts, entertainment, and recreation, repair of household goods and other services	7.32E+08	2.14E+10
Renewable energy	8.03E+08	0.00E+00

As given, transformities of industrial sectors based on "economic network data" were on average 78 times higher compared to the transformities based on "energy network data". This result shows that transformities based on "energy network data are more efficient in processing emergy flows to maintain 1 unit of structure (organisation). The economic services are provided by the industries as an investment to other industries tend to increase the total emergy support to the process (industry). More detailed inspection shows that the transformities obtained from economic network data for "electricity, gas, water supply, sewerage, waste, and remediation services", "mining and quarrying", "agriculture, forestry, and fishing", and "manufacturing" are 730, 253, 63 and 51 times higher, respectively. This means that while these sectors receive the highest investment among industrial sectors of Vienna's economy to produce their products (i.e., investments into livestock sales barns), their actual sales to the other industries are rather small (intermediate consumption of these four sectors in Table 1). This could be related to the dependency of "agriculture, forestry, and fishing", "mining and quarrying", "electricity, gas, water supply, sewerage, waste, and remediation services", and "manufacturing" sectors on imported products and relatively small own production of these sectors compared to the demand on their products. The Smart City Wien Development strategy till 2050 included the adjustment of those industries in its program through respective subgoals: energy consumption (renewable imports and efficiency), urban farming, urban mining (from non-renewable to recycled products), and productive city (eco-industrial park).

On the other hand, the most efficient industries were “information and communication” and “financial and insurance activities” with the divergence of only 2 and 3, respectively. This result means that transformities based on “economic network data” are 2 and 3 times lower compared to the transformities based on “energy network data” for “information and communication” and “financial and insurance activities”, respectively. This result also implies that these two services (tertiary sectors) were still underdeveloped in 2015. The high transformity values based on “energy network data” associated with these two sectors are related to their considerable direct energy consumption and their position in the middle of the energy conversion chain (Zhang et al., 2014b). Therefore, the other priority should be to increase energy utilisation efficiency and decrease the direct energy consumption of those sectors.

The transformities based on “energy network data” of “construction”, “accommodation and food service activities”, and “public administration and defence, social security” were the highest and were about 4 times that of the “manufacturing” sector (6.44E+08 seJ/J). The “public administration and defence, social security” is at the end of the industrial supply chain, indicating that its transformity based on energy flows should be low. The transformities of “construction” and “accommodation and food service activities” are higher than the energy and basic industrial sectors. Therefore, the energy consumption of these sectors should be reduced, and the technology should be upgraded to improve energy utilisation efficiency. The transformities based on “economic network data” of “electricity, gas, water supply, sewerage, waste, and remediation services”, “mining and quarrying”, “agriculture, forestry, and fishing”, and “manufacturing” sectors were the highest: 6.26E+11 seJ/€, 2.17E+11 seJ/€, 5.39E+10 seJ/€, and 3.26E+10 seJ/€, and these transformities were 95, 33, 8 and 5 times that of the sector with the lowest magnitude, namely “financial and insurance activities”. These sectors are positioned at the beginning of an industrial supply chain, indicating that their transformities based on economic flows should be the lowest. Therefore, these sectors should decrease their dependence on machinery by promoting labour force, substituting expensive machinery and raw materials (i.e., crude oil, steel) with the cost-effective solutions (i.e., solar energy, fuelwood) and increasing the reuse and recycling of materials (i.e., use of animal waste to produce biogas and renewable diesel to satisfy “energy “and “transportation” demands, respectively).

Finally, the results show that the matrix inversion method overcame the problems of initial guess or estimation of transformities that could lead to a different solution vector as the solar energy vector is known prior to the analysis.

3.3. *Results of Hybrid-unit emergy input-output analysis of Vienna region*

Table 4 summarises the results obtained from the hybrid-unit emergy input-output model for Vienna for the year 2015. The complete sectoral transactions are provided in Tables S–E in the supporting information file “S2”. The “energy” industries include industries involved in energy extraction and production. The energy extraction category includes “agriculture, forestry, and fishing” and “mining and quarrying”. According to the SEEA-Energy energy production category incorporates “electricity, gas, steam and air conditioning supply” and a few sub-processes in the “manufacture” sector (i.e., Manufacture of coke and refined petroleum products). We used highly aggregated data on “electricity, gas, water supply, sewerage, waste, and remediation services” and “manufacturing” sectors since detailed information on sub-sector and sub-processes involved in energy production was not available. Other industries were considered non-energy industries (Guevara and Domingos, 2017).

In this study, the “Renewable energy sector” was considered a separate category of energy industries.

Table 4
Total emergy use for Vienna region.

Sector	Emergy use (seJ)
Renewable energy	2.08E+19
Electricity, gas, water supply, sewerage, waste, and remediation services	1.03E+19
Agriculture, forestry, and fishing	1.03E+18
Mining and quarrying	6.82E+16
Manufacturing	6.37E+18
Construction	4.07E+18
Wholesale and retail trade, repair of motor vehicles	5.92E+18
Transportation and storage	1.36E+19
Accommodation and food service activities	7.80E+18
Information and communication	1.32E+18
Financial and insurance activities	1.06E+18
Real estate activities	1.24E+18
Professional, scientific, technical, administrative, and support service activities	2.01E+18
Public administration and defence, social security	1.95E+19
Education	2.05E+18
Human health and social work activities	1.13E+19
Arts, entertainment, and recreation, repair of household goods and other services	1.76E+18
Total emergy use	1.10E+20

Emergy use of each sector allows us to understand the magnitude of emergy support to each industry of Vienna’s economy. The “renewable energy” sector uses the most emergy among sectors, while the consumption of “mining and quarrying” was the lowest among sectors: 2.08E+19 seJ and 6.82E+16 seJ, respectively.

The lowest value of emergy consumption by the “mining and quarrying” sector highlights that the Vienna government is focused on improving renewable energy production (i.e., capturing of energy from biofuels by the agriculture sector) and circular economy strategies (i.e., use of buildings and vehicles inside Vienna as sources of processed raw materials such as copper and aluminium).

The sector “Agriculture, forestry, and fishing” uses only slightly more emergy (1.03E+18 seJ) compared to the “mining and quarrying” sector. Vienna’s Region is ranked the last by the yearly volume of agricultural production despite being the most populated region in Austria (Statistik Austria 2020), indicating that the “agriculture, forestry and fishing” sector is in a similar situation in terms of investments as “mining and quarrying” sector. Considering the importance of the “agriculture” sector in renewable energy production (i.e., bringing raw materials into the system), allocating more investments into this sector could assist the government in meeting economic and environmental targets. “Electricity, gas, water supply, sewerage, waste, and remediation services” is the second-highest user among upstream sectors. In fact, large power plants with an output exceeding 20 MW are in Vienna Region.

The “Renewable energy” sector is supported by a large emergy consumption, confirming the importance of renewable energy in the context of Vienna’s regional economy. Currently, organic agriculture occupies only 17% of the Vienna region’s agricultural land (Green and Open Spaces STEP, 2025). By 2030 this land for organic agriculture is planned to be expanded using city areas to promote the neighbourhood and community gardens for organic food production (Green and Open Spaces STEP, 2025). Thus, the use of renewable energy sources (i. e., solar energy) and their importance in social production and life is expected to increase in the future. Hence, it is recommended to improve the share of renewable energies in sectors’ consumption.

The “construction” sector uses less emergy, amounting to 4.07E+18 seJ. The moderate use suggests that this sector is still in the developing phase. The energy-intensive process such as “manufacture of coke and refined petroleum products” are located outside of the region. Therefore, the “manufacturing” sector uses emergy at a moderate level compared to other upstream industries. This result is similar to “construction”.

"Public administration and defence, compulsory social security", "transportation and storage" and "human health and social work activities" are characterized by the highest emergy consumption among industries: 1.95E+19 seJ, 1.13E+19 seJ, and 1.13E+19 seJ, respectively. Compared to other sectors, the highest value of those sectors confirms a strong policy commitment to provide high-quality social services oriented towards smart cities and urban sustainability in line with Vienna's development strategy (Urban Development Plan STEP, 2025). Since this sector is responsible for the provision of social services, more extensive development plans, require more investment into "public administration" to develop this sector to meet the demand for transportation infrastructure (80% of trips with eco-friendly means of transport such as bicycle by 2025) and social infrastructure (i.e., Vienna Hospital Concept 2030) (Economy and Innovation Vienna, 2030). "Wholesale and retail trade, repair of motor vehicles" consumed 6 times more emergy compared to the "agriculture, forestry and fishing". This difference stems from lower agricultural investments since the magnitude of the indirect consumption increases with progression along the supply chain. The wholesaling process (i.e., distribution of electricity, natural gas, farm, and pharmaceutical products, etc.) is more money-intensive compared to exchanges among upstream sectors (i.e., agriculture and manufacturing) due to benefits obtained from the expanded consumer market (long distribution channels of goods through numerous retail stores, tertiary consumers, or other manufacturing wholesalers) before reaching the end-consumer (i.e., households).

Since the investment of downstream industries into the upstream components (extractive and productive industries) drives the development and technological advancement of the upstream industries, two strategies can be considered. The first strategy regards supply-side interventions (i.e., to reduce non-renewable energy production by the traditional agriculture, enhancing sinks, fossil fuel offsetting, and increase the share of renewable energy production by the "agriculture" sector to promote and support the downstream sectors characterised by low emergy consumption such as financial and insurance activities) (Scherer and Verburg, 2017). To operate heavy farming machinery, process foods, refrigerate goods during transportation, create packaging materials, and manufacture and transport agrochemicals such as fertilisers and pesticides, a large amount of natural gas obtained from the Vienna Basin is necessary (Mayer and Schatz, 2020). Switching to natural fertilisers such as animal manure and adopting manure management practices to capture biogas via anaerobic digestion for energy might be a good solution for reducing non-renewable energy consumption (Scherer and Verburg, 2017). In addition, solar-powered water pumps for irrigation, solar dryers such as solar drying systems based on an evacuated tube collector (ETC), solar greenhouses based on concentrated PV thermal technology for their heating and cooling, and ventilation for agricultural enterprises such as pig farms to keep in check the temperature and air quality (Hussain and Lee, 2015). As of sink, the productivity of small areas associated with traditional agriculture in the Vienna Region should be improved through investments to save the natural area for the generation of environmental support to Vienna's economy and to reduce additional energy requirements stemming from agricultural yield losses associated with climate change and to provide an additional land area for renewable energy production (Scherer and Verburg, 2017). Supply-side interventions are mainly concerned with the improvement of productivity and deliver ability of producers, while demand-side interventions are concerned with consumers' consumption and receiver ability (Creutzig et al., 2016; Wang, 2020; Wieland et al., 2019). The agriculture and mining sectors are the most underdeveloped sectors in the region (Zhang et al., 2014b), with the least consumption originating from other sectors (both direct energy and indirect monetary consumption), thereby failing to satisfy the demands of "financial and insurance activities" and "real estate activities "for energy consumption, which in turn are unable to invest in the agricultural and mining production. Therefore, it is important to promote local direct renewable energy consumption and to increase the share of imported agricultural and mining products in the consumption of "financial and insurance activities" and "real estate activities "(Scherer and Verburg, 2017). This can be archived through the conversion of solar radiation into electricity for lighting purposes using photovoltaic cells and solar thermal energy to heat real estate properties such as condominiums. Vienna Government is mostly focused on subsidising the decarbonisation measures in the housing sector (final energy consumption of households) by the deployment of PV in the multi-apartment building sector is supported by subsidies through Photovoltaic Systems Program (Gollner et al., 2020; Komendantova et al., 2018; Neumann et al., 2021). These measures need to be extended for these two tertiary sectors to switch to renewable energy consumption for light and heating purposes (Komendantova et al., 2018). In addition, it is advisable to decrease the direct energy use by these two tertiary sectors. In addition, it is advisable to reduce the direct energy use from energy producers (energy and manufacturing sectors) by these two tertiary sectors. Decreasing energy production of secondary energy products (heat and electricity) by the energy sector used to manufacture plastics and paper products would reduce direct energy consumed by two targeted tertiary sectors. For this purpose, demand response by the end-users, short-term adjustments of users' consumption to renewable energy generation via a change in behaviour and use of technology such as a shift of energy consumption in time (using a building as energy storage), contributes to the decrease of electricity consumption and energy use efficiency by the tertiary sector, saving monetary resources (revenues from electricity cost reduction) for their development (Kirkerud et al., 2021; Wohlfarth et al., 2018). Kirkerud et al. (2021) found that territories with a high share of hydropower use benefit economically from applying demand response to electric space heating and water heating. Vienna Region also falls within this category (Vienna City Administration, 2015; "Austria: Power production share by source, 2021," 2022). Therefore, it may be a promising option for improving electricity management, leading to a decrease in direct energy consumption of non-residential buildings and the improvement of the investment capacity of two critical tertiary industries. The same measure also needs to be implemented in other service industries since saving their funds contributes to the investments in critical energy industries ("agriculture, forestry, and fishing" and "mining and quarrying") and tertiary sectors (financial and insurance activities" and "real estate activities "). Thus, the supply-side and demand-side interventions should be applied to improve the development of the Vienna metabolic system in terms of monetary generation and energy consumption by tertiary industries and energy production and monetary consumption by energy industries.

Furthermore, these results mean that the total emergy use of the Vienna region (1.10E+20) should be increased to accommodate the needs of the urban socio-ecological system. The higher total emergy use reflects the higher "real wealth" in the system (Campbell et al., 2014). According to the 4th principle of thermodynamics (Maximum Empower Principle), any system increases total emergy flow during its self-organization process to maximise its emergy flows exchange, production, and emergy use efficiency in the system to survive in the long-term perspective (Odum, 1983, 2007; Lahlou and Truffet, 2020). The regions are committed to grow GDP (economic growth) while decreasing their direct energy consumption, i.e., to minimize environmental impacts while sustaining urban welfare (human health and well-being) (Campbell et al., 2014; Donati et al., 2020). For survival and sustainability in the long-term perspective, the harmonious relationship between socio-economic and ecological sub-systems of the urban ecological system needs to be considered for the mutual benefits of humans and nature (socio-economic and ecological benefits). For this purpose, it is essential to increase monetary support (i.e., investments) to the sectors characterised by low emergy consumption ("agriculture, forestry, and fishing" and "mining and quarrying"). Thus, using a strategy that results in the more considerable total environment support provided to Vienna's socio-ecological system seems reasonable.

3.4. Research implications, limitations, and future scope

The hybrid-unit emergy input-output model can be applied to any region worldwide, subject to the availability of national monetary accounts and regional energy balances to construct the model. Statistical offices can use these data to improve the input-output databases with a more detailed description of emergy flows and economic transactions in cities and regions.

Researchers into urban metabolism and regional (local) administrators will benefit significantly from the application of those accounts to their works. The model will assist managers and policymakers worldwide in developing sustainable resource management policies targeting the improvement of vulnerable sectors in line with "integrated wealth assessment" and "circular economy" principles.

We encountered some practical problems during the estimation procedure. The outputs-inputs matrix Z constructed from economic network data does not have a zero 'eigenvalue' due to the regionalisation method employed instead of the survey or partial survey methods. For this reason, it is not possible to use Eigenvalue–eigenvector or Singular Value Decomposition (SVD) method to obtain transformities using regional monetary network data.

The other limitation was the unavailability of region-specific economic data to construct a regionalised version of the national monetary input-output table. Therefore, we regionalised the national tables using the industry earnings and location quotient approach to obtain the approximate version of the regional monetary input-output table. Three issues could lead to overestimating intermediate consumption and final demand from the regionalisation (downscaling) procedure. Firstly, production technology is assumed to be uniform among regions within a single country, resulting in regional production share associated with a specific industry, excluding imports, equal to the national one (Miller and Blair, 2009). However, suppose the technology used in the production process differs (coal-fired versus gas-fired power plant for electricity production). In that case, the share production is assumed to be the same as on the national level (i.e., coal-fired in all Austrian regions, even though no coal is used in Vienna). This suggests that industries with $LQ = 1$ might have a lower share of production than 1. For instance, the productivity of the energy industry can easily be underestimated since, nationally, hydropower plants are dominant, but in Vienna, nearly half of power plants operate using natural gas (40%) (Vienna City Administration, 2015; "Austria: Power production share by source, 2021," 2022). Assuming hydropower is the only source of power generation for electricity plants in Austria underestimated productivity of natural gas power plants located in Vienna leads to the underestimation of share of production of this industry in underestimating the share of production of this industry in the Vienna region. This non-uniformity in production recipes for electricity across regions in Austria is not incorporated into the LQ estimation procedure (Miller and Blair, 2009).

The other issue is that it is assumed that either net exporter or importer of the same products, leading to the overestimation either of imports ($LQ < 1$) or exports ($LQ > 1$) included in the location quotient of a specific industry. In our case, the share of imported goods and services used by "manufacturing" sector" might be underestimated since exports for this sector have not been incorporated in the estimation of location quotient ($LQ < 1$). The same applies to "transportation and storage" sector, for underestimation of exports of liquid biofuels such as biodiesel. Finally, there is an issue with the share of regional production (A^r) not exceeding the national one (A^n), as it is not clear if the percentage of the national output exceeds a national average. Some studies even emphasised that the share of regional production often transcends regional administrative boundaries. Industries usually represent economic clusters, agglomeration of industries that can have administration offices in the city, but its production activities associated with the Vienna region lie outside the administrative boundary (Pominova et al., 2021). The sector that falls under this requirement is the Manufacturing sector, for which a limit of 100% may be underestimated.

It's also important to note that we downscaled production (make matrix) and consumption (use matrix data). (Liu and Vilain, 2004; Miller and Blair, 2009). This approach has been applied only once to estimate the number of commodities sold to each industry in a commodity-by-industry format. In simple terms, they derived the supply-side version of the monetary use table (consumption of commodities by industries). On the other hand, we applied this approach to downscale national monetary supply, national energy supply, and use tables. The application of LQ to downscale both production and consumption data introduces the risk of underestimating the productivity of industries in the Vienna Region.

The location quotients should reflect production characteristics for the supply table (share of value-added, employment) and consumption characteristics (i.e., percentage of monetary of final energy demand) for the use table. The value-added of final demand data should be sufficient when both tables conform to the balance of production units ($W^T{=}Fe$). Application of the original version of the location quotient is associated with industrial input-output tables. Therefore, Liu and Vilain (2004) especially stressed that the use of energy inputs (products) evaluated in monetary terms could be overestimated (i.e., close to the national counterparts) due to the difference in usage of energy inputs between regions and nations. Therefore, the overestimation of monetary use by electricity, gas, water supply, sewerage, waste, and remediation services (D + E) results in an overestimation of this sector's emergy consumption. Lastly, the supply-driven commodity-by-industry input-output model assumes that any primary input from the environment or production factor (labour, value-added) drives changes in the total value of production (sectoral gross inputs) (Miller and Blair, 2009; Wieland et al., 2019). This implies the responsibility of industry energy extraction industries (direct users of natural resources such as crude oil, natural gas or their monetary equivalents) and other energy industries located at the beginning of the supply chain (Wieland et al., 2019). Our results suggest that the sectors with higher value of renewable energy inputs, imports and value-added among energy industries can have unrealistically large emergy consumption: Manufacturing (C), Electricity, gas, water supply, sewerage, waste, and remediation services (D + E). When the results are interpreted, these uncertainties associated with regionalisation should be taken with caution.

In addition, we encountered the sectorial aggregation problem in regional energy balances. The "service" sectors were aggregated into a single industry, and only the total intermediate consumption was available. We applied the location quotient to regionalise the national energy use table in this case. Lastly, the final results obtained from the hybrid-unit emergy input-output model can be overestimated for some industries since this model is more suitable for evaluating downstream consumption regionalised from national consumption and imports are excluded (limited to the regional boundary). These industries are "electricity, gas, steam and air conditioning supply" and "forestry". Since this model still has been only applied once to the national level, testing on different regional datasets is required to ascertain whether or not the consumption of these two sectors deviates from this application.

The approach used in this paper does not allow disaggregating the use of emergy in different resource categories for detailed analysis of ecosystem services supporting the sector in the Vienna Region because this approach is only applicable to the industry-by-industry input-output system (Guevara and Rodrigues, 2016). The hybrid-unit emergy input-output model is used to estimate the emergy consumption of each sector in the urban economy. The disaggregation using the location quotient approach to differentiate different sub-sectors (sub-processes) associated with each industry (production process) in terms of supply and use is also not possible. The minor detail of regional value-added and employment (AUSTRIA, 2015e). The regional value-added in the national statistical database is highly aggregated, containing only 16 industries. Regional data on final energy consumption by energy product is available for 11 sub-sectors associated with the "manufacturing" sector, five sub-sectors related to “transport and storage”, “mining and quarrying”, “construction”, and ‘tertiary sector’ (AUSTRIA 2015d). The most detailed data do not include any data on renewable energy input and energy residuals, sub-sector associated with the other 14 sectors following NACE classification, excluding “manufacturing” and” transportation and storage”. Therefore, the future directions could explore different models, such as the approximate multi-factor energy input-output model used to disaggregate the energy sector by sub-processes (Guevara and Rodrigues, 2016). The other option is to use Vienna’s household budget survey, which is compiled on a quinquennial basis and covers biennial data (i.e., 2014–2015). However, the monetary household consumption data can be used only when budget survey data is reallocated from the standardised UN Classification of Individual Consumption by Purpose (COICOP) to CPA 2008 classification through a concordance matrix (Smetschka et al., 2019). The same procedure should be performed for the Austrian household budget survey, which is also complied with using the COICOP classification (Smetschka et al., 2019). Then, the location quotient for each sector can be estimated and applied to downscale national monetary use data. Future studies should explore different options for disaggregation of monetary (and energy) supply data to allow a more detailed analysis of the ecosystem services used to support each of the sectors of Vienna’s economy.

The model can be handy in other hybrid-unit input-output applications such as detailed and complete energy, material consumption and GHG emissions accounting based on a ‘full life-cycle perspective’. In addition, this approach can be complemented with environmentally extended input-output analysis (EE-IOA) to obtain more reliable findings on sectors responsible for high consumption and emissions within city boundaries.

Future studies can refine our monetary and energy data by using an aggregated final demand vector from national research institutes. For example, for Vienna, the data can be obtained from the Austrian Institute of Economic Research (WIFO) and the Austrian Institute of Technology (AIT). Moreover, future research should estimate more realistic values of transformities from energy network data by using the reflexive method combined with Eigenvalue–eigenvector or Singular Value Decomposition (SVD) methods. Those methods use statistical criteria (least squares solution) that remove the need for the specification of numeraire (i.e., solar energy). Future studies can also combine this approach with ecological network analysis to determine if the urban metabolic system is emergy-efficient using a system’s resource efficiency index or to analyse the utility of relationships between the sectors to identify and assess the problems leading to the inefficient or unsustainable resource consumption processes. Those directions can provide a basis for understanding and improving the development of the urban metabolic system in terms of circular metabolism.

4. Conclusion

The results of this study show that the “Renewable energy” sector in Vienna’s Region is supported by a large emergy consumption, confirming the importance of renewable energy in the context of Vienna’s regional economy. Among the tertiary sectors, “public administration and defence, social security”, “transportation and storage”, and “human health and social work activities” are characterised by high emergy support, confirming a strong policy commitment to provide high-quality social services oriented towards smart cities and urban sustainability in line with the Vienna’s development strategy (Urban Development Plan STEP, 2025). The lowest emergy use of the “mining and quarrying” sector shows that Vienna’s government does not prioritise this sector and is focused on improving circular economy strategies and renewable energy production. Moreover, the demand for products of the “agriculture, forestry, and fishing” sector in this region is the lowest, leading to the lowest consumption. The most insufficient production of this sector among the Austrian regions relates to the high concentration of social services in the Vienna Region and large areas occupied by forest ecosystems. This sector is in the early stage of developing its distribution channels. In contrast, “electricity, gas, water supply, sewerage, waste, and remediation services” and “wholesale and retail trade, repair of motor vehicles” sectors are opposite. The investments in “agriculture, forestry, and fishing” sector should be prioritised due to the role of this sector in renewable energy production and its position in the supply chain: acceptance of renewable energy from the source and its transfer in the production and supply of agricultural products (i.e., farm products) to all other sectors.

Future strategies should consider applying supply-side and demand-side interventions to continue improving the share of renewable energies while promoting and supporting sectors with low emergy consumption (i.e., organic agriculture). Future research should focus on integrating our model with ecological network analysis to study the system-level emergy metabolism and relationships between system’s internal processes. Despite meeting the Sustainable Cities Goal seems challenging, the multi-criteria framework constitutes a tool to assess the resource efficiency aspects of cities.

The integration between emergy accounting and the hybrid-unit energy input-output model proved to help overcome shortcomings of single criteria approaches when investigating internal problems and associated external upstream environmental burden (environmental consumption). Particularly, this framework allowed to incorporate economic services provided by energy industries to each other and non-energy industries (tertiary sector), isolating and accounting separately for emergy consumption of energy and tertiary sectors in Vienna’s urban metabolic system. Finally, using a detailed representation of the energy and economic transactions according to the energy conversion process and levels of energy use in the economy provided by the framework allowed us to accurately identify emergy consumption by each energy and non-energy production sector. The proposed multi-criteria and system-based approach for studying urban system provide an avenue for exploring the interplay of environment, economy, and monetary and physical resources in any urban socio-ecological system worldwide and, ultimately, could support local managers and policymakers in charge of developing environmental policies based on the “integrated wealth assessment” and “circular economy” principles.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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PAPER III

5.3 Ecological network analysis of an urban metabolic system based on input–output tables: Model development and case study for the city of Vienna

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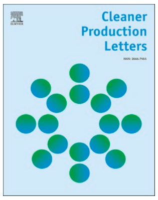

Ecological network analysis of a metabolic urban system based on input–output tables: Model development and case study for the city of Vienna

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Vienna

ABSTRACT

The rapid economic growth accompanied by health concerns and other global environmental problems in cities and regions has boosted the popularity of the ‘urban metabolism’ topic among academics and policymakers. Currently, 56.2% of the world’s population lives in cities, accounting for 80% of the global GDP. It is projected that the current trend for world economic growth complemented by population growth and migration will continue affecting the resource production and consumption in cities and the impact this has on other urban areas. Here, we developed a new model approach that combines emergy input-output tables with ecological network analysis to investigate urban metabolism generally, and applied it to Vienna, Austria. This novel approach allows researchers to study the hierarchy of sectors and functional relationships along all possible metabolic paths of ecological and socio-economic flows exchanging in an urban economy and between the urban economy and its environment. Then, using system-level analyses (flow and contribution analyses) we determined the status of the system components. Finally, the critical components responsible for the status (distribution structure of each industry) and emergy consumption of the other sectors were identified using pairwise control and utility analyses. The results showed that the “agriculture, forestry and fishing” and “mining and quarrying” sectors had the lowest ability to receive financial inputs from the other sectors, reflecting a shortage of agricultural and mining products to meet consumers’ demand. Moreover, “agriculture, forestry and fishing” had the highest energy dependence on the other sectors, indicating the lack of self-sufficiency in energy use and the inability of this sector to deliver energy effectively to consuming sectors. This also implies the importance of this sector in achieving the energy efficiency improvement and economic development goals for consumer cities. This work contributes to the existing literature on ecological network analysis via an introduction of the two-step approach that combines the diagnosis of low activity components in the system taken from traditional ecological network analysis with the novel identification of components behind the low activity of the other components. In addition, direct and indirect control, and indirect utility analysis were introduced for the analysis of the impact of the direct energy and indirect pairwise economic control and relational interactions of sectors in cities. Finally, this work explored the inner workings of the service part of the urban economy to reveal the role each tertiary sector plays in the development of primary and secondary sectors of an urban economy. The model developed in this study will provide support for city managers and policymakers to guide resource consumption towards an efficient and sustainable urban metabolic system worldwide.

1. Introduction

Along with a rising urban population and economic growth in face of the global environmental problems such as climate change and health concerns, research employing an ‘urban metabolism’ approach is becoming more popular among academics and policy makers. Globally, the planet’s 7.9 billion people generate 84.537-billion-dollar GDP, and by 2026 these figures are expected to grow by 6% and 31%, respectively

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(“World population projections,” 2020; “Global GDP, 2014–2024,” 2021). The population and GDP of Vienna have grown by 11% and 31%, respectively (“World population projections,” 2020; “Global GDP, 2014–2024,” 2021). Although urban areas occupy only 3% of the land surface (United Nations Environment Programme, 2019), they contribute the most to the world economy by generating more than 80% of the global GDP, about 6.2 billion dollars (United Nations Department of Economic and Social Affairs, 2019). Moreover, it is projected that the current pace of economic growth spurred by population growth will continue during the next decade, necessitating an increase of natural resources to support urban economies. Here, we track natural resources using an accounting framework based on embodied solar energy, referred to as *emergy* (Odum, 1996; Herendeen, 2004). This rise of emergy investment will affect distribution structure of trophic levels (consumer and producer), and utilities exchanged among sectors in cities, ultimately affecting emergy received and absorbed by the external environment. In this context, identification of critical sectors in production and consumption patterns in cities plays a key role in modifying the consumption of natural resources and in promoting efficient and sustainable development of other urban areas.

Input-output analysis, introduced by Leontief in 1966 for economic studies, has been extended to be applied to environmental elements, such as water (Hite and Laurent, 1971), energy (Casler and Wilbur, 1984; Zhang et al., 2016a), primary resources (Niza et al., 2009; Merciai and Schmidt, 2017), and wastes (Dias et al., 2014; Liang et al., 2017). This method covers final consumption activities and excludes the utilization of elements by producers. This problem has been resolved by integrating systems ecology perspective and economic input-output analysis (Chen, 2013; Chen et al., 2019). However, this method previously was limited to single elements, such as energy (Bullard and Herendeen, 1975; Li et al., 2020), water (Zhang et al., 2016b; Wang et al., 2020), greenhouse gases (Xia et al., 2019; Zhu et al., 2020). Although Xu et al. (2021) calculated embodied intensity of three elements (energy, water, and carbon), they failed to compare these elements due to the different units of measurement. This method also underestimates consumption of extractive industries (agriculture and mining) (Wieland et al., 2019).

Recently Guevara and Domingos (2017) improved the energy model used in this method to account more precisely for consumption of extractive sectors. However, their model was not tested at the regional scale (Bagheri et al., 2018) and only accounted for a single element (energy).

Input-output analysis did not estimate completely the environmental elements implied in utilization of intermediate products (indirect element consumption among sectors). To solve this problem, input-output analysis was combined with ecological network analysis to analyse the system’s structure and functions (Zhang et al., 2014c, 2014d). Ecological network analysis can account for the embodied consumption involved in producing intermediate products (Zhang et al., 2014c).

Hannon (1973) developed this method based on the Leontief approach and synecology perspective (Odum, 1959), which was later expanded by Patten (1978). Most of studies applied ecological network analysis to study natural ecosystems (Liu et al., 2019; Muhtar et al., 2021). In recent years, however, studies that examine urban ecosystems appeared more frequently (Chen et al., 2020; Zheng et al., 2021). Regrettably, only a single attempt has been made to account for an indirect and total emergy consumption of industrial sectors and environment using ecological network analysis (Zhang et al., 2009). However, due to the use of highly aggregated input-output data, the study failed to identify problematic sectors.

Consequently, this study could pave a pathway for improved analysis of structural distribution and functional relationships within urban socio-ecological systems by building an urban emergy metabolic network model. Therefore, the main research question is stated as follows: How to explore the functioning, organization, and complexity of city systems by integrating biophysical, systems, and network methods? To answer this question, we introduced a model that combines an emergy input-output model with ecological network analysis. The objective is to improve the accuracy in accounting for indirect and total emergy consumption of components in urban socio-ecological systems. Emergy was chosen in this study for two reasons: 1) using this approach, monetary and energy flows can be converted into common units (solar emergy joules) and compared (Zhang et al., 2009; Pulselli et al., 2015). 2) Emergy allows to count for the primary solar energy embodied in production by the ecological sub-system (Brownet al., 2012; Asamoah et al., 2017), allowing to analyse the total environmental and socio-economic support provided to each product or sector of urban economy (Viglia et al., 2018; Pan et al., 2021). For example, transformities incorporate plant biomass production through photosynthesis in addition to sugar fermentation processes to produce bioethanol. Thus, we can assess the status (total contribution exchange) and consumption of each industrial sector more accurately. For this reason, a high importance should be placed on accounting for both the environmental and socio-economic intersectoral flows.

The sectors in previous studies on ecological network analysis were assumed to be responsible for their status, not attempting to identify the source sectors (Yang et al., 2016; Tang et al., 2021). Our approach, however, introduces a two-step analysis (Morris et al., 2020). First, one identifies the system components’ status (traditional step in ENA), followed by a second step to identify the components (industrial sectors) behind the low status and emergy (total energy and monetary) consumption of the other sectors by using pairwise control and utility analyses.

In this study, we also introduced pairwise direct and indirect controls and indirect utilities to analyse how direct energy and indirect monetary transfer affect other system components, and the sectors affecting other sectors through the detrimental investment relationship (mutualism, competition or exploitation). In this way, the sectors responsible for the status and emergy consumption of other sectors could be identified more effectively and more relevant corrective measures can be proposed.

The rest of the article is organized as follows: Section 2 introduces briefly network properties (i.e., network mutualism) assessed in this study. Section 3 explains the methods and data used in this study. Section 4 discusses the results of this work. Finally, the article concludes in Section 5, and explores important implications for policy, limitations, and possible future recommendations based on findings.

2. Overview of network properties

2.1. Structural analysis

In this study, structural and functional properties of an urban network were assessed. Functional properties that were used in this study are flow and utility properties. Structural analysis was used to analyse pattern and connectivity of network models (Fath and Borrett, 2006).

Path analysis is one type of structural analysis that is used to identify all possible pathways between each pair of components in the network (Fath and Borrett, 2006; Fath, 2012). For this purpose, a structural connectance matrix (A^m) is used. A^m refers to the number of paths between compartments with different “m” pathway lengths. Assuming the network has a certain level of connectivity, as “m” increases, so does the number of indirect pathways (Fath and Borrett, 2006; Zhang et al., 2014c). It is an important feature since identifying pathways with significant metabolic length “m” reflects the highest indirect flows and cycling in the network (Fath and Borrett, 2006; Zhang et al., 2009). In addition, long path length is associated with the considerable economic cost and benefits of cycling (Zhang et al., 2009).

This analysis estimates structural connectance matrix, number of nodes, network connectance, link density and rate at which paths increase (called path proliferation) using the *Matlab* software (Fath and

Borrett, 2006; Fath, 2012).

2.2. Functional analysis

Functional analysis consists of Flow, Storage, Utility, and Control Analyses. In this study, however, we did not use Storage Analysis because of the low quality of initial data available. It is important to note the system should be in a steady state in order to perform each type of the functional analysis (Allesina and Bondavalli, 2003; Fath et al., 2007; Matamba et al., 2009).

2.2.1. Throughflow analysis

This type of analysis is compatible with the Input-Output Analysis (Matamba et al., 2009). This means that flow input data from the input-output table can be directly used in this analysis (Fath and Borrett, 2006). Throughflow serves as a measure of the energy, matter, or trade volume flows in each model node, and it can be an indicator of the relative importance of each node (Borrett, 2013; Borrett and Scharler, 2019). Two types of flows are determined by throughflow analysis: direct flows between nodes and indirect flows (flows passing along two or more paths before reaching a target node) (Zhang et al., 2014c). Ultimately, Flow Analysis is used to determine direct, indirect, and integral (direct plus indirect) flow intensity matrices. The integral matrix (N) represents the amount of direct and indirect input flows (total input flows) required to produce 1 unit of input flow from the external environment (boundary flow). This matrix can be used to determine total flow into the system, if the inputs from the environment are known (Fath et al., 2001).

2.2.2. Control analysis vs Contribution Analysis

Control Analysis measures total dependence and control between each pair of components (Fath and Borrett, 2006; Lu et al., 2012; Yang et al., 2016; Yang et al., 2017). Correspondingly to Throughflow Analysis, flows can also be portioned into direct, indirect, and integral flows (Lu et al., 2012; Yang et al., 2017).

This approach, however, does not estimate the control or dependence of each component in a holistic way (Fath and Borrett, 2006; Li et al., 2018; Yang et al., 2016). Zhang et al. (2014a), however, introduced a method that allowed to estimate the dependence and the influence of each component on all other components within the context of analysing the development pattern of Beijing (China). In their work, the Throughflow Analysis was complemented with Contribution Analysis to estimate the contribution weights of each component in the system based on backward linkages (control of the system) and forward linkages (dependence on the system) (Zhang et al., 2014d). Contribution Analysis can assist the policy makers in developing corrective measures to deal with supply and use imbalances along the ‘full supply chain’ (Zhang et al., 2014d). However, the Contribution Analysis cannot reveal the dependence and control relationships between each pair of components (Zhai et al., 2019; Xia and Chen, 2020). This is also a serious limitation since the proportion of integral (total) control or dependence between each pair of sectors cannot be estimated. In other words, we cannot determine which sector in the network is more responsible for high (low) levels of total consumption by the target sector. Zhai et al. (2019) applied both Contribution Analysis and Control Analysis to estimate direct and integral influences and dependences of components on regional energy metabolic systems. However, in their study the indirect and direct control relationship between each pair of components was not addressed. Therefore, in this paper, both analyses were applied to identify the hierarchy of each component in the system based on its influence on pairwise and systemic level (Fath et al., 2001) and the reasons behind their status in urban metabolic system based on indirect and total dependence in pairwise (dependence on specific component) and systemic levels (dependence on all other components) between system and target sector (Fath et al., 2001) to improve the functioning development of Vienna’s metabolic system.

2.2.3. Utility analysis

The distribution of benefits and costs between each pair of components in the system can be determined by Utility Analysis (Fath and Patten, 1998; Fath, 2012). This analysis is used to assess both direct and integral (direct and indirect) benefits and costs between any two components (Fath, 2012; Zhang et al., 2014b). This analysis reveals a nature of relationship between any two components: mutualism (+,+), competition (−,−), control (−, +), exploitation (+, −), and neutral relationships (0,0) (Zhang et al., 2009). Integral relationships are divided into mutualism, exploitation, and competition (Fang and Chen, 2015). The analysis can be stopped on assessing integral utility of relationships between pairwise sectors (Lu et al., 2012) or it can assess an overall mutualism and synergism of the system: the ratio of positive to negative utility in the network system and total importance of mutualistic and competitive relationships, respectively (Lu et al., 2012; Guan et al., 2019). The two indicators above allow us to assess the state of the system in terms of fitness and symbiosis (Guan et al., 2019). This is especially relevant to the urban metabolic system since higher overall symbiosis and mutualism among industries contribute to the better ecological element utilization efficiency (Boons et al., 2016; Zhang et al., 2014b).

3. Methods and data

This section introduces the overall methodology used to develop and analyse a network model of Vienna’s metabolic system used in this study.

3.1. Development of the urban metabolic network model

The emergy input-output model consists of 16 production components (industrial sectors) and consumption components (final demand). Names and abbreviations of the components and sub-sectors names are

Table 1
Names and abbreviations of sectors and sub-sectors.

Sector	Sector names	Sub-sector names
AGR	Agriculture, forestry, and fishing	
MIN	Mining and quarrying	
MAN	Manufacturing	
EC	Electricity, gas, water supply, sewerage, waste, and remediation services	Electricity, gas, steam and air conditioning supply Water supply; sewerage, waste management and remediation activities
CON	Construction	
WR	Wholesale and retail trade, repair of motor vehicles	
TS	Transportation and storage	
AC	Accommodation and food service activities	
INF	Information and communication	
FIN	Financial and insurance activities	
RA	Real estate activities	
OBS	Professional, scientific, technical, administrative, and support service activities	Professional, scientific and technical activities Administrative and support service activities
ADS	Public administration and defence, social security	
ED	Education	
HS	Human health and social work activities	
ER	Arts, entertainment, and recreation, repair of household goods and other services	Arts, entertainment and recreation Other service activities Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use

presented in Table 1. The components represent Vienna's socio-economic sub-system (Vienna's metabolic system) (Zhang et al., 2014c). In addition, inputs from environment and to environment represent the ecological subsystem of Vienna socio-ecological system. Previous studies already emphasized the importance of environmental support to the socio-economic subsystem (Zhang et al., 2014c, 2014d; Wang et al., 2019).

In this study, the 'environment' includes the internal environment within Vienna's regional boundary: open green spaces within the city (i.e., Vienna's Danube area) and countryside (i.e., the border area of the Vienna Woods, Viennese part of the Marchfeld region), and the environment outside of the investigated system (i.e., renewable energy imported from outside of Vienna Region Thus, the studied system is limited to the natural environment within the administrative boundary of Vienna city, and the natural environment is outside this region. The consumption sector (domestic sector) was not included in the model since domestic sectors do not produce products (Zhang et al., 2014d). Therefore, inclusion of this sector compromises the steady state of the system (Fath et al., 2007). The emergy input-output model used in this study is shown in Table 2. To construct this model, the following research methods were utilized. The supply-side commodity-by-industry input-output (Liu and Vilain, 2004) and location quotient (LQ) approaches based on value added and final energy consumption were used to obtain the regional shares of monetary and energy production, respectively. Then, these shares were applied to disaggregate Vienna's monetary and energy balance data. Consequently, the regional energy use data were integrated with regional energy supply data through the Leontief's "commodity by industry model". The matrix inversion method was integrated with the reflexive method to estimate transformities of industrial sectors (Patterson, 2014). Regional monetary and energy input-output tables were multiplied by their respective transformity values and summed to build the emergy input output table.

A network model of Vienna metabolic system based on balanced emergy input-output table is shown in Fig. 1. Each pair of components is denoted by letters 'i' and 'j', and the flow from component i to the component j is denoted as 'f_{ji}'. In this way, this model allows the capture of the whole socio-ecological system of Vienna, and its exchanges with the natural environment (Zi and Yi) (Wang et al., 2019).

The next step is to classify all components of the network model using the trophic pyramid as analogy. Unlike the previous studies, we did not combine the components in accordance with the trophic level but only grouped them. The reason for this decision was because an aggregation of compartments can limit the quality of the results obtained, particularly the higher indirect effects and mutualism in the network (Baird et al., 2009). In other words, internal factors responsible for unsustainable or inefficient structural distribution of industries and detrimental functional relationships within the system cannot be identified when complex systems are analysed as simple networks (Zhang et al., 2014b; Yang et al., 2016; Zhu et al., 2019). This allowed us to disaggregate the tertiary sector into 11 sectors showed in the lower right corner of Table 1 and to use them as separate compartments to uncover the extent of status in terms contribution exchange with other sectors (status) and consumption, and to what extent they affect other sectors statuses and consumption of energy and monetary resources. Uncovering metabolism of the tertiary part of urban economy is very important because they are drivers of industrial development, and by them the sectors restricting or contributing to the industrial base in cities could be identified. More generally, the largest proportion of indirect flows allocated mainly to consumers (other sectors of service economy) can lead to the rapid economic development affecting surrounding ecosystems through land use and cover change and associated carbon emissions (Xia and Chen, 2020). Overdevelopment of the industrial sector (primary and secondary sectors) affects consumers using services provided by the tertiary industries (Zhai et al., 2019; Guan et al., 2019).

The primary producers in the urban metabolic system are sectors that can directly utilize natural resources (i.e., solar energy, water, minerals). 'Agriculture, forestry and fishing' and "mining and quarrying" sectors are included in this category. Primary consumers, on the other hand, utilize primary products to produce secondary products (i.e., crude oil, hard coal, natural gas).

The Table 1 contains names and abbreviations of 16 production components (industrial sectors) and sub-sectors (industrial sub-processes) of Vienna's emergy input-output model.

All values in Table 2 are expressed in 10^{15} seJ. Each value in the table represents a sum of ecological and socio-economic flows (emergy flows implied in direct paths) exchanged among industrial sectors in Vienna's metabolic system expressed as solar emergy joules (abbreviated sej). Solar equivalent joule (sej) is a unit used to measure the quality of available solar energy consumed both directly and indirectly in transformations to make a product or service.

These sectors include "manufacturing", "electricity, gas, water supply, sewerage, waste, and remediation services". It is not clear in which category 'construction' sector should be placed. Zhang et al. (2014a) placed the "construction" sector into 'consumer category based on trophic level analogy. Zhai et al. (2019) applied Zhang's analogy to the energy metabolism to refine the classification of compartments in the urban metabolic system in accordance with the embodied energy production and consumption patterns. Since this study focuses on emergy embodied in energy and monetary flows among the sectors, placing this sector in tertiary consumer category will help to understand the role of this sector in the emergy metabolic system. Tertiary consumers include sectors that utilize both primary and secondary products to provide their

Table 2
Sectoral emergy consumption driven by final demand in Vienna's metabolic system (10^{15} seJ).

In Out	AGR	MIN	MAN	EC	CON	WR	TS	AC	INF	FIN	RA	OBS	ADS	ED	HS	ER
AGR	0.51	0.0003	0.17	0.071	2.1	7.2	2.6	2	0.51	1.3	0.23	3.6	1.5	0.46	0.59	0.75
MIN	0.0001	0.021	0.15	0.44	7.1	8.2	26	5.3	1.3	1.6	1.4	4.5	4.7	3.8	2.3	1.1
MAN	74	1.3	9.9	43	51	200	300	130	40	24	14	47	74	27	26	15
EC	170	1.3	8.6	18	110	160	520	210	39	44	16	57	130	83	38	18
CON	36	1.8	780	100	1700	320	310	230	24	39	46	150	240	39	23	23
WR	37	1.3	280	280	160	1100	1500	840	220	140	200	270	340	130	140	180
TS	43	28	2800	1000	310	1000	5300	700	96	92	96	350	520	150	140	60
AC	330	4.2	840	1200	320	830	390	1300	73	100	230	190	260	38	220	400
INF	6.5	0.62	180	290	9.7	72	47	35	200	8.3	8.9	22	86	17	50	27
FIN	0.65	0.022	110	85	14	41	120	130	47	170	10	43	100	36	23	14
RA	0.002	0.017	11	71	430	54	73	98	17	120	120	91	86	8.7	32	16
OBS	3.5	0.24	110	50	31	150	260	480	150	35	27	180	180	110	73	29
ADS	250	21	700	3900	220	350	760	640	180	130	230	250	9300	170	260	96
ED	0.0018	0.08	110	230	89	95	130	200	39	24	43	50	70	290	69	26
HS	59	7.1	430	2900	190	530	420	620	120	77	140	170	240	250	4800	280
ER	18	0.56	47	110	62	120	230	170	44	26	37	55	97	27	37	160

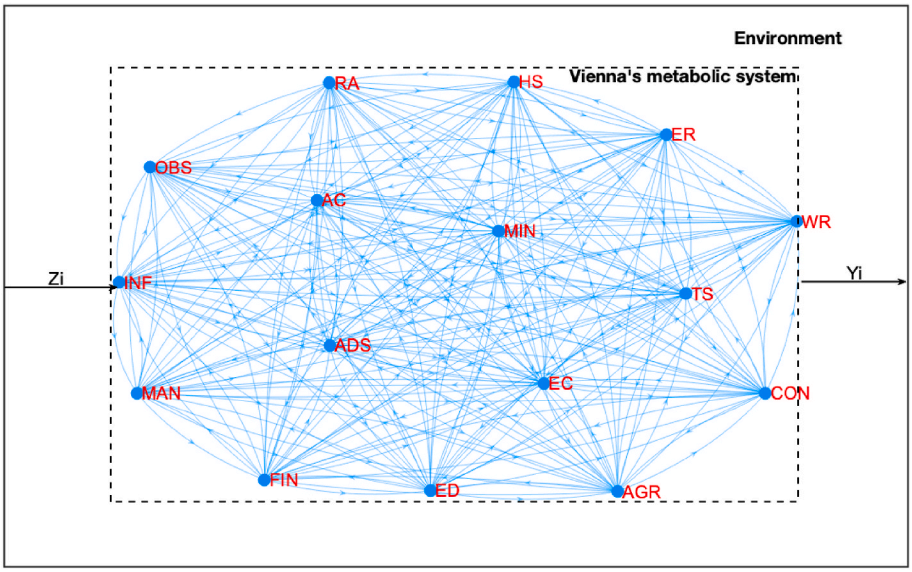


Fig. 1. Network model of Vienna's metabolic system. Zi and Yi represent inputs from and to the external environment of the urban metabolic system, respectively.

goods and services. This group includes tertiary industries and domestic sector. Tertiary industries also fall under that category since those sectors consume products produced by primary producers, primary and secondary consumers. Domestic sector is located at the top of food chain. This sector mainly consumed finished products (i.e., electricity, heat) provided by the other sectors.

3.2. *Ecological network analysis of urban metabolic system*

The model should meet steady-state requirements in order to perform ecological network analysis (Fath et al., 2001; Fath and Borrett, 2006). This means that the model should conform to the first law of thermodynamics and mass conservation (Fath et al., 2001; Zhang et al., 2014b; Li et al., 2018). Unless this condition holds, other analysis methods are needed. The steady-state requirement is given by Equation (1) (Fath and Borrett, 2006):

$$T_i = T_j \tag{1}$$

where T_i and T_j represent sum of flows into each sector i and out of each sector j, respectively.

This formula further could be written as in Equation (2):

$$f_{ij} + Z_i = f_{ji} + Y_i \tag{2}$$

where Z_i and Y_i are emergy embodied in natural energy inputs and outputs, respectively.

Therefore, the system is at steady state if the sum of total flows from each compartment i and from the environment Z_i is equal to the sum of total flows out of each compartment i and out of environment Y_i.

The next step involves estimation of indirect and integral flows between each pair of components. For this purpose, non-dimensional input-oriented transfer efficiencies along all pathways in the system must be known (Fath et al., 2001; Zhang et al., 2009, 2014c). The elements of non-dimensional output-oriented transfer efficiency matrix (G) are estimated using Equation (3):

$$g_{ij} = \frac{f_{ij}}{T_i} \tag{3}$$

where g_{ij} is the amount of emergy embodied in total (direct and indirect) input flows to each sector i (T_i) required to produce 1 sej of emergy flow from each sector j to each sector i (f_{ij}). Thus, the matrix (G) is called an input-oriented non-dimensional ecological element exchange efficiency matrix (Zhang et al., 2014c). It is based on forward linkages in the system of interest (Fath et al., 2001; Fath and Borrett, 2006). This matrix shows how much of original input emergy is actually used in exchange between each pair of sectors. This efficiency decreases along with the increase in path length between i and j due to dissipation (Fath et al., 2001).

The sum of the initial, direct, and indirect transfer efficiencies represents the output-oriented integral (total) transfer efficiency between each a pair of sectors in the system, Equation (4):

$$N = G^0 + G^1 + G^2 + G^3 \ldots + G^m + \ldots = (I - G)^{-1} \tag{4}$$

where G^0 is 'cyclic feedback matrix' that involves flows within each sector. The values of this matrix are equivalent to the identity matrix (I) (Fath, 2012). G^1 is an intensity of emergy exchange between each pair of sectors along the direct path. G^2, G^3 *and* G^m are indirect intensities of emergy exchange between each along various lengths of m $(m \geq 2)$.

Then, we can obtain the integrated emergy flow transfer matrix (Y) where each element (y_i) reflects the total contribution to each sector i from all other sectors (Zhang et al., 2014c; Zheng et al., 2016; Zhai et al., 2019). This matrix is given by Equation (5):

$$Y = diag(T_i) \times N \tag{5}$$

where $T_i\, and\, N$ as above.

Knowing this allows us to compute "integral pulling force weight (W_i)" and "integral driving force weight (W_j)":

$$W_i = \sum\nolimits_{j=1}^{n} y_{ij} \Big/ \sum\nolimits_{j=1}^{n} \sum\nolimits_{i=1}^{n} y_{ij} \tag{6}$$

$$W_j = \sum\nolimits_{i=1}^{n} y_{ij} \Big/ \sum\nolimits_{j=1}^{n} \sum\nolimits_{i=1}^{n} y_{ij} \tag{7}$$

where $\sum_{j=1}^{n} y_{ij}$ is the total emergy contributed by the system to sector i and $\sum_{i=1}^{n} y_{ij}$ is the total emergy contributed by sector i to the system. The driving force weight indicates the ability of the sector i to provide emergy support to other sectors through backward linkages (supply linkages). It can reveal the degree of control of sector i to the other sectors in the system (Grimm et al., 2008; Zhai et al., 2019). The pulling force weight reflects the ability of the sector i to receive emergy inflows from other sectors through forward linkages (demand linkages). This factor reflects the degree of dependence of sector i on other sectors in the system (Zhai et al., 2019; Zhang et al., 2021). These two factors can provide insight on the development stage and role of each sector in the system (Zhang et al., 2014a; Zhai et al., 2019).

However, the indirect contributions, which have been explored by Zhai and et al. (2019), affect total contribution weights (integral pulling and driving force weights) considerably. Therefore, it is crucial to determine and compare indirect and direct pulling and driving force weights (Zhai et al., 2019), Equations (8) and (9).

$$F_i = \sum\nolimits_{j=1}^{n} e_{ij} \Big/ \sum\nolimits_{j=1}^{n} \sum\nolimits_{i=1}^{n} e_{ij} \tag{8}$$

$$F_j = \sum\nolimits_{i=1}^{n} e_{ij} \Big/ \sum\nolimits_{j=1}^{n} \sum\nolimits_{i=1}^{n} e_{ij} \tag{9}$$

where F_i *and* F_j are direct pulling and driving force weights, respectively, and $\sum_{j=1}^{n} e_{ij}$ is the direct contribution by the system to sector i (in emergy units) and $\sum_{i=1}^{n} e_{ij}$ is the direct contribution by sector i to the system (in emergy units).

Knowing both integral and direct pulling and driving force weights, the indirect pulling and driving force weights can be determined by Equations (10) and (11):

$$E_i = W_i - F_i \tag{10}$$

$$E_j = W_j - F_j \tag{11}$$

where E_i *and* E_j are indirect pulling and driving force weights, respectively. In this way, direct and indirect flow contributions in output and input directions can be compared (Zhai et al., 2019).

Secondly, Utility Analysis should be performed to reveal the nature of relationship between each pair of sectors (Fath and Borrett, 2006; Zhang et al., 2014b; Zhai et al., 2019). This involves computing integral utility intensity matrix (U) based on the elements of direct utility intensity matrix (D). Direct utility intensity matrix (D) is given by Equation (12):

$$D = \frac{(f_{ij} - f_{ji})}{T_i} \tag{12}$$

Matrix (D) is used to determine the relations between any pair of sectors in the urban metabolic system based on direct intensity of ecological elements exchanged between them (Fath, 2012). Initially, the matrix is computed using the Equation (12). Then, the positive and negative signs are taken from exchanges (nondimensional intensities of net flows) between sector i and sector j. Finally, the signs are combined to determine relationships between each pair of sectors: mutualism (+,+), competition (−), control (−, +), exploitation (+, −), and neutral relationships (0,0) (Zhang et al., 2009; Li et al., 2018).

If matrix D reveals only the nature of direct relationship, integral utility intensity matrix (U), on the other hand, reveals the total benefits or total costs of any relation between each pair of components (Lu et al., 2012; Xia and Chen, 2020). As with flows, indirect benefits and costs are more responsible in change of system's state from stable to unstable, and vice versa (Lu et al., 2012). The integral utility intensity matrix (U) is given by Equation (13).

$$U = D^0 + D^1 + D^2 + D^3 \ldots + D^m + \ldots = (I - D)^{-1} \tag{13}$$

where D^0 utility of flows (benefits) generated in the sectors themselves (Zhang et al., 2014d), D^1 utilities (benefits or costs) between each pair of sectors along the direct path, D^2, D^3 *and* D^m are indirect utilities (indirect benefits or costs) of emergy exchange between each pair sectors along various lengths of m ($m \geq 2$). D^0 is also equal to identity matrix (I). Then, matrix U should be dimensionalized to obtain values of total benefits and costs from the relations between each pair of sectors in the system (Zhang et al., 2016b). The dimensionalized integral utility matrix (Y) is obtained from Equation (14):

$$Y = diag(T_i) \times U \tag{14}$$

From this matrix mutualism index (M) and synergism index (S) can be estimated, Equations (13) and (14):

$$MI = \frac{Sign\ U(+)}{Sign\ U(-)} \tag{15}$$

$$SI = \sum Y(+) + \sum Y(-) \tag{16}$$

where $\sum U(+)$ and $+\sum U(-)$ are sum of flows with positive and negative utilities, respectively. Mutualism index (MI) is the ratio of the number of positive signs of U to the number of negative signs of U. If MI is greater than 1, it means that the total benefits of interactions outweigh costs in the system and hence the system can be considered mutualistic and healthy (Tan et al., 2018). The synergism index is a ratio of integral flows with positive utilities to the integral flows with negative utilities (Tan et al., 2018). When $S > 0$, synergism is said to occur, i.e., systems have positive net benefits (greater benefits than costs) resulting from relations between each pair of sectors (Zhang et al., 2016b).

The last step involves the network control analysis. It follows the similar logic to the Flows and Utility Analysis in that transfers efficiencies are divided into initial, direct, and indirect to determine integral (total) transfer efficiency between each pair of sectors in the system (Lu et al., 2012). However, integral transfer efficiencies are determined in terms of both backward and forward linkages in the system of interest. The elements of non-dimensional input-oriented transfer efficiency matrix is estimated from Equation (17):

$$g_{ji} = \frac{f_{ji}}{T_j} \tag{17}$$

Then, following the Flow Analysis procedure, the input-oriented integral (total) transfer efficiency between each pair of sectors in the system (N^i) was estimated, Equation (14) (Tan et al., 2018; Zhai et al., 2018), Equation (18):

$$N^i = (G^i)^0 (G^i)^1 + G^i)^2 + (G^i)^3 \ldots + (G^i)^m + \ldots = (I - G^i)^{-1} \tag{18}$$

where $(G^i)^0$ is input-oriented 'cyclic feedback matrix' that involves flows within each sector (Zhai et al., 2019). $(G^i)^1$ is an input-oriented intensity of flow between each pair of sectors along the direct path. $(G^i)^2, (G^i)^3$ *and* $(G^i)^m$ are input-oriented indirect intensities of emergy flows between each pair of sectors along various lengths of m ($m \geq 2$).

The pairwise integral control relationships between sectors can be expressed by matrix (CN) (Fath and Borrett, 2006; Zhai et al., 2018, 2019), as per Equation (19):

$$CN = \frac{N}{N^i} \tag{19}$$

where N and N^i as above.

Each element of CN matrix represents the proportion of the integral flow from sector i to sector j to the integral flow from sector j to sector i (Li et al., 2018). This matrix was subsequently modified, so that when $n_{ji}/n'_{ij} < 1$, $cn_{ji} = 1 - n_{ji}/n'_{ij}$, otherwise, $cn_{ji} = 0$ (Yang et al., 2012; Zhai et al., 2018, 2019).

The values of the modified matrix were limited to range between 0 and 1 (Yang et al., 2012). The component i depends on j if i provides to j less output than it receives from j ($cn_{ij} = n_{ji}/n'_{ij} < 1$). On the contrary, if the sector i provides more output to j than it receives from j, then the sector i controls sector j (Li et al., 2018; Zhai et al., 2018, 2019).

As the total pairwise control or dependence is equal the sum of direct and indirect controls or dependencies. Thus, based on the CN matrix, the pairwise indirect control relationships can be determined (IN) (Equation (20)).

$$IN = \frac{N - G^0 - G^1}{N^i - (G^i)^0 - (G^i)^1} \tag{20}$$

The following modification was introduced to avoid negatives and values of indirect control been larger than integral values: when $0 < in_{ij} < cn_{ij}$, $in_{ji} = in_{ij}$, otherwise, $in_{ji} = 0$. Thus, total dependence of each sector was updated by adding emergy implied in indirect flows. Thus, data applied to contribution, control and utility analysis allowed us to reveal the status and functions of each sector within the system and systems' state (mutualism and synergism). Finally, the dependence in pairwise and systemic levels, then, allowed us to detect the sectors responsible for the condition of each target sector. By this methodology, any issues in organisation and functioning in any system characterized by complex interactions such as urban metabolic systems can be identified and assessed.

3.3. *Data collection and sources*

In this study, we used Vienna's emergy input-output table referred to the year 2015. Since the original model was not in the steady state required to perform ecological network analysis, the model was updated. By using the Generalized RAS (GRAS) balancing approach (Temurshoev et al., 2013), we estimated a new matrix with the same column and row totals as the original one (Temurshoev, 2021). The resulting model conformed to the steady state rule and included the intersectoral, boundary input and output flows.

The compartmental storage data were not available. The capital formation reflects a steady-state storage value of each sector of Vienna's metabolic system (Zhang et al., 2014a). A prior knowledge of steady-state storage values of the donating sectors is an essential requirement to perform the Storage Analysis (Fath et al., 2001; Fath and Borrett, 2006). Since this analysis is out of scope of our work, the total value of final demand of the urban economy was assigned to storage vectors. This category was chosen because the storage values at the donating and the receiving sectors are equal at steady state (Fath et al., 2001). Since the capital formation is an integral part of 'final demand', the storage values used in our study were overestimated. Nevertheless, the assembled system was sufficient to perform ecological network analysis.

4. Results and discussion

This section will discuss the results of ecological network analysis applied to the emergy input-output table of Vienna region.

4.1. *Flow analysis*

In this study we obtained an integrated emergy flow transfer matrix (Y). The elements of this matrix revealed the total emergy consumed by each sector in the urban metabolic system. Results are shown in Fig. 2.

The Fig. 2 shows the total emergy consumption for each sector in the urban metabolic system. We noticed that the hierarchy of all sectors in terms of the total emergy consumption remains the same. The division of sectors based on their consumption is presented in Appendix A.

The results of ecological network analysis indicate that the 'public administration' plays a key role in the urban metabolic system. Along with the economic growth more financial investments and labour force required to drive an increased demand on general activities of public administration such as provision of transport infrastructure. The high indirect consumption of TS, HS and EC sectors could be related to the promotion of development of these sectors by local administration. On the hand, the AC, MAN, WR, CON, ED, OBS, ER and INF sectors are underrepresented in the Vienna region. The moderate consumption of 'manufacturing', 'wholesale and retail' and 'construction' conforms to their respective positions in supply chain, indicating that their demand are in line with their general consumption characteristics (e.g., tertiary industries indirectly consume ecological elements). The indirect consumption of information and communication' sector is lower than expected, indicating that the more efforts should be put to develop this sector. The proportion of the direct emergy consumption was higher than indirect consumption. The low indirect consumption of 'real estate activities' and 'financial and insurance activities' was also unexpected. These sectors do not contribute to the consumer part of economy, which supports development of industrial base through investments. It should be obvious that these sectors use few pathways to transfer most of their emergy. Thus, it is necessary to improve energy transfer and utilization efficiency to decrease direct consumption of those sectors and to increase demand of producing sectors on their products. The structure of emergy consumption for each sector in the system is presented in Appendix B.

4.2. *Contribution Analysis*

We used this analysis to assess the total influence and dependence of each sector on the urban metabolic system (Zhai et al., 2018, 2019). This approach not only assesses the influence in a more holistic way than

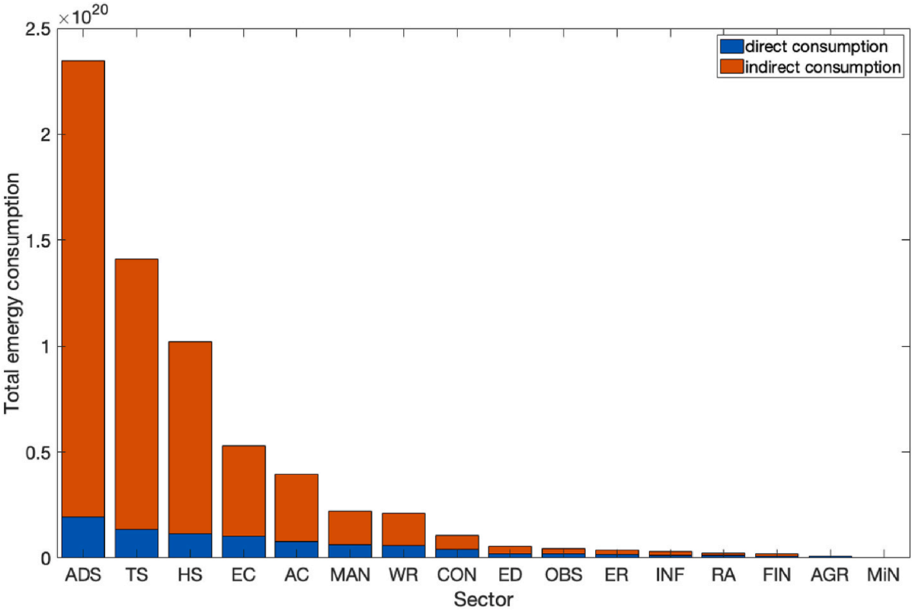


Fig. 2. Total emergy consumption for each sector of Vienna's metabolic system.

control analysis but also considers both the forward and backward linkages in the system of interest (Zhai et al., 2018). Fig. 3 shows that the pulling force hierarchy represents an irregular inverted pyramid structure. This result reveals an existence of sectors that obstruct functioning of the system because upper consumers do not have enough support to pull development in lower producers (Zhai et al., 2019).

This structure is caused by insufficient pulling weight of AGR and MIN sectors and too strong pulling weights of ADS, TS and HS sectors. Those results conform to the dominating nature of tertiary industries, and supplementary nature of production industries in Vienna's economy. This all means that Vienna's economy is not dominated by production industries. The indirect pulling force of the EC and MAN sector was lower than direct, suggesting investment to these sectors from the rest of the economy lags far behind their production. Therefore, these sectors should not be targets of economic development of the Vienna region. ADS and TS sectors also receive more emergy in direct ways than in indirect, but their integral pull weight is the highest. This highlights their key role in promoting development of the Vienna region. The rest of the sectors can be characterized by decreases in their indirect pulling weights.

The highest decrease in indirect pulling weight was detected in CON and WR sectors: −0.04 and −0.03, respectively. This compromises their integral contribution to the upstream industries (AGR and MIN). The structure of those sectors should be regulated to increase their indirect consumption of emergy implied in payments provided by tertiary industries for their products. The high decrease of indirect pulling weight are also observed in AC, ED and ER sectors. Therefore, their demand for services of other tertiary industries should be increased to receive more payments from the downstream sectors in exchange of purchased services and to develop enough to also promote economic development of other two sectors (CON and WR). Also, this suggests that investments into these three sectors fall behind the demand for their services.

This reflects Vienna's position as financial capital with most of the investment in education, research, and tourist attractions generated within the region as of 2015 (The Municipal Department 23 - Economic Affairs, Labour and Statistics, 2016), leading to the high pulling ability.

Fig. 4 shows ecological hierarchy of driving weight. This structure partially resembles an irregular inverted pyramid. Overall, this structure represents a satisfactory state of development because some sectors with internal problems can still be identified. It indicates that producers do not support some consumers. AGR and MIN sectors had high total driving weights that suggested that their ability to deliver emergy is far too strong. From one point of view, they provide the basic support for Vienna's economy. However, Fig. 4 indicates that their indirect driving force weight is much higher than direct. This indicates that demand for investments by downstream sectors is ahead of their demand for agricultural and mining products. Therefore, those sectors are forced to use services from tertiary industries to upgrade their production base, and in this process tertiary industries benefit from labour and payments received from the AGR and MIN sectors. However, the long distance of transferring emergy to downstream sectors for these type of sectors (Zhai et al., 2018) also means that not all flows reach their destination due to dissipation (i.e., ER, HS, ED in Fig. 3). Thus, it is advised to increase pulling force weight of AGR and MIN sectors, and to decrease indirect delivery ability of those sectors by increasing efficiency of emergy transfer along shorter paths. AGR and MIN sectors, unlike other industries, do not only produce and transfer their products to intermediate sectors but also deliver energy to intermediate sectors due to their producer function. Thus, the decentralised generation of electricity for tertiary industries for these two producers such as standalone agro-photovoltaic system might be a solution to reduce energy losses stemming from the long central distribution channels and to avoid intermediate consumers, if such system is positioned to have a direct connection with its consumers (Ha & Kumar, 2021; Weselek et al., 2019).

If all the energy supply reaches their destination, then tertiary (service) industries will save the funds for their development, thereby decreasing their dependency on payments to producers (AGR and MIN) for their services. The increased efficiency of monetary transfers along shorter paths lies in a transition from indirect to direct distribution channels characterized by a minimum number of intermediate industries possible to reach consumers (tertiary industries and households) (i.e., direct farm sale to consumers, on-farm retail market where farmer sells their directly their produce to retailers such as food processors) (Brown and Miller, 2008).

The direct distribution channel facilitates the delivery of agricultural and mining products of the tertiary consumers, but also minimises the losses associated with the payment from tertiary industries reaching AGR and MIN sectors in full, leading to the increase of its indirect and total pulling force weights. These two measures should improve the efficiency of emergy (energy and monetary) transfer along the shortest paths to decrease indirect delivery ability of AGR and MIN sectors, and

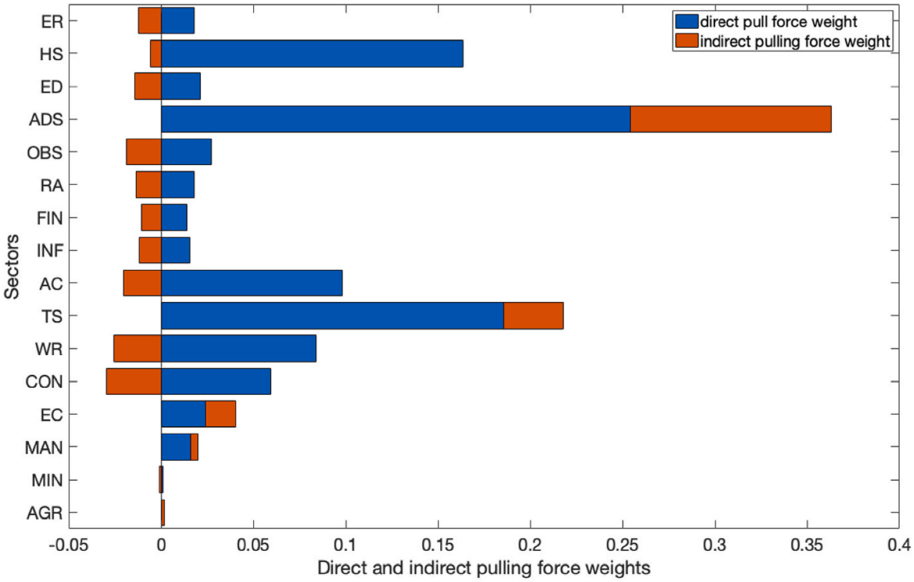


Fig. 3. Input-oriented direct and indirect weights of each sector in 2015. The figure shows direct energy and indirect monetary contribution of all industrial sectors in the Vienna's urban metabolic system to each industrial sector separately.

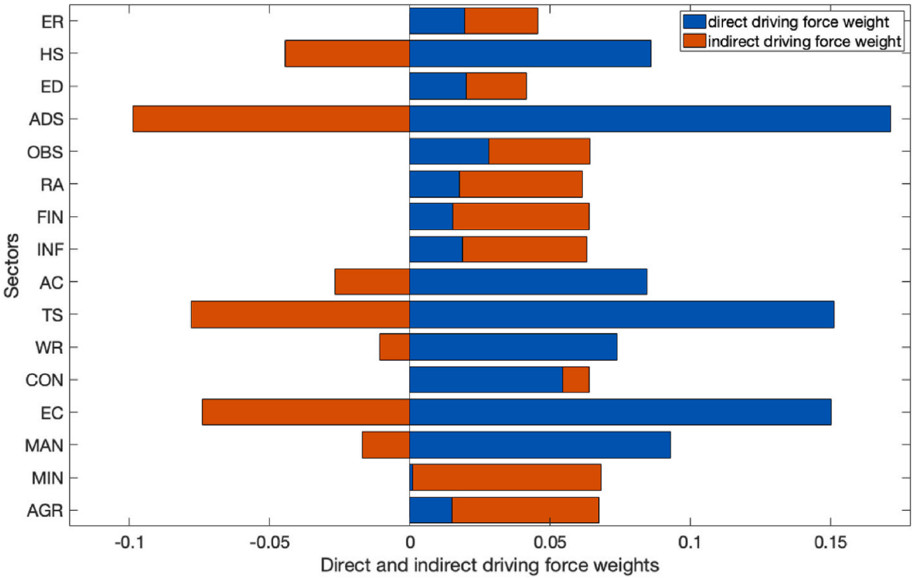


Fig. 4. Output-oriented direct and indirect weights of each sector in 2015. The figure shows direct energy and indirect monetary contribution of each industrial sector to all the sectors in the Vienna's urban metabolic system.

to increase their pulling force weights.

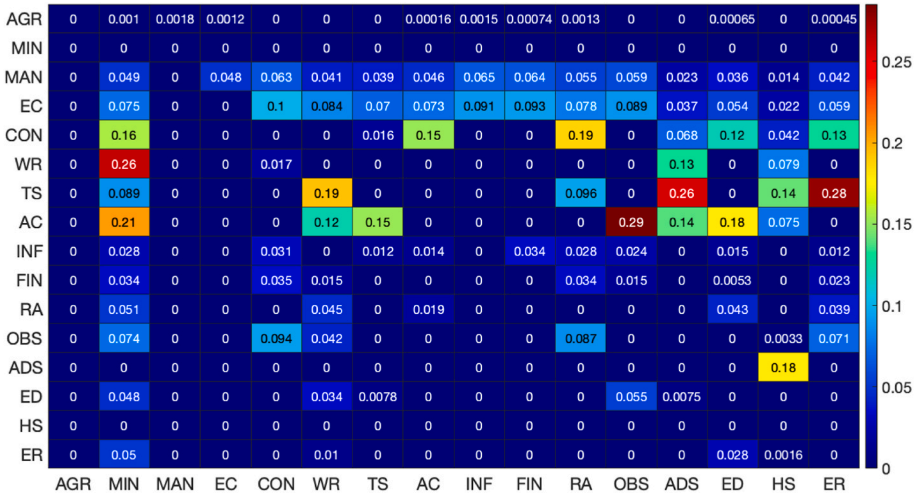
Contrary to the producers, WR and CON have a poor delivery ability to downstream sectors. And their direct driving force is five times higher than indirect. This implies that these sectors mainly use indirect pathways to deliver emergy to downstream sectors and that the efficiency of emergy transfer is low. Their low indirect and total consumption is going against Vienna's development strategy aimed to further promote development of commercial and service industries. The normal functioning of those sectors could be achieved through policy intervention to increase their indirect delivery abilities in the process of emergy utilization. The significant drop in indirect driving weights is noticeable in ADS, TS and EC sectors: -0.1, -0.08 and -0.07, respectively, implying that the investments into production of these sectors fall behind demand for their investments by the other sectors. For TS and EC sectors this reflects most products used by these sectors (i.e., natural gas, diesel) are imported from outside of the Vienna region. In the case of the ADS sector, it shows that this sector does not contribute much to the economy despite being a key sector responsible for provision of social services. The reorganisation of this sector is recommended to provide its services to the growing population. Overall, their productivity should be improved to efficiently transfer emergy along indirect pathways to AGR and MIN sectors since the structure of pulling weight depends on those industries. MAN and AC sectors were in proper shape in terms of the total driving weights and drop in indirect weights were insignificant: -0.02 and -0.01, respectively. Industrial development is also one of priorities of Vienna's government. Therefore, this is in line with their policy. Since among all downstream sectors only 'construction' uses manufacturing products directly to produce finishing products (i.e., buildings), higher indirect contribution from 'manufacturing' to the downstream sectors is required for healthy development of urban metabolic systems. Lastly, shapes of FIN, RA, INF and OBS sectors deviate from norm due to the small indirect and integral driving weights: 0.05, 0.04, 0.0.4 and 0.03, respectively. Generally, the role of those sectors is to indirectly drive the technological advancements in upstream sectors (Zhai et al., 2018). Due to their social function these sectors connect other sectors through indirect paths (Zhai et al., 2018). Thus, it is necessary to develop those industries to upgrade the ability of AGR and MIN sectors to receive emergy.

4.3. Control analysis

The pairwise indirect control relationships in 2015 are shown in Fig. 5. The values of the IN matrix range from 0 to 1, with the latter being a maximum indirect influence of one component on another component. Dark blue colour represents the absence of control of one component on another component or the absence of dependence of the latter. Conversely, the dark red colour stands for a complete influence of one component on another component or a complete dependence of the latter. For example, $in_{12} = 0.98$ means the dependence of AGR on MIN was 98% in 2015 or the control of MIN over AGR was 98% (Li et al., 2018; Piezer et al., 2019; Zhai et al., 2018). The elements of control matrix range from 0 to 0.29, indicating that indirect control is much lower than direct and, therefore, do not contribute significantly to the integral pairwise relationships between components. However, four pairwise relationships deviate from this pattern, exhibiting some degree of control and dependence. The OBS had the highest control in the network, while the AC sector had the highest dependence. This means that AC is a self-sufficient sector and moderately stable in terms of indirect flows (dependence <50%).

The high dependence of the AC sector on the OBS sector points to the low production capacity of the AC sector. This inhibits the AC sectors ability to meet demands of other sectors on its service (i.e., short term accommodation to hold conference). Therefore, the AC sector relies on imports (i.e., monetary) from OBS sector to purchase event accommodation to have a capacity to provide more services to satisfy demand of OBS sector conference venue. Thus, the higher the dependence the more the sector relies on imported products from other sectors to replenish its production to meet demand of consuming sectors (i.e., electricity for TS sector to provide purely battery-electric buses to transport labour force to respective tertiary sector such as OBS) (Ajanovic et al., 2021). The 98% (out of 100%) control of OBS sector over AC sector means that AC sector's dependence on OBS is 98%. Generally, in this way, control and dependency of a sector indicate the extent of self-sufficiency of the sector in emergy (monetary and/or energy) use.

Also, the second and third by magnitude control were effectuated by ER and ADS sectors over TS, respectively. This simply shows that AC receives the most emergy implied in direct energy transfer through the OBS sector. The same applies to TS in relation to ER and ADS sectors. Generally, these degrees of control fall within stability thresholds. In addition, in a healthy system majority of flows between tertiary sectors



	AGR	MIN	MAN	EC	CON	WR	TS	AC	INF	FIN	RA	OBS	ADS	ED	HS	ER
AGR	0	0.001	0.0018	0.0012	0	0	0	0.00016	0.0015	0.00074	0.0013	0	0	0.00065	0	0.00045
MIN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAN	0	0.049	0	0.048	0.063	0.041	0.039	0.046	0.065	0.064	0.055	0.059	0.023	0.036	0.014	0.042
EC	0	0.075	0	0	0.1	0.084	0.07	0.073	0.091	0.093	0.078	0.089	0.037	0.054	0.022	0.059
CON	0	0.16	0	0	0	0	0.016	0.15	0	0	0.19	0	0.068	0.12	0.042	0.13
WR	0	0.26	0	0	0.017	0	0	0	0	0	0	0	0.13	0	0.079	0
TS	0	0.089	0	0	0	0.19	0	0	0	0	0.096	0	0.26	0	0.14	0.28
AC	0	0.21	0	0	0	0.12	0.15	0	0	0	0	0.29	0.14	0.18	0.075	0
INF	0	0.028	0	0	0.031	0	0.012	0.014	0	0.034	0.028	0.024	0	0.015	0	0.012
FIN	0	0.034	0	0	0.035	0.015	0	0	0	0	0.034	0.015	0	0.0053	0	0.023
RA	0	0.051	0	0	0	0.045	0	0.019	0	0	0	0	0	0.043	0	0.039
OBS	0	0.074	0	0	0.094	0.042	0	0	0	0	0.087	0	0	0	0.0033	0.071
ADS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.18	0
ED	0	0.048	0	0	0	0.034	0.0078	0	0	0	0	0.055	0.0075	0	0	0
HS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ER	0	0.05	0	0	0	0.01	0	0	0	0	0	0	0	0.028	0.0016	0

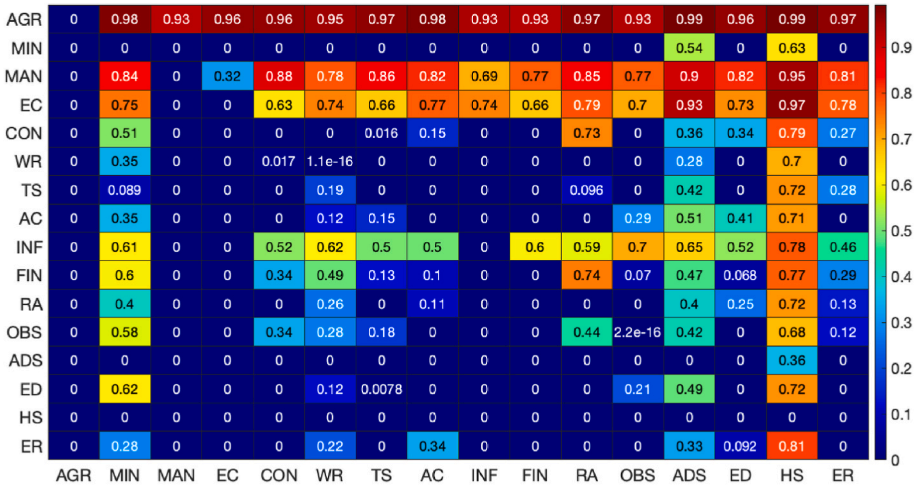
Fig. 5. Pairwise control relationship between components along indirect paths in 2015. Warm colours represent total control and cold colours represent total dependence received or transferred between each pair of sectors. Note: The columns and rows describe degree of control and dependence, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

are received in an indirect way considering their social function (Zhai et al., 2018). TS and AC meet this stability condition (direct dependence lower than indirect). Finally, the WR sector is slightly dependent on the MIN sector, not even 0.27. However, the ability of the WR sector to deliver emergy to MIN is worthier than its ability to receive emergy from MIN. This demonstrates that the WR sector does not effectively support the MIN sector. Therefore, the production structure WR sector should be regulated to effectively transfer emergy to MIN sector.

The number of sectors that rely on the MIN sector is 14, while there are 2, 1 and 0 sectors depending on EC, MAN and AGR. Conversely, EC, MAN and AGR are dependent on 13, 14 and 9 sectors, respectively. From the demand-side perspective, EC, MAN and AGR are sectors that require direct support from other sectors to deliver flows to them (Zhang et al., 2014a; Li et al., 2018). Therefore, input of other sectors would affect direct energy consumption of those three sectors. The production structure of the three sectors must be adjusted to reduce their direct energy consumption. This would necessitate a further study to break these industries into sub-processes and then to employ ecological network analysis to see how much direct and indirect pulling and driving weight each sub-process has in the system. Then, we can identify the most affected sub-processes by other sub-processes to propose the corrective measures targeted at the specific sub-processes. For example, the manufacture of chemicals and chemical products could have the highest energy dependence in the Manufacturing sector. This additional detailed step is out of the scope of this study.

In general, energy intensive sub-processes in these sectors could also be substituted with labour intensive ones. In addition, it is important to substitute energy intensive process such as manufacturing cement with manufacturing of timber or other low energy consumption sub-processes. It is important to use unprocessed materials such as corn, timber, or natural gas in manufacturing process directly. For example, substituting traditional manufacturing with the low carbon manufacturing (LCM) will decrease direct energy consumption (Tridech and Cheng, 2011). Lastly, introducing more energy dependent sub-processes within each sector will lead to the energy consumption deficit among sub-processes and associated mutual energy consumption reduction. Conversely, if the sub-processes directly control each other, namely deliver excessive amount of energy to each other, decreasing the energy delivery from one sub-processes will result in decrease of the energy delivery from a second one (Li et al., 2018).

Integral pairwise relationships between sectors are shown in Fig. 6. The MIN sector completely dominates the system by heavily controlling



	AGR	MIN	MAN	EC	CON	WR	TS	AC	INF	FIN	RA	OBS	ADS	ED	HS	ER
AGR	0	0.98	0.93	0.96	0.96	0.95	0.97	0.98	0.93	0.93	0.97	0.93	0.99	0.96	0.99	0.97
MIN	0	0	0	0	0	0	0	0	0	0	0	0	0.54	0	0.63	0
MAN	0	0.84	0	0.32	0.88	0.78	0.86	0.82	0.69	0.77	0.85	0.77	0.9	0.82	0.95	0.81
EC	0	0.75	0	0	0.63	0.74	0.66	0.77	0.74	0.66	0.79	0.7	0.93	0.73	0.97	0.78
CON	0	0.51	0	0	0	0	0.016	0.15	0	0	0.73	0	0.36	0.34	0.79	0.27
WR	0	0.35	0	0	0.017	1.1e-16	0	0	0	0	0	0	0.28	0	0.7	0
TS	0	0.089	0	0	0	0.19	0	0	0	0	0.096	0	0.42	0	0.72	0.28
AC	0	0.35	0	0	0	0.12	0.15	0	0	0	0	0.29	0.51	0.41	0.71	0
INF	0	0.61	0	0	0.52	0.62	0.5	0.5	0	0.6	0.59	0.7	0.65	0.52	0.78	0.46
FIN	0	0.6	0	0	0.34	0.49	0.13	0.1	0	0	0.74	0.07	0.47	0.068	0.77	0.29
RA	0	0.4	0	0	0	0.26	0	0.11	0	0	0	0	0.4	0.25	0.72	0.13
OBS	0	0.58	0	0	0.34	0.28	0.18	0	0	0	0.44	2.2e-16	0.42	0	0.68	0.12
ADS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.36	0
ED	0	0.62	0	0	0	0.12	0.0078	0	0	0	0	0.21	0.49	0	0.72	0
HS	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ER	0	0.28	0	0	0	0.22	0	0.34	0	0	0	0	0.33	0.092	0.81	0

Fig. 6. Pairwise control relationship between components along integral paths in 2015. Warm colours represent total control and cold colours represent total dependence received or transferred between each pair of sectors. Note: The columns and rows describe degree of control and dependence, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

all other compartments. This sector also shows moderate direct dependence only on 2 sectors: HS and ADS, which suggests that this industry has not been developed in the Vienna region. The AGR sector is ranked as the highest emergy receiver in the system based on colour. Extremely high total control over this sector is demonstrated by 2 upstream sectors (MIN and EC) and 5 downstream sectors (CON, AC, RA, ADS and HS). Conversely, the MIN sector has control over 13 sectors, while only the ADS and HS sector have a control over it. AGR and MIN sectors need to deliver a large amount of flows to downstream industries in order to receive the feedback required for their development. This means that these sectors should effectively supply and receive emergy flows. Thus, both sectors are inadequate in terms of control and dependence. Also, the dependence of the AGR sector on 7 sectors is predominantly direct, suggesting that AGR has low capacity to receive emergy indirectly from the other sectors. The indirect dependence of the AGR on MIN and EC sectors is much lower than direct, suggesting the AGR sector poorly receives indirect inputs (payments) from EC and MIN, which hinder its production capacity. Moreover, the production of the AGR sector depends on energy inputs from MIN and EC to meet demands of downstream industries, leading to low direct deliver ability of this sector. CON, AC, RA, ADS and HS are sectors that normally are not in direct contact with upstream sectors (Zhai et al., 2018). There are no sectors depending on AGR, suggesting that AGR sector lacks self-sufficiency in emergy use and, therefore, is the most vulnerable sector to shortages of energy flows in Vienna Region. Therefore, adjustment in production structure is necessary to reduce direct energy consumption of the AGR sector and to improve its ability to receive emergy indirectly. The other important measure is to increase the demand for mining products in Vienna region followed by an increase of payments provided to the MIN sector. Finally, stimulating the demand for agricultural products by tertiary sectors at the middle of supply chain (i.e., demand for agro-waste such as sugar beet waste named carbonation lime residue as partial replacement of cement in "construction" sector) should improve indirect receiving capacity of AGR while avoiding too long circulation paths that limit the acceptance of investments by AGR sector. These policy measures would contribute to the healthy development of Vienna's metabolic system.

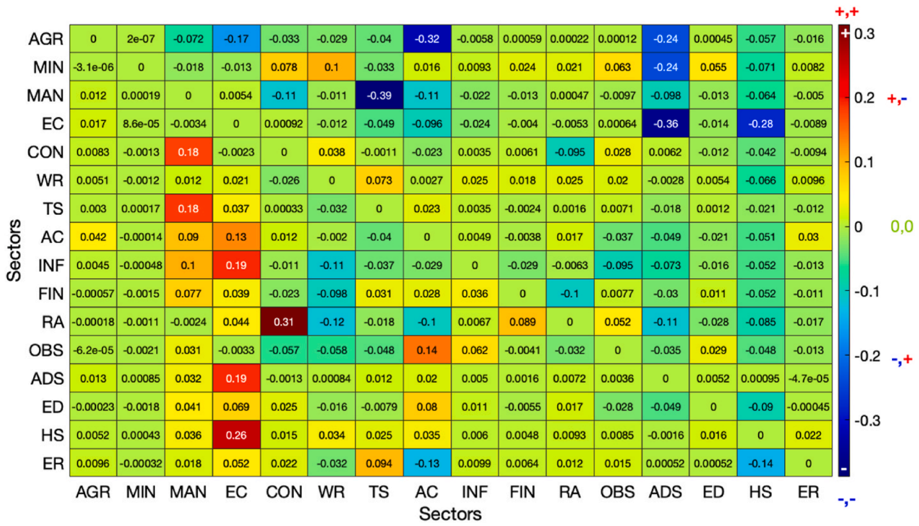
4.4. Utility analysis

Based on the results of direct utilities in Vienna's metabolic system along direct paths, Fig. 7 reveals the mutual emergy metabolic relationships between each pair of sectors. There were a few large gaps in emergy metabolic relationships among sectors, but most relationships were homogeneous.

In Fig. 7 the beneficial relationships are represented by warm colours, while disadvantageous relationships are represented by cold colours. Judging by the colour of different grids, the neutral pairwise relationships between sectors dominated along diagonal during the study year. This means that there was not any direct benefit of sector's flows to itself (Zhai et al., 2019). From Fig. 4 the EC sector is exploited by three tertiary industries: ADS, HS and INF. Also, the CON sector is exploited by the RA sector. This simply shows that the EC sector is in constant pressure of expansion to meet energy demand of the growing pillar tertiary sectors. This also means that energy production lags behind the economic growth (Zhang et al., 2014d). Moreover, the energy requirements of the CON sector grow to keep up with the growing demand for non-residential properties such as hospital buildings (Zhang et al., 2014d). A similar problem is associated with the exploitation relationship between TS and MAN. Although the development of the MAN sector is in line with the urban development plan till 2025 (Anthopoulos, 2019; Vienna City Administration, 2014, 2019), the energy requirements of MAN sector are also far behind demand of TS sector for its manufacturing products (i.e., rolling stock). Therefore, EC, CON and MAN should indirectly exploit the other industries to improve their competitiveness, or their productivity should be increased until the development of the ADS, HS, INF, RA and TS sectors will stabilize. The same solution can be applied to the direct exploitation of ER by AC.

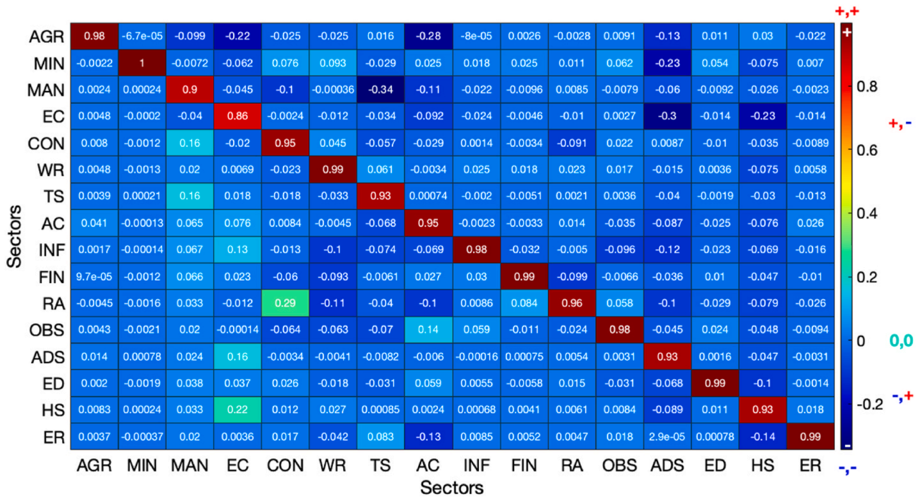
The strong exploitative relationships were identified between AC and AGR, ADS and AGR, ADS and MIN and week exploitation between AGR and MIN. The fact that AGR and MIN are exploited by ADS and AC suggests that these sectors (AGR and MIN) have a low ability to satisfy the energy demand of all downstream industries, resulting from their dependence on imports. All tertiary sectors need to improve their competitiveness to exploit or to be in mutualism with AGR and MIN sectors. The competitiveness of downstream sectors could be improved by exploiting other industries (EC and MAN) for energy or be in mutualistic relations with them (Zhai et al., 2018). Fig. 7 shows that CON, TS, INF, ADS and HS pursue this strategy. Furthermore, improving the competitiveness of MIN sector and managing development of AGR and MIN sectors in an integrative manner will contribute to the mutual relationships between these sectors.

Fig. 8 presents a pairwise integral relationship between components. Based on colour of different grids, values on diagonals outweigh the non-diagonal values due to indirect flow that occur within each sector always provides positive self-feedback (benefits) to itself (Zhai et al., 2019). Judging by the colour of different grids competition relations occupy almost all cells in the Fig. 8, which suggest that indirect utilities have a little positive effect on the system. However, Yang and et al. (2016) found that any relationships that fall in range from −0.5 to 0.5 can be



Sectors	AGR	MIN	MAN	EC	CON	WR	TS	AC	INF	FIN	RA	OBS	ADS	ED	HS	ER
AGR	0	2e-07	-0.072	-0.17	-0.033	-0.029	-0.04	-0.32	-0.0058	0.00059	0.00022	0.00012	-0.24	0.00045	-0.057	-0.016
MIN	-3.1e-06	0	-0.018	-0.013	0.078	0.1	-0.033	0.016	0.0093	0.024	0.021	0.063	-0.24	0.055	-0.071	0.0082
MAN	0.012	0.00019	0	0.0054	-0.11	-0.011	-0.39	-0.11	-0.022	-0.013	0.00047	-0.0097	-0.098	-0.013	-0.064	-0.005
EC	0.017	8.6e-05	-0.0034	0	0.00092	-0.012	-0.049	-0.096	-0.024	-0.004	-0.0053	0.00064	-0.36	-0.014	-0.28	-0.0089
CON	0.0083	-0.0013	0.18	-0.0023	0	0.038	-0.0011	-0.023	0.0035	0.0061	-0.095	0.028	0.0062	-0.012	-0.042	-0.0094
WR	0.0051	-0.0012	0.012	0.021	-0.026	0	0.073	0.0027	0.025	0.018	0.025	0.02	-0.0028	0.0054	-0.066	0.0096
TS	0.003	0.00017	0.18	0.037	0.00033	-0.032	0	0.023	0.0035	-0.0024	0.0016	0.0071	-0.018	0.0012	-0.021	-0.012
AC	0.042	-0.00014	0.09	0.13	0.012	-0.002	-0.04	0	0.0049	-0.0038	0.017	-0.037	-0.049	-0.021	-0.051	0.03
INF	0.0045	-0.00048	0.1	0.19	-0.011	-0.11	-0.037	-0.029	0	-0.029	-0.0063	-0.095	-0.073	-0.016	-0.052	-0.013
FIN	-0.00057	-0.0015	0.077	0.039	-0.023	-0.098	0.031	0.028	0.036	0	-0.1	0.0077	-0.03	0.011	-0.052	-0.011
RA	-0.00018	-0.0011	-0.0024	0.044	0.31	-0.12	-0.018	-0.1	0.0067	0.089	0	0.052	-0.11	-0.028	-0.085	-0.017
OBS	-6.2e-05	-0.0021	0.031	-0.0033	-0.057	-0.058	-0.048	0.14	0.062	-0.0041	-0.032	0	-0.035	0.029	-0.048	-0.013
ADS	0.013	0.00085	0.032	0.19	-0.0013	0.00084	0.012	0.02	0.005	0.0016	0.0072	0.0036	0	0.0052	0.00095	-4.7e-05
ED	-0.00023	-0.0018	0.041	0.069	0.025	-0.016	-0.0079	0.08	0.011	-0.0055	0.017	-0.028	-0.049	0	-0.09	-0.00045
HS	0.0052	0.00043	0.036	0.26	0.015	0.034	0.025	0.035	0.006	0.0048	0.0093	0.0085	-0.0016	0.016	0	0.022
ER	0.0096	-0.00032	0.018	0.052	0.022	-0.032	0.094	-0.13	0.0099	0.0064	0.012	0.015	0.00052	0.00052	-0.14	0

Fig. 7. Pairwise utility relationship between components along direct paths in 2015. The warm colours reflect the direct benefits (+), and the cold colours reflect the direct costs (−) received or transferred between each pair of sectors. The values in matrix ranges from −1 to 1. The four combinations of signs result in four pairwise relationships between sectors: mutualism (+,+), competition (-,-) exploitation (+,-), exploited (-,+) and neutral (0,0). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)



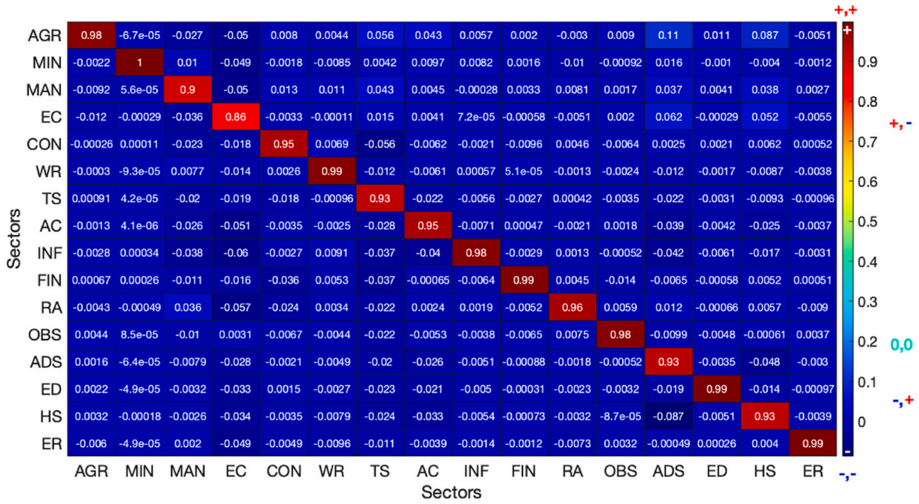
	AGR	MIN	MAN	EC	CON	WR	TS	AC	INF	FIN	RA	OBS	ADS	ED	HS	ER
AGR	0.98	-6.7e-05	-0.099	-0.22	-0.025	-0.025	0.016	-0.28	-8e-05	0.0026	-0.0028	0.0091	-0.13	0.011	0.03	-0.022
MIN	-0.0022	1	-0.0072	-0.062	0.076	0.093	-0.029	0.025	0.018	0.025	0.011	0.062	-0.23	0.054	-0.075	0.007
MAN	0.0024	0.00024	0.9	-0.045	-0.1	-0.00036	-0.34	-0.11	-0.022	-0.0096	0.0085	-0.0079	-0.06	-0.0092	-0.026	-0.0023
EC	0.0048	-0.0002	-0.04	0.86	-0.0024	-0.012	-0.034	-0.092	-0.024	-0.0046	-0.01	0.0027	-0.3	-0.014	-0.23	-0.014
CON	0.008	-0.0012	0.16	-0.02	0.95	0.045	-0.057	-0.029	0.0014	-0.0034	-0.091	0.022	0.0087	-0.01	-0.035	-0.0089
WR	0.0048	-0.0013	0.02	0.0069	-0.023	0.99	0.061	-0.0034	0.025	0.018	0.023	0.017	-0.015	0.0036	-0.075	0.0058
TS	0.0039	0.00021	0.16	0.018	-0.018	-0.033	0.93	0.00074	-0.002	-0.0051	0.0021	0.0036	-0.04	-0.0019	-0.03	-0.013
AC	0.041	-0.00013	0.065	0.076	0.0084	-0.0045	-0.068	0.95	-0.0023	-0.0033	0.014	-0.035	-0.087	-0.025	-0.076	0.026
INF	0.0017	-0.00014	0.067	0.13	-0.013	-0.1	-0.074	-0.069	0.98	-0.032	-0.005	-0.096	-0.12	-0.023	-0.069	-0.016
FIN	9.7e-05	-0.0012	0.066	0.023	-0.06	-0.093	-0.0061	0.027	0.03	0.99	-0.099	-0.0066	-0.036	0.01	-0.047	-0.01
RA	-0.0045	-0.0016	0.033	-0.012	0.29	-0.11	-0.04	-0.1	0.0086	0.084	0.96	0.058	-0.1	-0.029	-0.079	-0.026
OBS	0.0043	-0.0021	0.02	-0.00014	-0.064	-0.063	-0.07	0.14	0.059	-0.011	-0.024	0.98	-0.045	0.024	-0.048	-0.0094
ADS	0.014	0.00078	0.024	0.16	-0.0034	-0.0041	-0.0082	-0.006	-0.00016	0.00075	0.0054	0.0031	0.93	0.0016	-0.047	-0.0031
ED	0.002	-0.0019	0.038	0.037	0.026	-0.018	-0.031	0.059	0.0055	-0.0058	0.015	-0.031	-0.068	0.99	-0.1	-0.0014
HS	0.0083	0.00024	0.033	0.22	0.012	0.027	0.00085	0.0024	0.00068	0.0041	0.0061	0.0084	-0.089	0.011	0.93	0.018
ER	0.0037	-0.00037	0.02	0.0036	0.017	-0.042	0.083	-0.13	0.0085	0.0052	0.0047	0.018	2.9e-05	0.00078	-0.14	0.99

Fig. 8. Pairwise utility relationship between components along integral paths in 2015. The warm colours reflect the total benefits, and the cold colours reflect the total costs received or transferred between each pair of sectors. The values in matrix ranges from −1 to 1. The four combinations of signs result in four pairwise relationships between sectors: mutualism (+,+), competition (−,−) exploitation (+,−) and exploited (−,+). Indirect effects changed neutral (0,0) into mutualistic relations (+,+). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

defined as weak linkages. In our case all relationships, except values on diagonals, fall in that range as shown in Figs. 8 and 9. The only strong exploitation relationship based on Fig. 9 is between RA and CON, where indirect contribution is too small (>0.1). The CON is exploited by the RA sector through emergy inputs to satisfy requirements of RA sectors, which contributes to expansion of the housing market. However, Fig. 9 shows the RA is exploited by the CON sector through investments to satisfy requirements of CON sector. Thus, RA sector should be supported indirectly by the other sectors to improve its competitiveness. However, this indirect support is originated from weak mutualistic relationships between RA and MAN, RA and WR, RA and AC, which are sufficient to offset weak negative utilities resulted from indirect exploitation relationship between CON and RA.

Also, this shows that CON sector is not good in receiving inputs indirectly (investments) due to large indirect consumption implied in the products or services of this sector (Zhai et al., 2018). Thus, reducing the number of indirect paths will improve its indirect receiving ability and push this sector to shift to the harmonious relationship. It is also evident that the producers (AGR, MIN) are in competition with consumers, with EC being the highest competitor to AGR in terms of integral and indirect utilities. Those sectors also compete in an indirect way with all other sectors in the system, meaning that the AGR sector has low ability to drive other industries, but this ability is wasted due to competition for investments allocated to other sectors. Therefore, the eventual mutualism between these two components (AGR and EC) could be attained by decreasing energy consumption of EC to the level of AGR to shift to the competitive relationship, conductive to the mutual energy consumption reduction (Lu et al., 2012; Li et al., 2018), and through indirect support of AGR and EC sectors by other sectors. Conversely, the shift from competition relationship between AGR and all other sectors (except MIN), to a normal state where AGR sector indirectly exploit all consumers will contribute to the system-level mutualism (Zhang et al., 2014b; Zhai et al., 2019).

The mutualism index (MI) and synergism index (SI) resulting from the ecological network analysis are 0.93 and 12.53, respectively. This implies that negative relationships outweigh beneficial relationships in the system and, therefore, with MI < 1, the system is not as healthy and mutualistic as many of the observed ecosystems. Conversely, the value of SI implies that much more benefits are obtained from the relationships compared to costs (SI > 0), and that the level of cooperation between sectors in the management of Vienna's metabolic system is extremely high (Fan and Fang, 2019). However, for system mutualism to occur MI should be more than 1 and SI should be more than 0 (Lu et al., 2012). Although SI seems to be high, the high value resulted mainly by indirect benefits generated by sector themselves, rather than intersectoral relationships (Tan et al., 2018). Therefore, overall symbiosis (excluding diagonal elements) is much lower than calculated SI (−2.79). The system provides less benefits at higher costs (Tan et al., 2018). These results stem from competitive indirect relationships between each pair of components. Aside from recommendations discussed above,



	AGR	MIN	MAN	EC	CON	WR	TS	AC	INF	FIN	RA	OBS	ADS	ED	HS	ER
AGR	0.98	-6.7e-05	-0.027	-0.05	0.008	0.0044	0.056	0.043	0.0057	0.002	-0.003	0.009	0.11	0.011	0.087	-0.0051
MIN	-0.0022	1	0.01	-0.049	-0.0018	-0.0085	0.0042	0.0097	0.0082	0.0016	-0.01	-0.00092	0.016	-0.001	-0.004	-0.0012
MAN	-0.0092	5.6e-05	0.9	-0.05	0.013	0.011	0.043	0.0045	-0.00028	0.0033	0.0081	0.0017	0.037	0.0041	0.038	0.0027
EC	-0.012	-0.00029	-0.036	0.86	-0.0033	-0.00011	0.015	0.0041	7.2e-05	-0.00058	-0.0051	0.002	0.062	-0.00029	0.052	-0.0055
CON	-0.00026	0.00011	-0.023	-0.018	0.95	0.0069	-0.056	-0.0062	-0.0021	-0.0096	0.0046	-0.0064	0.0025	0.0021	0.0062	0.00052
WR	-0.0003	-9.3e-05	0.0077	-0.014	0.0026	0.99	-0.012	-0.0061	0.00057	5.1e-05	-0.0013	-0.0024	-0.012	-0.0017	-0.0087	-0.0038
TS	0.00091	4.2e-05	-0.02	-0.019	-0.018	-0.00096	0.93	-0.022	-0.0056	-0.0027	0.00042	-0.0035	-0.022	-0.0031	-0.0093	-0.00096
AC	-0.0013	4.1e-06	-0.026	-0.051	-0.0035	-0.0025	-0.028	0.95	-0.0071	0.00047	-0.0021	0.0018	-0.039	-0.0042	-0.025	-0.0037
INF	-0.0028	0.00034	-0.038	-0.06	-0.0027	0.0091	-0.037	-0.04	0.98	-0.0029	0.0013	-0.00052	-0.042	-0.0061	-0.017	-0.0031
FIN	0.00067	0.00026	-0.011	-0.016	-0.036	0.0053	-0.037	-0.00065	-0.0064	0.99	0.0045	-0.014	-0.0065	-0.00058	0.0052	0.00051
RA	-0.0043	-0.00049	0.036	-0.057	-0.024	0.0034	-0.022	0.0024	0.0019	-0.0052	0.96	0.0059	0.012	-0.00066	0.0057	-0.009
OBS	0.0044	8.5e-05	-0.01	0.0031	-0.0067	-0.0044	-0.022	-0.0053	-0.0038	-0.0065	0.0075	0.98	-0.0099	-0.0048	-0.00061	0.0037
ADS	0.0016	-6.4e-05	-0.0079	-0.028	-0.0021	-0.0049	-0.02	-0.026	-0.0051	-0.00088	-0.0018	-0.00052	0.93	-0.0035	-0.048	-0.003
ED	0.0022	-4.9e-05	-0.0032	-0.033	0.0015	-0.0027	-0.023	-0.021	-0.005	-0.00031	-0.0023	-0.0032	-0.019	0.99	-0.014	-0.00097
HS	0.0032	-0.00018	-0.0026	-0.034	-0.0035	-0.0079	-0.024	-0.033	-0.0054	-0.00073	-0.0032	-8.7e-05	-0.087	-0.0051	0.93	-0.0039
ER	-0.006	-4.9e-05	0.002	-0.049	-0.0049	-0.0096	-0.011	-0.0039	-0.0014	-0.0012	-0.0073	0.0032	-0.00049	0.00026	0.004	0.99

Fig. 9. Pairwise utility relationship between components along indirect paths in 2015. The warm colours reflect the indirect benefits (+) and the cold colours reflect the indirect costs (−) received or transferred between each pair of sectors. The values in matrix ranges from −1 to 1. The four combinations of signs result in four pairwise relationships between sectors: mutualism (+,+), competition (−,−) exploitation (+,−) and exploited (−,+). Indirect neutral relationships (0,0) did not exist in a such matrix. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

eco-industrial parks can contribute to emergy utilization efficiency and overall mutualism by sharing output residuals among industries (Zhang et al., 2014b) and by developing selective high-value linkages through collaborative learning (Boons et al., 2016), such as transactions of agrivoltaic systems between MAN and AGR to improve productivities of land and assembly lines.

4.5. Research implications, limitations, and future scope

An Emergy network model of urban metabolic system allows to assess the magnitude of 'economic services' among all sectors in urban economy. There are many hidden pathways that are not captured by traditional input-output analysis leading to an underestimation of indirect flows in the urban metabolic system (Zhang et al., 2014c). The major disadvantage of this approach is the impossibility of accommodating multiple currencies in the network model. To allow multiple currencies (i.e. water and energy) multiple models need to be constructed. Moreover, those models cannot be easily unified and compared (Fath et al., 2007). The emergy network analysis overcomes this problem, allowing to study both the ecological and socio-economic intersectoral flows in urban economy and between urban economy and environment. As a result, this model provides a more comprehensive description of emergy flows in the urban metabolic system. The final difference between our study and previous research is that we not only covered integral and direct flows but also examined pairwise indirect control and utilities, as well as indirect driving force and pulling force weights. These properties assess the contribution of indirect effects of system internal processes to the status and role of each sector in urban metabolic system, which reveals hidden problems in internal structure and functions caused by indirect interactions not evident in previous studies.

This approach can be used to prioritize the consumption and footprints of sectors in urban economy to inform supply-side and demand-side climate mitigation policies (Wieland et al., 2019). This model can also assist decision makers with development of industrial structure towards efficient and sustainable emergy consumption (i.e., stability of components and synergy among them).

In this study, we also discovered some limitations that should be addressed. The first limitation is related to the application of ecological network analysis. To run this analysis the system should be in steady state. This requirement prevents analysing urban metabolic systems represented by non-square matrices (underdetermined or overdetermined) unless it is converted to the determined system of equations by removing final demand categories (consumption of households, capital formation, government, and exports) and balancing the table. The other problem was that the values of pairwise direct (DN) and indirect control relationships (IN) ranged from −1 to 1, which was unacceptable since rescaled integral control matrix (CN matrix) was populated with values on the interval [0,1] (Yang et al., 2012; Zhai et al., 2018). Therefore, we were required to apply amendments to the IN matrix to avoid negatives and values of indirect control being larger than integral values: if $0 < in_{ij} < cn_{ij}$, $in_{ji} = in_{ij}$, otherwise, $in_{ji} = 0$.

Future studies can incorporate information indices (ascendency, overhead and robustness index) to analyse the impact of each sector resulting from indirect control weights to the overall system's efficiency and stability. This could provide insights on key sectors that limit system efficiency and the most vulnerable sectors in the system. Then, analysis of indirect pairwise controls and utilities between compartments can help to identify the sectors responsible for inefficiency or vulnerability of each target sector in the system. Consequently, future directions can follow a path of analysis of changes in system's efficiency and stability over time to monitor Vienna's metabolic system performance in terms of emergy utilization and system's performance. These directions would promote more sustainable and efficient development of Vienna's metabolic system.

5. Conclusion

The analysis of system-level hierarchy of sectors revealed that producers ("agriculture, forestry and fishing" and "mining and quarrying") are unsupported by downstream industries in an indirect way and, therefore, cannot satisfy demand of downstream sectors for their production. Moreover, there are many problems within tertiary industries preventing them from supporting producers. Some consumers pull most of development in the system ("public administration and defence, social security" and "human health and social work activities"), while other sectors rely on imported products ("electricity, gas, water supply, sewerage, waste, and remediation services" and "transportation and storage"), leading to the low indirect driving abilities of these sectors. In addition, few sectors have no importance in the system ("wholesale and retail trade, repair of motor vehicles" and "construction").

The pairwise control and utility analyses identified sectors responsible for disorders in the target sector. The results showed that the lack of monetary control of "wholesale and retail trade, repair of motor vehicles" over "mining and quarrying" sector contributed to the low energy consumption of the "mining and quarrying" sector. In addition, low monetary and strong energy dependence of "agriculture, forestry and fishing" sector on "mining and quarrying" and "electricity, gas, water supply, sewerage, waste, and remediation services" sectors hindered production capacity of "agriculture, forestry and fishing" sector. Finally, we found that the competition between "agriculture, forestry and fishing" and "electricity, gas, water supply, sewerage, waste, and remediation services" sectors contributed the most to the unstable state of "agriculture, forestry and fishing". The low values of system-level indicators (mutualism and synergism) reflected the dominance of pairwise competitive indirect relationships in the system. The establishment of numerous eco-industrial parks can improve the overall level of mutualism and synergism in Vienna's metabolic system in long-term perspective.

Future studies could identify the key sectors limiting the system's efficiency by applying information indices to the network analysis. Another possible direction would be to add the time data for monitoring the system stability and efficiency in terms of emergy utilization. These directions would contribute to the healthier state of Vienna's metabolic system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Consumption-based sectoral classification

The position of sectors in the industrial supply chain affects the total emergy consumption. Zhang et al. (2014c) divided sectors into five categories based on the magnitude of gap between the direct and indirect consumption intensity. This classification was applied in this study for flows. Firstly, the flows were divided into three groups based on the consumption: “highest” total consumption ($\geq 1.5E + 20\,sej$), high total consumption (between $0.5E + 20\,sej$ and $1.5E + 20\,sej$), and low total consumption $\leq 0.5E + 20\,sej$). Then, the first two groups were subdivided based on relative proportions of direct and indirect emergy flows. The first group (higher total consumption; indirect is higher than direct consumption) includes only “ADS”. The second group with both high total consumption and higher indirect consumption (between $0.5E + 20\,sej$ and $1.5E + 20\,sej$) includes ‘TS’, ‘HS’ and ‘EC’. The third group is characterized by moderate total consumption, indirect is higher than direct consumption. This group includes ‘AC’, MAN′, ‘WR’, ‘CON’, ‘ED, ‘OBS’, ‘ER’ and ‘INF’. The fourth group incorporates sectors with low total consumption with indirect consumption being lower than direct consumption. ‘RA’, ‘FIN’, ‘AGR’ and ‘MIN’ fall in this category.

Appendix B. Structure of emergy consumption

The total emergy consumption for each sector should be correlated with the structure of emergy consumption for each sector in the system to determine where policy interventions should be most likely applied to decrease emergy consumption.

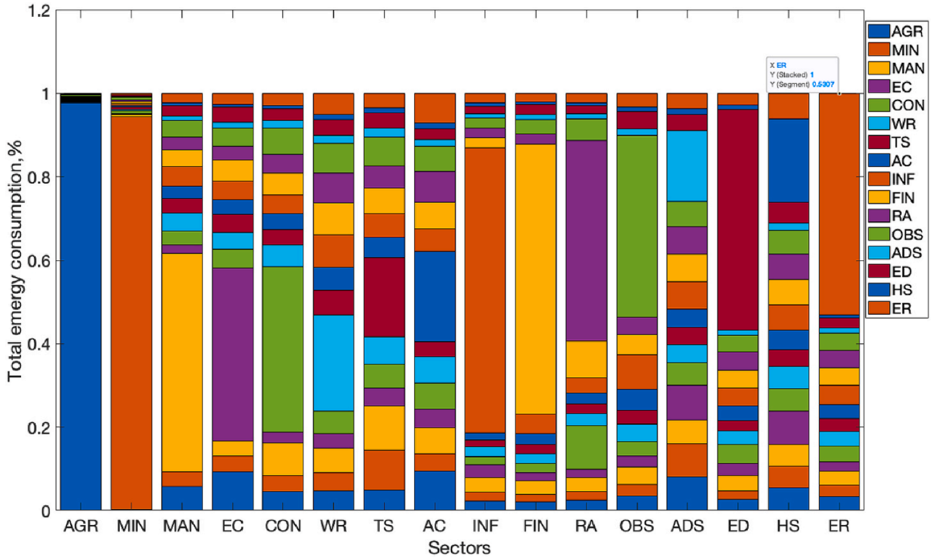

Fig. B.1. Emergy metabolic structure for each sector of Vienna’s metabolic system.

Figure B.1 reveals that the largest proportion of total emergy consumption in the ADS and HS sectors is attributed to the inputs from other sectors: 92% and 80%, respectively. Surprisingly, it shows that these sectors are receiving compartments and, therefore, should play a more active role in donating emergy to other sectors. This reflects the lack of self-sufficiency in emergy use and vulnerability to the external risks, such as sudden price change. Therefore, the productivity of public administration activities, hospital activities and other sub-processes in these sectors should be improved.

‘AGR’ and ‘MIN’ are self-sufficient sectors because they mostly consume directly their own primary products 98% and 95%, respectively. However, their total consumption is far too low to satisfy demand of other sectors (except for EC, MAN and TS sectors). Therefore, it is important to decrease the huge direct emergy consumption, improve emergy utilization efficiency of all processes in these sectors and to increase their indirect emergy consumption (to increase demand of consumers on their products).

The highest use of INF and FIN is attributable to their own consumption: 68% and 65%, respectively. They have capacity to deliver more emergy to other industries than they receive from them. Thus, it is necessary to promote development of those industries by increasing the share of emergy supplied from other industries, especially, underrepresented agricultural and mining products in the use of those sectors. The own production of ER, ED and EC is also higher than the emergy imported from other industries. Thus, these sectors should be modified to increase their own production and to promote development of ‘AGR’ and ‘MIN’ sectors. In addition, the CON sector has the capacity to contribute 40% out of the total emergy use to the other sectors and its products are consumed mostly by downstream industries (i.e., TS, HS). This result suggests that it is necessary to adjust this component to satisfy demand of tertiary industries. All other sectors from the third and fourth category only utilize the emergy supplied from other sectors and do not contribute to the system. Therefore, the structure of those sectors should be adjusted to promote their capacity to deliver flows to other industries.

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PAPER IV

5.4 An urban emergy footprint: Comparing supply- and use-extended input-output models for the case of Vienna, Austria

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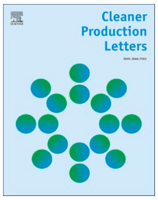

An urban emergy footprint: Comparing supply- and use-extended input-output models for the case of Vienna, Austria

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ABSTRACT

Urban activities currently consume 75% of global final energy demand, which is expected to increase given absolute and relative population growth in cities. Assessments of both producer (upstream) and consumer (downstream) ecological and socioeconomic impacts of urban inter-industry exchanges are needed to reduce energy consumption and resource use behind the industrial footprints of cities. Environmental extensions in the input-output analysis are designed from the user side perspective, focusing only on commercial energy supply and use. This study introduced emergy-evaluated supply-extended and use-extended carbon footprint models for Vienna and compared their empirical and conceptual implications. Emergy-evaluated footprints of Vienna's urban consumption were estimated by combining industrial and systems ecology approaches as per the research question, based on previous investigations of GHG emissions and energy supply- and use-extensions. Results showed that the ranking of footprints of final product categories is sensitive to the evaluation method, with products of extractive and manufacturing industries differing by more than 10% depending on whether emergy or carbon evaluation is chosen. The emergy-based comparison further reveals that for products of extractive industries, the difference between use and supply extension results can be more than 20% as opposed to carbon-based comparison with the difference between supply and use extension results for services not even amounting to 5%. Future studies could address the over-estimation of direct energy supply to the economy, under-estimation of product and service, inconsistency in standard use-extension design, and challenges in assembling emergy-evaluated supply and use extensions. Fundings are relevant for unified responsibility assessment of upstream and downstream sectors without prioritising structural features.

1. Introduction

Cities directly and indirectly consume around 75% of the world's final energy and future final energy demand is projected to increase (*World population prospects 2022: Summary of results, 2022*). Clearly, urban social-ecological systems need to be reorganized in a more sustainable manner, to decrease energy consumption as well as the economic-driven growth in resource use and industrial footprints (Bahers and Rosado, 2023). Taking into consideration the ecological and socioeconomic impact arising from exchanges between and within urban sectors, an assessment of industries' impacts on both the producer (upstream) and consumer (downstream) perspectives is needed.

One method widely used for urban sustainability assessments is environmentally extended input-output (EE-IO) analysis (Yetano Roche et al., 2014). EE-IO is often used for consumption-based accounting formed by complementing traditional monetary input-output accounts with physical extensions, representing primary inputs from the environment or direct demand of households. In this manner, it is possible to evaluate the total environmental footprint of final products or final demand categories (Kitzes, 2013).

Outstanding critical issues for EE-IO remain, such as 1) how environmental extensions (supply and use) are actually derived from the underlying data, 2) what principles are used, and 3) what are the implications for interpreting and applying the results (Owen et al., 2017; Schaffartzik et al., 2015). In this literature, two types of principles for building extensions have been identified. Already Costanza and

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Herendeen (1984) identified different outcomes from the use of both supply and use extensions. Many studies since then have applied either supply or use extensions. The majority of researcher used supply-extension design to address diverse unrelated issues such as footprint reduction based on lifestyle choices (Koide et al., 2021), global energy footprint of natural gas (Kan et al., 2019), and supply pattern of energy and water footprints. Another group of authors focused on methodological improvements and investigation of supply-extension designs. Some endogenized human labour inputs into supply-extension design (Rocco and Colombo, 2016a, 2016b). Other researchers disaggregated product footprints to identify multi-regional footprints of final demand and associated categories (Chen and Wu, 2017; Wu and Chen, 2017a, 2017b). The use extensions were applied to issues where supply-extensions were not reliable enough such as ranking of countries based on their level of decoupling of energy consumption (Akizu-Gardoki et al., 2018), identification of technology and consumption drivers inducing Spanish carbon emissions (Cansino et al., 2016), identification of regions and economic sectors behind wastewater footprint in China (Han et al., 2021), separation of regions with dominant consumption-based emissions from regions with dominant production-based emissions in Japan (Hasegawa et al., 2015). Other scientists worked on combined use of use-extended IO model and network science methodology to the study relationship between internal process, use-extended footprint, and the condition of the metabolic systems. Some scientists developed network models to analyse relations and systemic activities of economic sectors contributing to the use-extended footprint such as Guangdong carbon network model (Li et al., 2018), energy, water, and carbon models of China (Xu et al., 2021), Beijing's energy network model (Zhang et al., 2014a) and study contribution of regions and economic sectors to stability and sustainability (robustness) of China's national metabolic system (Zheng et al., 2021a). Recently, studies directly compared supply and use extensions (Owen et al., 2017) and scrutinized the underlying methodological choices (Schaffartzik et al., 2015), usually at national to international scales.

The analysis of urban energy and carbon flows as embedded into globalized networks of production and consumption has gained increasing attention in recent years, (Fry et al., 2021; Wiedmann et al., 2020; Jin et al., 2021). Some studies analysed city-scale energy footprints with use-extensions (Zhang et al., 2014b; Zheng et al., 2016, 2019; Zhai et al., 2019).

Another important issue is that existing energy analysis and derived supply- and use-extensions are usually confined to standard definitions on technical energy use and do not include anything preceding the extraction phase of the energy carriers (e.g., mining of coal) (Bullard and Herendeen, 1975a; Bullard and Herendeen, 1975b; Heun et al., 2018). The boundary and temporal limits of use- and supply-extensions employed across most studies do not include direct solar energy inputs into ecosystems and indirect solar energy embodied in ecosystem processes and socio-economic activities to produce products or services.

Emergy is an accounting approach that records direct and indirect solar energy used up across all transformations over time, which were involved to make an ecological product or human service. This method was invented by Odum (1971) to measure energy quality of natural and anthropogenic inputs (Pincetl et al., 2012; Patterson, 2014). During the 1970s, Odum used fossil fuel and coal equivalent as numeraire before adopting solar energy equivalent in 1980. It was not until 1983 that 'emergy' and 'transformity' terms started to be used by D. Scienceman and H.T. Odum in order not to confuse them with 'available energy' counterparts (Patterson, 2012).

Cities have been widely studied using emergy synthesis, with Chinese cities being the most widely studied (Amaral et al., 2016). Studies integrated this approach with carbon footprint to extend it to include ecosystem loss of emergy invested by nature, the human society to sustain households, as well as carbon flows resulting from household consumption (Yang et al., 2013; Ali et al., 2018). Other studies used emergy-based ecological footprint (ecological economic footprint) analysis to evaluate sustainable performance of urban social-ecological systems based socio-economic and social ecological pressures on energy (Pan et al., 2019), and water resources (C. Liu et al., 2021), or ecosystems (Zhang and Ma, 2021). Some studies also evaluated the socio-economic (labour force or investments) and ecological causes (biological, energy resource and food consumption) of pollutant emissions (Geng et al., 2014; He et al., 2016; Pan et al., 2019). Therefore, emergy-based ecological footprint approach has been widely used since 2005 to estimate social-ecological footprint of cities (Zhang et al., 2010; Amaral et al., 2016). However, only a single attempt has been made to integrate input-output analysis with emergy synthesis on national scale (USA) (Baral and Bakshi, 2010). In this study, however, footprint of final demand categories has not been estimated. Thus, the study did not encompass the whole supply chain, thereby, not allowing to trace downstream destinations of upstream sources.

Herein, emergy results from supply- and use-extensions for the city of Vienna were estimated based on previous investigations of Vienna's GHG emissions under production- and consumption-based perspectives (Schmid, 2020). Thus, the research question is formulated as follows: How to determine emergy costs of urban consumption, by combining industrial and systems ecology approaches? The answer to this overarching question requires the following sub-questions to be addressed: 1) How to develop supply-extended and use-extended emergy footprint models? 2) How to compare these model results with carbon footprint results using Vienna as case study?

To address this problem, social-ecological footprint framework integrating environmentally extended IOA and the emergy accounting approach is proposed. The rest of the article is organized as follows: Section 2 explains the methods and data used in this study. Section 3 discusses the results of this work. Finally, the article concludes in Section 4 and discusses important implications, limitations, and future recommendations based on this work.

2. Methods and data

The method section proceeds with an explanation how the supply and use extensions were derived, before summarizing how the emergy evaluation was conducted. Then, a summary is given how the monetary and physical IO tables and the final demand data for Vienna was developed. Finally, data sources were summarized. Fig. 1 illustrates the development of emergy-based carbon footprint model which we used to guide our research.

2.1. Derivation of supply and use extensions

The downscaled vector of total sectoral energy supply and use as supply-extension was used. The downscaled energy supply table contained information on natural inputs, wastes, and imports to source sectors. Information on the methodology used to downscale physical energy flow accounts can be found in Section 2.3.4. To construct the supply extension, several steps were necessary. Firstly, direct primary and secondary energy use were allocated to end-users (e.g., gasoline to households), government, investments, and exports. This corresponds to the own consumption of energy industries (Ue), final energy use and non-energy use of industrial sectors (u_{in}), transformation and transportation losses (L) as well as direct energy use of households (F_h). Then, transportation losses were also allocated to each energy consumers among 16 NACE sectors and final demand categories (i.e., households, exports) (Owen et al., 2017).

This method of allocation of transformation losses to final consumers was chosen because the allocation could be performed in just two steps (Owen et al., 2017; Wieland et al., 2019). Namely, Owen employed two-step allocation procedure, in which transformation losses were allocated directly to the consumption industries along the supply chain. This approach resulted in the removal of second order energy

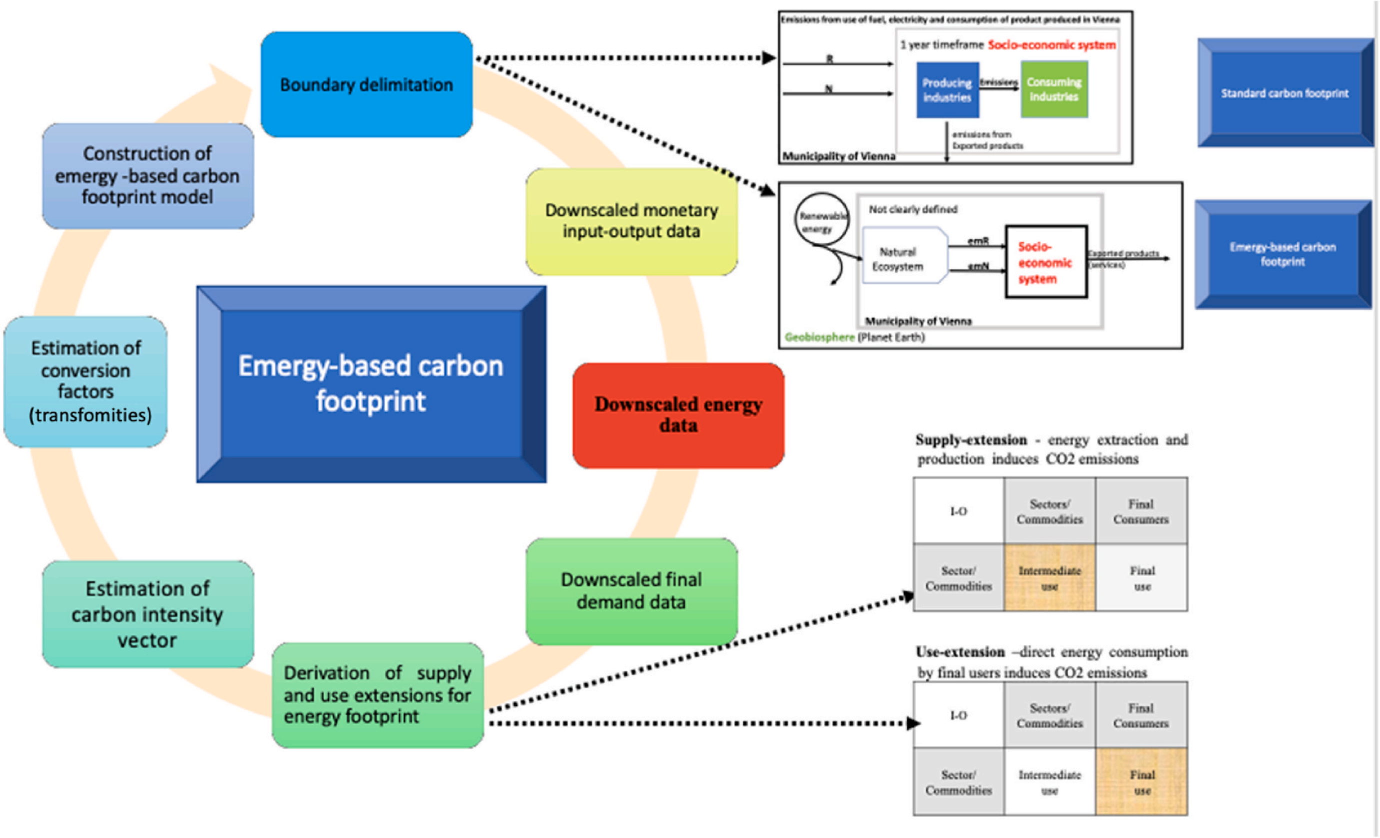

Fig. 1. The development of emergy-based carbon footprint framework. R and N represent renewable and non-renewable primary energy inputs, respectively, and emR and emN represent emergy-evaluated primary renewable and non-renewable inputs, respectively.

requirements from the allocation procedure. For example, final energy consumption (final energy and non-energy use) was not allocated to energy consuming industries but used as starting point to build use extension. The same balance between total energy supply and use was reached (both equal gross inland energy consumption). In Wieland's and our study, energy supply and use were balanced using Energy Accounts (EA).

After constructing energy extensions, the energy supply and use extension should be equal to ensure that the energy supply into Viennese economy conforms to the energy used by the economy; see Equation (1) (Wieland et al., 2019):

$$E + P + IM + S_{with} = (u_{in} + F_h + S_{add} + EX + L + O) \tag{1}$$

Where E-local (renewable and non-renewable energy products), P-wastes, IM-imported energy products, EX-exported energy producers, F_h-direct household consumption, S_{add}-addition to stock, L-transportation and transformation losses, O-energy industry own consumption, u_{in}-industries energy and non-energy use.

To estimate the carbon footprints, energy supply and use were converted into g CO_2 equivalents. Then, carbon intensity vector was estimated by dividing a carbon emission vector (C) obtained from Air Emission Accounts (Statistik Austria, 2015) by total energy industrial output in TJ obtained from physical energy flow accounts (Statistik Austria, 2015); see Equation (2).

$$e = C/G \tag{2}$$

where *e*-carbon-intensity vector, *C*- vector of carbon emission by economic activity (NACE classification), and *G*-total energy output by economic activity (NACE classification) in TJ.

This vector was aggregated to align with the total energy output of 16 industrial sectors we had after downscaling was performed.

Then, this carbon-intensity vector was multiplied by energy extension data (Pe) to arrive at carbon-evaluated version of environmental extension (Pc); see Equation (2):

$$P_C = e \times Pe \tag{3}$$

Final energy demand was then converted to CO_2 equivalents using the same formula since Air Emission Accounts contain the data on CO_2 emissions from households by economic activity in NACE format. However, the households' emissions are reported as a single total number. Therefore, the same proportions of carbon emissions to households as for economic activities were assumed. Thus, the biggest uncertainty of the model that affects the results obtained from standard environmental extensions (Owen et al., 2017; Wieland et al., 2019) stems from the use of national carbon intensity vector and from the assumption of equal share of emissions from households as from economic activities. The carbon-evaluated version of environmental extension is presented below; see Equation (4):

$$F_C = e \times F_{use} \tag{4}$$

Using the carbon-evaluated version of environmental extension and fuel use in households allowed authors of this study to estimate carbon footprints using supply and use extension design. Firstly, direct carbon requirements matrix was estimated; see Equation (5):

$$q = Pc \times x^{-1} \tag{5}$$

where q refers to carbon emitted in direct energy consumption (environmental extension) per € of total purchase, Pc represents the carbon-evaluated environmental extension, and x refers to the total monetary industrial output in **€.**

A single region IO model following commodity-by-industry approach (Miller and Blair, 2009) was constructed following approach by Wieland to derive energy supply and use extensions. The only difference was that he constructed this model using Austrian monetary supply-use tables (MSUTs). In this work, on the other hand, Viennese monetary supply-use tables were used. An industry-by-commodity total requirement matrix is presented below; Equation (6):

$$L = D \times (I - BD)-^{1} \tag{6}$$

where D, is the matrix of commodity output proportions, B-the commodity-by-industry coefficient matrix, and $(I-BD)-^{1}$ is commodity-by-commodity total requirements matrix derived from MSUT tables on basic prices (OECD Statistics, 2015a).

BD carries the same meaning as input requirements matrix (A), the matrix of technical coefficients in the traditional industry-by-industry-approach (Miller and Blair, 2009; Wieland et al., 2019). Therefore, matrices of commodity-by-commodity total requirements and industry-by-commodity total requirements are equivalent to the Leontief Inverse $(I-A)-^{1}$. Then, multiplying direct carbon requirements matrix by commodity-by-commodity total requirements $(I-BD)-^{1}$ the supply -extension can be derived; see Equation (7):

$$Q_{is} = q \times D(I - BD)\ -^{1} \times F_m \tag{7}$$

where Q_{is} represents carbon footprint of final products.

In this way, the standard supply extension was derived. In addition, by summing along the rows of matrix Q_{is}, the author calculated carbon emitted from energy consumed by source industry (Owen et al., 2017).

To build standard use-extension, we added emissions from direct energy consumption by final demand (Viennese households, exports, and stock) to Equation (4); see Equation (8):

$$Q_{iu} = Pc \times D(I - BD)^{-1} \times F_m + Fe \tag{8}$$

where Q_{mu} represents carbon footprint of final products. Here, author also calculated the emission from energy consumed by source industry following the same principle (Owen et al., 2017).

2.2. *Derivation of emergy-based supply and use extensions*

To build emergy-based supply and use -extension this study carried out the estimation of transformities (energy quality factors) based on carbon network data. The transformities were estimated using the matrix inversion method. The vector of transformities in this method is estimated by multiplying solar energy inputs into industrial sectors by total direct and indirect economic requirements of industrial sectors (Patterson, 2012, 2014). In this study, on the other hand, solar energy inputs were converted into carbon equivalents by through appropriate conversion factors, namely 50 g of CO_2 equivalent per kilowatt hour generated by solar panels (Bilek et al., 2008). The mean value of life-cycle GHG emission estimates generated by solar panels from these two data sources was used assuming 50% of electricity generated from PV technologies during their lifecycle (Bilek et al., 2008). Therefore, it was assumed that around 50% of electricity generation capacity by PV technologies is used in Vienna.

The matrix inversion approach is presented below; Equation (9).

$$p = g(U - V)^{-1} \tag{9}$$

where “U” is the Vienna’s monetary supply matrix (m × n), “V” is the Vienna’s monetary use matrix (m × n), “g” is the numeraire vector (1 × n) of indirect emissions from manufacturing the solar panels used by industries to “harvest” solar energy, and “p” is the transformity vector (1 × m).

Transformities in this study are the same for both the supply and use extensions. The estimation of use-based transformities required the disaggregation of single value of solar energy input to final demand by final demand categories and then, by end-product to arrive at direct solar energy input from ecosystems used for generation of each 64 end-product of MSUT. Only after this matrix of total embodied solar energy reequipments (transformities of product) can be estimated.

The emergy-based supply extension should contain emergy directly and indirectly demanded by intermediate industries. Firstly, the direct emergy requirement vector (emergy intensity) that shows emergy implied into direct energy consumption per € of total purchase was obtained. In simple terms this vector reflects direct environmental burden (direct emergy-based carbon emission per € of total purchase). This intensity was estimated from Equation (10).

$$f_d = (\varepsilon \times P_c) \wedge x^{-1} \tag{10}$$

The next step was to derive cumulative (direct and indirect) emergy consumption per € of purchase (embodied solar energy intensity). This matrix was obtained by multiplying direct emergy intensity by Leontief inverse in product and industry terms; see Equation (11):

$$f_c = (\varepsilon\ \times P_e) \wedge x^{-1}(I - A)^{-1} \tag{11}$$

where ε-is is the transformity vector (1 × m) based on “carbon network data”, Pe is n × 1 carbon-evaluated environmental extension, and $(I-A)^{-1}$ is Leontief inverse estimated as commodity-by-commodity total requirements and industry-by-commodity total requirements matrix.

The multiplication of cumulative environmental burden per € of purchase (f_c) by the vector of total monetary consumption by final demand categories F_m yielded emergy-evaluated carbon footprint, which follows supply extension design; see Equation (12):

$$F_s = f_d \times (I - A)^{-}1 \times F_m \tag{12}$$

To archive this transition vector Fe (emissions from direct fuel use by Viennese households) needed to be translated to the embodied solar energy equivalent through its pre-multiplication by the transformity vector (ε-) based on “carbon network data”; see Equation (13):

$$F_{use} = \varepsilon \times Fe \tag{13}$$

where refers F_{use} refers to the solar energy implied in carbon emissions induced by the direct fuel use in households (i.e., electricity and heating).

Then, by adding F_{use} to the emergy-based footprint estimated using supply-extension design, emergy-based use-extension design was derived in Equation (14):

$$F_u = f_d \times (I - A)^{-1} \times F_m + F_{use} \tag{14}$$

In other words, the study determined environmental cost of total CO2 emissions by a Vienna socio-economic system (F_u). This total environmental cost (environmental support) can be viewed as the sum of the environmental costs associated with production CO2 emissions and the cost associated with final demand CO2 emissions.

2.3. *Development of monetary and physical input-output and the final demand data for Vienna*

2.3.1. *The monetary supply and use tables*

For intermediate monetary consumption and final monetary demand categories, Austria’s national monetary supply and use data for year 2015 was downscaled to arrive at Vienna-specific data. Austria’s national monetary use and supply data were regionalized using a supply-side, commodity-by-industry input-output model, also known as the “Ghosh model” and location quotient approach (measure of industrial concentration). Firstly, a direct-output coefficients matrix was obtained by dividing the corresponding row of national monetary use table by the corresponding row of gross commodity output. This matrix denotes a national supply side commodity by industry model. Then, a national monetary supply and use commodity-by-industry model were downscaled based on value added data (earnings generated by production of goods and services) to estimate the share of commodity inflows to the

Vienna region using a simple location quotient (LQ) technique (Liu and Vilain, 2004). Here, aggregation of industrial sectors in the Austrian supply and use tables needed to be performed to match aggregated gross value-added data by NACE industry (Statistik AUSTRIA, 2015e).

To construct regional monetary supply and use tables, the total regional commodity supply (or use) in monetary was a prerequisite. A vector was obtained through a Ghosh "commodity-by-industry model" thoroughly described by Shao and Miller (1990, page 8). The Ghosh commodity-by-industry total requirement matrix and value added were used to estimate this vector of total commodity output. Finally, multiplying the regional proportions derived from monetary supply and use tables by the vector of total commodity output (total supply or use) yielded Vienna's regional monetary supply and use tables (Miller and Blair, 2009).

2.3.2. *Monetary household consumption data*

The next step was an estimation of urban monetary household consumption. Consumption data for Viennese households, containing detailed expenditure data on goods and services, were taken from the household budget survey 2009/2010 (AUSTRIA, 2013), which was compiled and prepared for IO analysis in previous work (Smetschka et al., 2019). This source rather than a more recent survey was used because such data are not openly accessible free of cost. To estimate SRIO-based monetary vector of household consumption, the study linked the household budget survey, which is compiled using the COICOP nomenclature to SRIO, which is based on CPA 2002 classification. Therefore, a concordance matrix between COICOP and CPA2002 classifications from previous work was used (Smetschka et al., 2019). The total regional household consumption was reallocated from the household budget survey to the CPA classification. The resulting vector represents the final demand of household consumption (F_h).

2.3.3. *Monetary governmental consumption and capital formation for Vienna*

To estimate the Viennese government consumption and capital formation, monetary final demand vectors from national accounts were used as a starting point (Austria 2015). Two approaches to overcome data constraints were combined because city-scale data for these two final demand categories were not available (Millward-Hopkins et al., 2017). First, like previous studies, researcher adopted an approach to downscale these two final demand categories, which assumes that every Austrian citizen benefits from government expenditures in the same way. Thus, the downscaled government consumption from national to local level on an equal per capita basis (Minx et al., 2013; Millward-Hopkins et al., 2017; Schmid, 2020). Second, the alternative estimate for local government consumption was collected from annual balance sheets of government spending contained in Statistical Yearbook of the City of Vienna for the year 2016 ("Statistisches Jahrbuch der Stadt Wien, 2016") (MA 23 2016), which however does not contain all federal/national spending occurring in Vienna. Consequently, the mean value of these two data sources (per capita downscale of national final demand vector and balance sheet of the Vienna's government expenses) was used to estimate government consumption, considering statistical uncertainty of data and questionable assumption that every Austrian citizen benefit from government expenditures in the same way. The same downscaling approach was also applied to fixed capital formation due to the lack of the respective statistical data (Schmid, 2020). Summing across categories household consumption, government consumption, capital formation, and exports yielded final demand vector F_m.

2.3.4. *The physical energy flow accounts and physical extension data*

For energy extension and final energy demand of households, physical energy flow accounts (PEFA) were downscaled. For this purpose, scientists needed to align the more detailed PEFA classification (88 sectors) with MSUT classification (64 sectors). The concordance table developed by Wieland et al. (2019) was used for this purpose. The simple LQ (location quotient) approach was used to determine the shares of production by NACE industry in the region, in order to downscale physical energy flow accounts (physical energy use and supply tables). To calculate the footprint's physical extension and intermediate monetary consumption should have the same number of NACE industries. Therefore, Wieland et al. (2019) aggregated physical energy supply data and use until 16 industries remained. Total energy and use by product were taken from Vienna energy balances (VEB, 2015). The total regional energy supply and use by product (total commodity output in TJ) were obtained from the regional energy balances (VEB, 2015). The author used this total supply (or use) as energy extension in this study. The regional energy supply and use tables were then built using the supply side model (Ghosh "commodity by industry model") to estimate the proportion of commodities used by various industries in Austria. Then, multiplication of regional proportions derived from energy supply and use tables by the by total energy supply (or use) from Vienna energy balances (VEB, 2015) yielded Vienna's regional energy supply and use tables (Miller and Blair, 2009). Then, energy supply and use data was used as a physical extension. This physical extension used in this study represents value added by each industrial sector value added from energy extraction and production by each industrial sector.

2.3.5. *Final energy demand data*

Renewable energy sources and some of energy products used in households were taken from Vienna's regional energy balances (VEB, 2015) as it already contains data on total consumption of households, energy exports, and stocks. The data contained in energy balances were based on the territory principle: all energy commodities used by residents and non-residents in Vienna are accounted for. To calculate the other part of direct energy use vector by households, the annual total expenditure of gasoline, diesel, heating oil, natural gas, and electricity direct energy consumption of households as well as national average energy prices for years 2014/2015 (Statistik Austria, 2015) was a prerequisite. The average energy price for gasoline was further estimated using the Austrian annual total spending on each fuel ("Austria- Petrol sales till 2019 for 2015 | Statista," 2020) to quantify the total gasoline consumption of final consumers in physical units. Moreover, the energy content of total gasoline used by household using calorific values of each fuel (Smetschka et al., 2019). Then, data on energy exports and stocks by product were also obtained using regional energy balances (VEB, 2015). To match the data obtained from EB with the data on product classification reported in PEFA (39 energy products) data were aggregated by summing the products categories from EB. Some data in energy balances were not available (i.e., coal-based energy is not used in energy conversion chain anymore) or missing to differences between Vienna's energy structure and national one. Finally, summing across direct energy exports, stocks and households' energy consumption categories yielded vector of direct energy consumption by final demand (F_e). This vector was needed to derive use-extension from supply-based one.

2.3.6. *Air Emission Accounts*

For carbon intensity vector, carbon emission vector by economic activity was obtained from Air Emission Accounts (OECD Statistics, 2015b). The procedure used to estimate this vector is presented in Section 2.1.

2.4. *Overview on all data sources*

For this study, data on energy extension, final energy demand of households, intermediate monetary consumption, monetary as well as final monetary demand categories associated with Vienna municipality was used. In addition, carbon intensity vector was used. The summary of sources used to build emergy-based carbon footprint model is presented in Table 1.

Table 1

Overview of data sources for emergy-based carbon footprint model of Vienna.

	Temporal coverage	Population Covered	Sample size	Number of categories	Source
Austrian household budget survey- households inside Vienna	04/2009–05/2010	Vienna's households	1246 households, Sample	53 categories, derived based COICOP classification	Statistics Austria −2013
Vienna physical supply and use tables- downscale of national data	2015	Austrian territory	Complete representation of national economy and its energy exchanges with environment 88 sectors	NACE*88	Statistics Austria (2015a)
Vienna monetary supply and use tables- downscale of national data	2015	Austrian territory	Complete representation of national economy 64 sectors	CPA*64	Statistics Austria (2015b)
Vienna government consumption vector – downscale of national data	2015	Austrian territory	Complete representation of national economy 64 sectors	CPA*64	Statistics Austria (2015b)
Vienna gross fixed capital estimation vector– downscale of national data	2015	Austrian territory	Complete representation of national economy 64 sectors	CPA*64	Statistics Austria (2015b)
Vienna's energy balances-use of fuels in Household	2015	Vienna Municipality	Complete energy use in regional economy 88 energy sources and 24 final energy users	IEA*88	Statistics Austria (2015c)
Austrian Air Emission Accounts-	2015	Austrian territory	Complete representation of national economy 64 sectors (industries and households)	NACE*64	OECD Statistics −2015

3. Results

This section discusses and compares the results derived for emergy footprints based on supply- and use-extended SRIO models with their carbon counterparts, for an industry-by-commodity model. Emergy and carbon consumption-based accounts (CBA) by final products, and final demand categories by final products were aggregated by source industry categories to determine if there any considerable differences in the carbon footprints of final demand categories. Then, emergy and carbon footprints by source industry were assessed if any empirical differences in the energy consumed to satisfy Vienna consumption by source industry stems from emergy and carbon evaluation methods used in footprint analysis.

3.1. Total emergy footprints by product groups in supply- and use-extensions

The footprint ranking changed dramatically when carbon footprint is evaluated in emergy terms (see Fig. 2). The products of agriculture, hunting and related services (A01) have a highest difference, with emergy footprint (20.06%) exceeding carbon footprint (3.58%) by 16.5% for this product. This product changed its rank from 2nd to 1st, reflecting the largest emergy footprint of agricultural products in the emergy extensions. The footprint with the second largest difference is the electricity, gas, steam and air-conditioning (D + E) where emergy footprint (9.49%) exceeds carbon footprint (0.81%) by 8.7%. The rank of this product grown from 17th place to 2nd place. This product follows by public administration and defence, social security services (O), which climbs from 9th to 4th place, overshooting carbon footprint by 3.5 %. In general, it was found that products of extractive industries and services

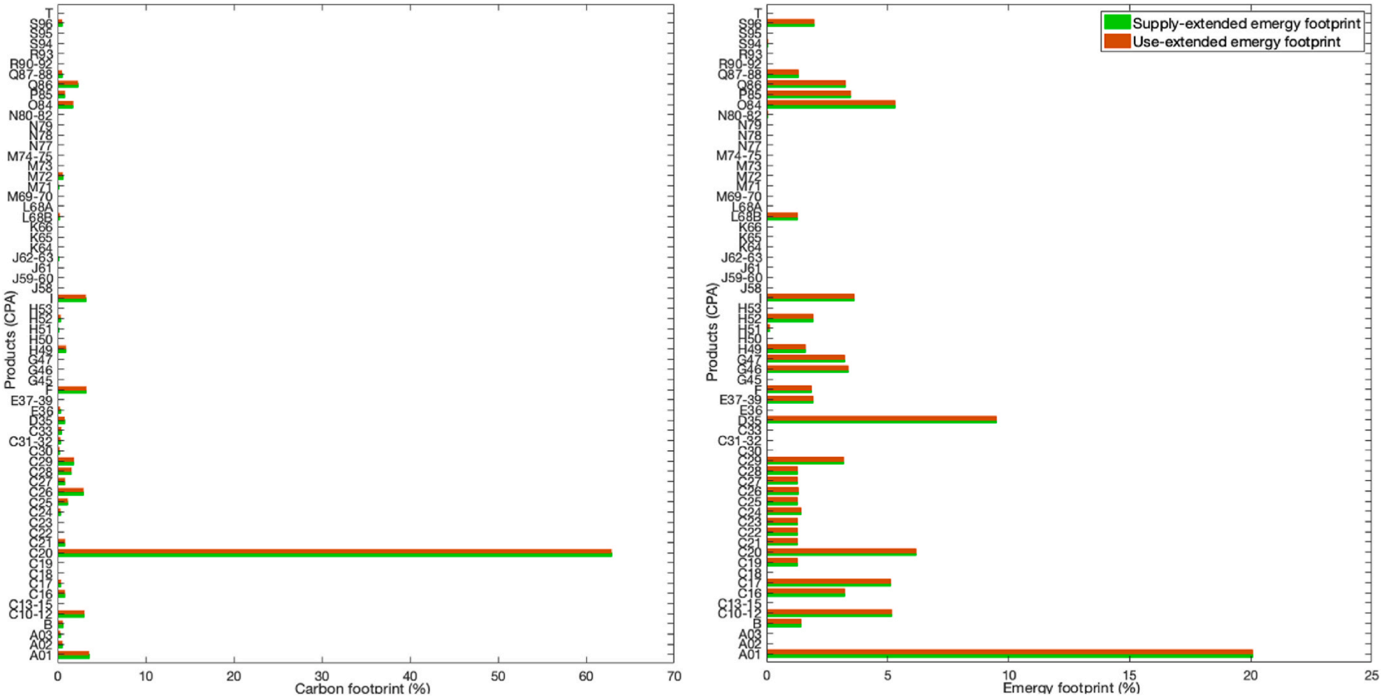

Fig. 2. Carbon footprints (left) and emergy-based carbon footprints (right) for final goods and services, estimated from a commodity-by-commodity IO model, showing the difference between the supply-extended (green) and the use-extended model (red), for Vienna 2015. The complete carbon footprint and emergy-based carbon footprint details are found in the supporting information "S2 in Table S-A and S-B, respectively. Product categories follow CPA classification. Names, abbreviations of products are presented in Tables S–C in the supporting information. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

became larger in magnitude compared to the manufacturing products when emergy footprinting is chosen. Fig. 2 shows that among services the highest increase is found in *public administration and defence services, social security services* (O84), education services (P85), human health services (Q 86) 6.14 E+07 Tera seJ, 3.84 E+07 Tera seJ, and 3.84 E+07 Tera seJ, respectively. The product that deviates more strongly from this pattern is chemical *and chemical products* (C20). Here, the emergy footprint ranks 3rd position, moving down from 1st place in the carbon footprint ranking. This footprint is also characterized by the largest difference with carbon footprint (62.9%) exceeding emergy footprint (6.2%) by 56.7% for this product.

Fig. 3 shows that carbon supply-extended and use-extended models vary depending on whether an emergy-evaluated or carbon-evaluated approach is chosen. The most pronounced difference among supply-extended and use-extended models was found in the products of agriculture, hunting, and related services (A01), printing and recording services (C18), and fabricated metal products, except machinery and equipment (C25), where use-extension exceeds supply-extension footprint by 4.9%. Publishing services and motion picture, video and television programme production services, sound recording (code J58), and music publishing; programming and broadcasting services (code J59-60) also differ the highest among carbon supply and use extensions, with supply-extension exceeding use extension footprint by 4.9%. In general, it was found that services differ by a larger extent when carbon supply-extended design is chosen as opposed to products of extractive and manufacturing industries having a larger difference when use-extension is chosen. Fig. 3 shows that emergy supply-extended and use-extended model distributes emergy to final products according to a more homogenous pattern. The products of agriculture, hunting, and related services (A01) vary the most with supply-extension exceeding use extension footprint by 21.5%. This product is followed by electricity, gas, steam and air-conditioning (code D35) where use extension exceeds supply extension footprint by 15%. In general, the supply and use extended model when evaluated in emergy terms allocates more emergy to services and extractive industries at the expense of manufacturing products. The more emergy was allocated to services when supply extension is used as opposed to extractive industries when use-extended design was chosen. The product that deviates more strongly from this pattern is publishing services (J58) and motion picture, video and television programme production services, sound recording and music publishing; programming and broadcasting service (J59-60). Here, the use extension exceeds supply-extension footprint by 14.9%.

3.2. Emergy footprints by final demand categories

This section presents results of the carbon and emergy-based footprint of final products disaggregated by final demand categories.

The strongest divergence between emergy evaluated and carbon evaluated models, in absolute terms, is found for footprints of households (Fig. 4). The household's footprint estimated using emergy-evaluated IO model exceeded its counterpart in the carbon evaluated IO model by 45%. This category ranks 1st, reflecting its largest emergy footprint in the emergy extensions. Exports followed as next strongest divergence with a 37% difference between emergy and carbon extensions. The variation in the footprint of other final demand can be attributed foremost to differences in the footprint of government consumption, with 50% when using emergy-evaluated IO model and 21% when applying carbon-evaluated IO model. The lowest divergence in relative terms was found for the footprint of capital formation with 50% and 41% divergence when using emergy and carbon evaluation

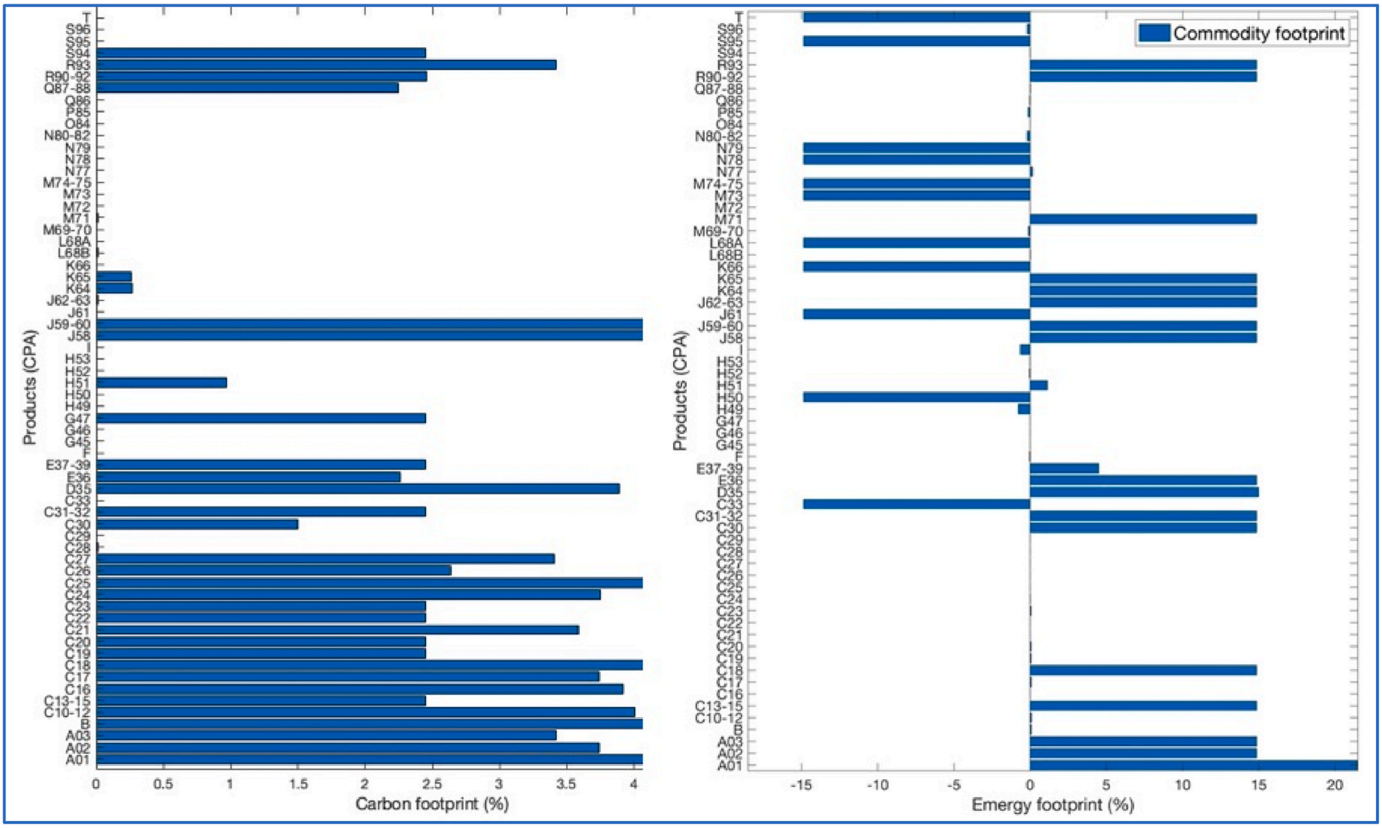

Fig. 3. Differences between the supply-extended and the use-extended model based on carbon footprint (left) and emergy footprint for final goods and services (right), estimated from a commodity-by-commodity IO model for Vienna 2015. The complete carbon footprint and emergy-based carbon footprint details are found in the supporting information "S2 in Table S-A and S-B, respectively. Product categories follow CPA classification. Names, abbreviations of products are presented in Tables S–C in the supporting information.

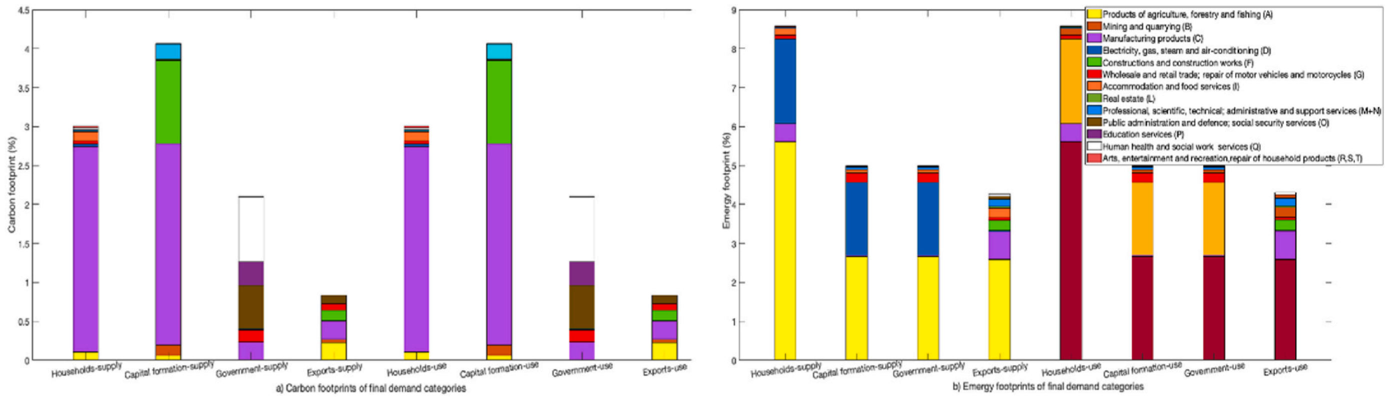

Fig. 4. Carbon and emergy-based carbon footprints of final demand categories broken down by final products and aggregated by intermediate sector categories, 2015; Carbon footprints are shown in the left bar (a) while emergy-based carbon footprints are shown in the right bar(b). In the both bars the total footprints of products by final demand categories based on supply-extended model is shown on the left and footprints based on use-extended model on the right. The initial data are found in Tables S–E in the supporting information "S2". Note: The households-supply and households-use bars were divided by 10 to display all bars in a common scale.

methods, respectively.

The relatively strong divergence in the household footprints led to different rankings of the footprints of the government consumption category in emergy extension. When applying carbon evaluation Household consumption occupied the first place. This category was followed by Capital formation government consumption, and exports. When applying emergy-extension households and export categories retained their ranks., while both capital formation and government consumption shared the second position. Although both the capital formation and government consumption were equally sharing second place, the relative differences between emergy-evaluated government consumption and carbon counterpart were larger than the relative differences of capital formation: 29% and 9%, respectively. This could be related to the higher indirect solar energy cost required to produce energy (i.e., electricity) directly consumed by government, including the nature of the source (i.e., its ability to produce work), distance to the source to the final user and the number of intermediate industries consuming the solar energy from the same source as capital formation.

When researcher compared results obtained emergy (and carbon) supply and use extensions the differences were far less pronounced. The highest difference was found in Export category, where emergy-evaluated use-extension exceeds emergy-evaluated supply-extension footprint by 1.34%. In comparison, emergy-evaluated household footprint estimated using use-extension exceeds its supply-extended counterpart by only 0.2%. The ranking of the footprints of the final demand categories is therefore sensitive to evaluation method used to estimate them.

3.3. *Emergy footprints from consumption by source industry*

The footprint ranking changed dramatically when carbon footprint was evaluated in emergy terms (see Fig. 5). The highest difference was found Manufacturing (C), where emergy-evaluated footprint exceeds carbon-evaluated footprint by 45%. Highlighting the role of this sector as key source. This sector followed by Agriculture, forestry, fishing (A) with emergy-evaluated footprint exceeding carbon-evaluated one by 19% and retained 1st position when industrial footprints were estimated using emergy-evaluated footprint. This sector also retained its second position in the both emergy and carbon-evaluated IO models. The third by magnitude divergence was detected in *electricity, gas, water supply,*

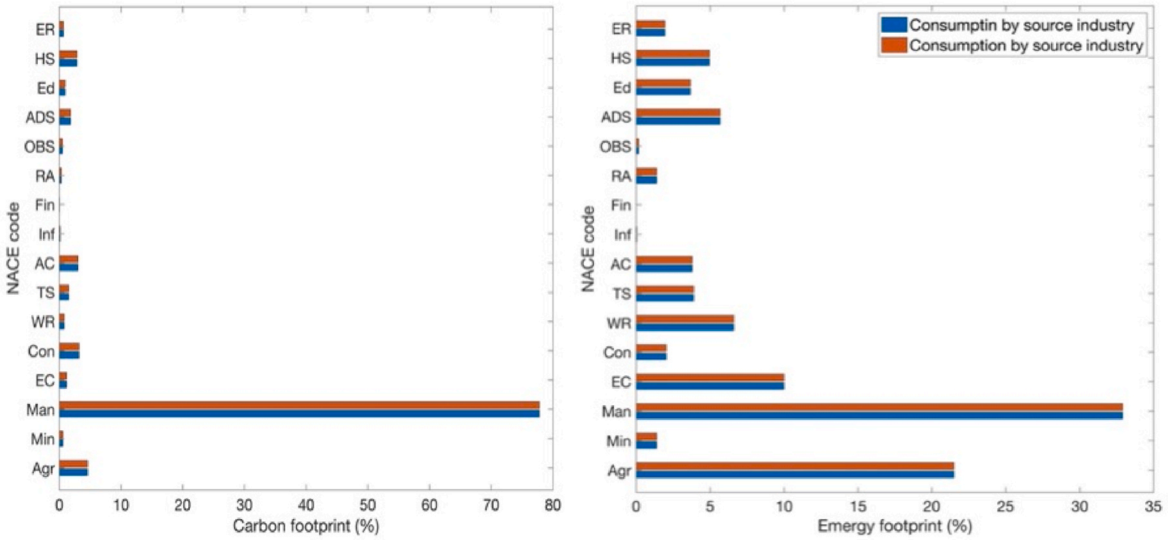

Fig. 5. Carbon consumption (a) and emergy consumption (b) by source industry estimated from the supply-extended (red) and the use-extended model (blue) for Vienna 2015. The complete carbon and emergy footprint details are found in the supporting information "S2" in Table S-G and S-H, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

sewerage, waste, and remediation services, which moved up ranks from the 6th to 3rd position when estimations are done based on the emergy-evaluated footprint model. This emergy-based and carbon footprint for this sector differ by 8%. In general, footprints of extractive and productive industries are larger than services. The only exceptions were *electricity, gas, water supply, sewerage, waste, and remediation services* (D + E) and Mining and quarrying sectors (B). Mining and quarrying (B) were three times lower in comparison to services, while footprint of *electricity, gas, water supply, sewerage, waste, and remediation services* (D + E) exceed services by few percent.

Regarding the differences between carbon and emergy evaluated extensions for source sectors, Manufacturing (C) deviated the most, with carbon-evaluated use extension exceeding carbon-evaluated supply-extension footprint by 39% (Fig. 6). The second and third largest divergence was attributed to Wholesale and retail trade; repair of motor vehicles and motorcycles (G) and Human health and social work services (Q): 10 and 9%, respectively. The other sector with considerable difference (8%) was Transportation and storage (H). In general, the largest difference in Manufacturing (C) compared to service sectors can be observed. The differences between emergy-evaluated footprints were less pronounced, as can be seen in Fig. 5. The difference of Agriculture, forestry, and fishing (A) is only 2%, while both the Transportation and storage (TS) and Manufacturing (C) differ by a smallest value (1%). The largest variation between emergy-evaluated extensions was found in *electricity, gas, water supply, sewerage, waste and remediation services* (D + E), where use-extension exceeds supply-extension footprint by 98%. This huge gap in *electricity, gas, water supply, sewerage, waste and remediation services* (D + E) can only be attributed to the indirect solar energy implied in the direct energy consumption of households (i.e., electricity and heat demanded by households).

4. Discussion

The comparison between emergy and carbon footprints revealed that footprints based on the single region input-output (SRIO) model of Vienna Region built from downscaled Austrian monetary supply and use tables (Miller and Blair, 2009) are sensitive to the method applied to estimate them, leading to variations in rankings of the footprints of the final products categories. This is in line with previous research for other countries and cases (Baral and Bakshi, 2010; Li et al., 2018; Park et al., 2016; Sun and An, 2018). In this section, the benefits and limitations derived from the combined approach, which integrates emergy synthesis with supply and use extended energy-based carbon footprint models are discussed in the following order: major findings, conceptual implications and limitations, complementarity of emergy-evaluated models.

4.1. Methodological implications

The comparison of results between emergy-evaluated and carbon footprints of final products showed that products of extractive and service industries were larger when applying emergy-evaluated footprint as opposed to the manufacturing products being larger when applying the carbon footprints. There are two main reasons behind these differences. First, when emergy accounting is applied by itself, services are always higher than energy products since they are used indirectly to support infrastructures for any production process to occur from the larger scale of economy (Franzese et al., 2009; Russo et al., 2014; Qu et al., 2017; Huang et al., 2018), to national input-output analysis (Baral and Bakshi, 2010) and to natural ecosystems, where services have the highest transformities (Campbell and Brown, 2012; Z. Liu et al., 2021). Second, products with high share of renewable energies are characterized by lower environmental work required to produce them. Therefore, the question could be posed whether the large share of importing non-local renewable energy products is the reason for footprints of products of extractive industries being larger than for services (i.e., products of agriculture, hunting, and related services).

When footprints are displayed by source sector, sectors engaged in energy extraction and production industries (i.e., Manufacturing and Agriculture, forestry, and fishing) usually have larger footprints than other sectors. However, this was not the case for electricity*, gas, water supply, sewerage, waste and remediation activities* (D + E) and Mining and quarrying sector (B) despite their crucial role as commercial energy producers in the economy. From the statistical data used, it was clear that territorial urban production from these sectors was too small to satisfy final demand of Viennese consumers. The majority of mining ores and energy production facilities as of 2015 are located at distance from Vienna municipality and are in decline in terms of production based on temporal trend of mining production from 2009 to 2019 (Koerbler.com, 2013; Mining and quarrying," 2019; MINLEX - Austria Country Report,

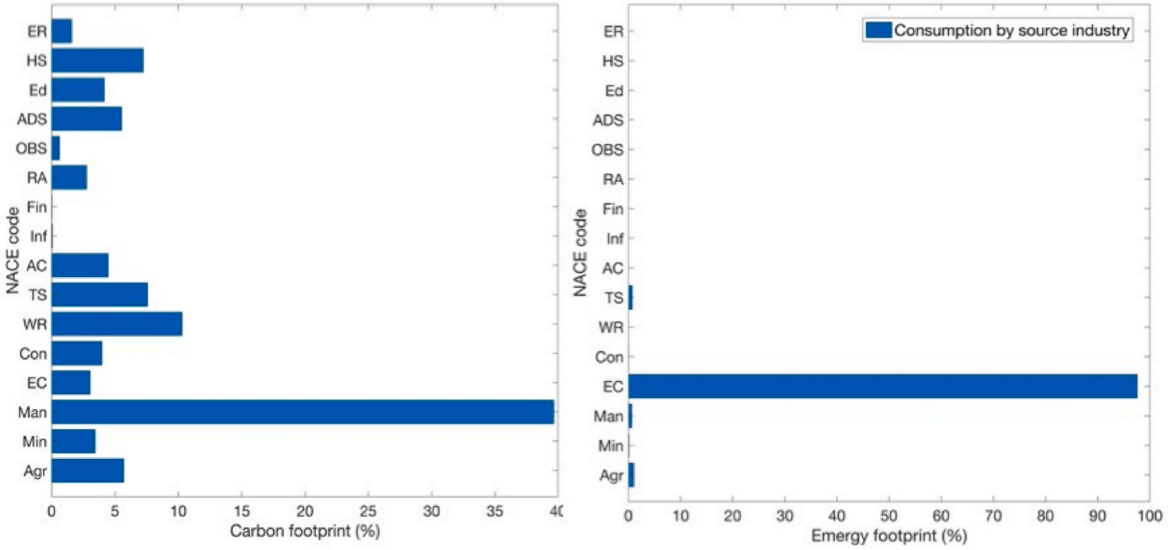

Fig. 6. Differences between the supply-extended and the use-extended model-based carbon footprint (left) and emergy footprint for source sectors (right), estimated from a commodity-by-commodity IO model for Vienna 2015. The complete carbon footprint and emergy-based carbon footprint details are found in the supporting information "S2 in Table S-A and S-B, respectively. Product categories follow CPA classification. Names, abbreviations of products are presented in Tables S–C in the supporting information.

2017). The alternative form of mining (urban mining) based on the recovery of raw materials (electronic waste) is considered a viable alternative for the future (Brunner, 2011). In case of electricity, the Vienna Government is more concerned with the improvement of share of renewable energies in the energy supply chain by equipping building with photovoltaic panels and renewable heating systems (Austria, 2050; Ardak et al., 2020; City of Vienna, 2019). The disaggregation of end-products by final demand categories showed that Exports category in emergy-evaluated extension design had a small difference compared to the supply-extended design. It is obvious that export flows of energy products are also integral, leading to the question about magnitude of direct energy exports. The export of agricultural and energy products contributed the most to the small differences in the category of Exports also pointing to the small direct energy export of biofuels including environmental costs of biofuel production, not of local origin.

4.2. *Conceptual implications*

The system boundary of the emergy-evaluated extension design compared with the energy one is completely different. The emergy boundary is global and inter-temporal, as it covers all solar energy inputs originally captured in ecological processes during earth's entire history, as it is directly and indirectly embodied in fossil fuels available nowadays. According to this approach, an urban socio-economic system is embedded in global environmental support system (biosphere). In the urban IO analysis, the boundary covers the city and only one year; specifically, the fossil fuels and other energy carriers as utilized within the city, within one year (Dong et al., 2016; Schmid, 2020). These boundaries translate into supply and use extension design via energy quality factors (transformities), making an adoption of new allocation assumptions necessary. While supply extension design applied by Owen et al. (2017) and Wieland et al. (2019) employed straightforward allocation of environmental burden by economic value used in traditional LCA, Owen's allocation assumption for use-extended design differed from that of Wieland. Wieland employed three-step allocation, while Owen employed two-step allocation procedure, in which transformation losses are allocated directly to the consumption industries along the supply chain. Wieland, on the other hand, allocated transformation losses to the energy producers (Wieland et al., 2019). Owen's approach resulted in the removal of second order energy requirements (i.e., energy for processing) from the allocation procedure. For example, final energy consumption (final energy and non-energy use) was not allocated to energy consuming industries but used as starting point to build use extension. In the end, the same balance between total energy supply and use was reached (both equal gross inland energy consumption). In Wieland's and our study, energy supply and use were balanced using Energy Accounts (EA). Which extension is more appropriate for when emissions are accounting using territory versus residence principle, and whether one of these allocation assumptions could lead to double counting, should be addressed in future studies.

The other difference that should be noted is that direct energy consumption by final demand categories (households, exports, stocks) became integral (direct and indirect) when transformities are applied to the final demand. This can lead to the great variation between the results obtained from standard and emergy-evaluated use extension design (i.e., direct, and indirect solar energy implied in electricity use is allocated to households). It significantly affects the results since energy use of fuels allocated to final demand categories is not of first order anymore. It introduces the question of inconsistency of the allocation procedure used in standard use-extension design for emergy-evaluated use-extension design. When transformities are applied to the environmental extension there is no effect on the allocation procedure used to build supply-extension. However, natural inputs and wastes and imports became also integral (direct and indirect). For example, production of natural gas not only includes extraction of natural gas from shale formations but also incorporates biomass production under heat and pressure in Earth's crust. The question of whether standard supply allocation is appropriate for emergy-evaluated supply extension needs to be checked. For example, the solar energy inputs can be allocated to the producer (agriculture) and, then be distributed to other industries based on monetary payments. Therefore, emergy-evaluated extension design questioning the allocation procedures adopted for supply-extension design.

4.3. *Interpreting disagreement from a conceptual point of view*

Following the stated differences between emergy-evaluated and standard energy extension design, it is noted that both extensions are conceptually different: emergy-based design is used to assess depletion of natural resources (donor side perspective) while standard design is more concerned with footprint of production and consumption activities in cities (user side perspective). The emergy footprint gives more weight to the environmental dimension and thus reflecting the global environmental processes as drivers behind energy supply. Therefore, environmental support to the production of energy generates the same sale of energy and generation of revenue. Particularly, both the energy production and monetary consumption of final users (i.e., households) in the city stimulate renewable energy supply from global environmental system. The emergy-use design was more focused on direct and indirect consumption of production processes and consumption activities and put more emphasize on socio-economic dimension and reflects the final users as drivers behind energy use, which exploit global environmental system. In this case, global environmental support to final energy users generates direct and indirect energy consumption. Therefore, this extension ignored the monetary dimension, namely production factors such as labour and services (indirect monetary contribution such as investments) to production and consumption activities. In other words, this extension better captured direct emergy consumption and energy quality of direct energy products sectors in urban economy, while the first extension better reflect indirect monetary support and energy quality of services. However, the emergy-evaluated extension was better suited to evaluate total environmental pressure of each energy user. Thus, results of both extensions provide completely different type of information despite the both being based on matrix algebra and input-output analysis.

4.4. *Limitations of emergy footprint accounting*

Homogeneity price assumptions not only influence the divergence between energy supply and use extension (Wieland et al., 2019) but also have a different impact on emergy-evaluated extension. This impact had a different meaning compared to the standard supply and use extension due to conceptual differences stated in Chapter 4.3. Emergy-evaluated supply extension assumes economy-wide average energy prices faced by industries and final consumers (Guevara and Domingos, 2017; Wieland et al., 2019). It is crucial for complete accounting of direct ecological (emergy) and indirect socio-economic flows (monetary) to have an information on the prices faced by industries in the MIOT since only actual (direct) energy input from environment and monetary flows among the sectors of urban economy can be converted via transformities to solar energy equivalent flows. In addition, according to the emergy analysis, money is paid in exchange for imported energy products. Therefore, payments for energy products from intermediary sectors should reflect actual energy prices faced by them. In this regard, the exact and approximate hybrid-unit input-output models developed by Guevara and Domingos (2017) based on the both average prices faced by final consumers and economy-wide average energy prices, respectively, are more feasible for integration with emergy approach since the prices faced by intermediary sectors could be estimated using both the models.

The other limitation of the current study was that services that is invested from the larger scale of economy (i.e., national) used in Emergy Synthesis reflect monetary imports category of final demand (Raugei et al., 2014; Schmid, 2020). This led to underestimating investments provided to the Viennese production and consumption activities and the work of environment required to sustain them (Kamp et al., 2016). The consumption-based accounting approach includes indirect emissions from investments from outside of the municipality) (Harris et al., 2020; Schmid, 2020; Lenk et al., 2021). Therefore, to estimate completely the total environmental support (ecological and socio-economic) to the sectors of urban economy in emergy-extended supply design the footprints assessment should be based on consumption-based accounting.

The other uncertainty comes from the downscale the vectors of national monetary government consumption and capital formation on a simple per capita basis as done in three studies before (Minx et al., 2013; Millward-Hopkins et al., 2017; Schmid, 2020). This assumption leads to the underestimation of both supply-extended and use-extended footprint results since Vienna is capital region, the largest GDP contributor to the Austrian economy, and a service-based economy on its own (Vienna, 2020; Statistik Austria, 2020). Therefore, Austrian citizens living in Vienna benefit more from the government expenditures and capital investmnets than national average. Minx et al. (2013) addressing this issue by endogenizing capital formation and government consumtion. The issue, however, that capital formation does facilitate production of industries such as infrastructure replacement and capacity expansion) and, therefore, the formation of capital (fixed assets) can be linked to the to the sectors using capital goods in their production. The government spending, however, does not facilitate production of industries in any way, and, therefore, cannot be endogenizing into the intermediate consumption of monetary use table before downscaling. This issue, thus, should be addressed in the future when more studies that employ footprint analysis of city scale will be introduced.

Other uncertainty of the model stems from the Air Emission Accounts that contain GHG emissions by economic sector at Austrian scale (Statistik Austria, 2015). This uncertainty results in overestimation of carbon footprints estimated using supply-extended and use-extended IO designs. The more uncertainty stems from the assumption of equal share of emissions from households as from economic activities due to the GHG emission data on households being available as an aggregated single, instead of showing the data on carbon emitted in direct energy consumption of households by economic sector (NACE classification). This results in underestimate of carbon footprints of final products and source sectors in the results based on the use-extended IO design. This is the problem with the most of studies that the national emission data is used to estimate direct carbon emission by industry (Schmid, 2020; Fry et al., 2021) or use outdated GHG emission inventories for cities Wiedmann et al. (2020). Rather than inventing new downscaling approach, the data on carbon emissions by economic activity can be obtained from other service-based cities in EU for which data is available (reference cities) such as Stockholm and then, used to estimate Vienna-specific carbon intensity vector (Wiedmann et al., 2020). Therefore, this approach can be used to get better estimation of carbon intensity vector and reduce uncertainty stemmed from the use of national carbon emission vector. The approaches to disaggregate the data on households' emissions need to be proposed for EU cities due to lack of studies employing use-extension design at urban level in EU (Wiedmann et al., 2020) since or Chinese cities (or regions) with detail emission data availability can be used as a proxy for EU cities such as Beijing (Li et al., 2018), Tianjin and Shanghai (Zheng et al., 2021b). This way uncertainty associated with the use-extended carbon footprint results can be reduced.

The vector of solar energy inputs to industries in Vienna was obtained from downscaled energy use tables and Vienna energy balances for 2015. The total solar energy use in Vienna is based on the Energy survey by Statistik Austria (Statistics Austria, 2015). The methodology for calculating renewable natural energy inputs, including solar energy, is based on the territorial principle, which includes solar energy captured by all solar panels for electricity generation within the national territory and the share of imported solar energy for electricity generation purposes out of the total electricity import. However, this methodology leads to the overestimation of direct energy supply to the economy and the underestimation of transformities of products and services aggregated by the economic sector.

The other limitation of this methodology includes the temporal boundary setting, which could lead to the consideration of indirect carbon emitted during the manufacturing of solar panels in the Vienna Region. The actual efficiency of solar panels is not reported for Vienna, leading to uncertainty in the vector of solar inputs into economic sectors. The environment dimension is only defined as a single sector in PEFA, and the solar radiation captured by 'environment' is assumed to be utilized for electricity and heat purposes of energy industries, service industries, and households (City of Vienna, 2022). Therefore, energy flow within the 'environment' is not recorded, leading to uncertainty in accounting of direct solar energy inputs into industries and ecosystems.

The study also used the combined utilization of the location quotient approach (LQ) and commodity-by-industry version of 'supply-side' input-output model to downscale monetary and energy supply and use data. However, this methodology leads to differences in fuel consumption based on the residence principle and its counterpart based on the territorial principle. To overcome this problem, the Austrian shares of sales of each fuel type by land, air, and water transport and sales of other energy products were found by transforming the Austrian physical energy use table into the commodity-by-industry equivalent of 'supply-side' input-output model.

The supply-side commodity-by-industry model was used in this study because it facilitates the separate downscaling of monetary and energy supply and use tables. However, this model reflects export-oriented growth, which can lead to higher stress on local ecosystems due to the dependence on purchased goods and services (De Mesnard, 2009; Aroche Reyes and Marquez Mendoza, 2021). The simple location quotient downscaling approach used in this study also has limitations, such as the assumption of the same technology used in the production process in the targeted region and a country (Miller and Blair, 2009; Galychyn et al., 2022), and the exclusion of biodiesel exports by the transportation and storage sector.

In conclusion, the study's methodology for calculating solar energy inputs to industries in Vienna has limitations, including the overestimation of direct energy supply to the economy and underestimation of transformities of products and services. The location quotient approach and supply-side commodity-by-industry model used in this study also have limitations, such as the assumption of the same technology used in the production process and the exclusion of biodiesel exports by the transportation and storage sector. These limitations should be considered when interpreting the results of the study.

4.5. Complementarity of emergy-evaluated extensions and future development

Based on the discussion, this study concludes that both extensions are complementary. According to Owen et al. (2017), and Wieland et al. (2019) both extensions separately provide useful information with the choice biased towards the responsible party: ether producers or consumers, and the origin of energy consumption: upstream energy sources (extractive industries) or downstream energy sources (consumers) in the energy conversion chain. In this regard, both the emergy-evaluated and traditional extension-designs are useful since both the extensions stems from input-output analysis. However, emergy-based supply and use extensions are complementary because each of them can only account for part of the environmental cost of provided to the activities responsible for energy (or carbon) footprints. Total environmental cost (support) to each source industry, or final product can be only captured when direct emergy consumption from use extension is isolated and added to the emergy-evaluated supply-extension design.

This energy (carbon) supply and use extensions can only be used together to investigate distribution of emission responsibilities of economic activities along the supply chain, depending on whether energy use of production and consumption industries or indirect emergy consumption in downstream sectors is prioritized (Du et al., 2011; Zhang et al., 2014a; Sun and An, 2018). Accordingly, it is suggested to discard prioritization and simply consider the responsibility of the both upstream and downstream sectors, bringing the upstream data from supply-extension and use-related data from use extension into a unified framework (Ali et al., 2018; Chen and Chen, 2011; Zhou and Kojima, 2010; Zhang, 2013). Ultimately, the total environmental costs associated with upstream and downstream CO_2 impacts of producers can be effectively assessed and compared with traditional carbon footprint (CF) only when the compatible data from use-extension is extracted. When this step is archived the global environmental support to local impacts manifesting at global level can be estimated using the multi-scale nested MRIO tables (Fry et al., 2021) can be accessed. Therefore, these directions could inform policymakers, and to stimulate environmental policies based on biophysical constraints, consumption efficiencies and global implications of economic activities.

5. Conclusion

In this study, supply and use designs of emergy extensions were introduced. Our empirical comparison of emergy-extended and carbon-extended SRIO models results revealed considerable differences in relative importance between emergy and carbon footprints.

The comparison of emergy-evaluated footprint model results with carbon counterparts based final products revealed a usually high difference in footprints of agricultural products. This difference lies in large imported renewable energy supporting production of agriculture, hunting, and related services (A01). The comparison of emergy-evaluated and carbon footprints by source sector, however, revealed the low difference in footprints of electricity, gas, water supply, sewerage, waste, and remediation activities (D + E) and Mining and quarrying (B) sectors. Mining operations are in another part of country are no longer economically feasible and experience rapid decline in production, highlighting low importance of this sector as a source of energy for Vienna's economy. The recovery of electronic waste holds a great promise for the substitution of traditional mining in Vienna. In the case of electricity, Vienna Government is more concerned with the improvement of share of renewable energies such as adoption solar PV technologies for energy supply and geothermal pumps to heat new buildings. The small difference between use-extension footprint and supply-extension footprints of final demand categories was due to the direct energy use of biofuels by final demand categories (i.e., households) being far less pronounced compared to the final consumption by production (industries).

The Exports category was a little larger using emergy-evaluated use extension design compared to the supply-extended design mainly due to the low contribution of direct energy export of biofuels allocated directly to the final demand category of exports.

The conceptual differences, however, imply that emergy-evaluated supply-extension resembles the structure of traditional monetary IO, and therefore comparable with energy (carbon) supply-extension design. The emergy-evaluated use-extension, on the other hand, differ considerably from energy use-extension design and does not reflect the logic of emergy synthesis. Each extension provides different information despite utilizing input-output tables & similar matrix algebra. Therefore, combining the first step of emergy-evaluated use-extension design (direct energy consumption by final demand) with the emergy-evaluated supply-extension design (primary energy input from environment and contribution of human labour and economic services to industries), and adjusting the allocation assumption to reflect the logic of direct and indirect flows in Emergy Synthesis would result in more accurate estimation of total environmental pressure of each sector in an urban economy. Finally, this study highlights the importance of assembling emergy extensions from the multi-scale nested MRIO tables to promote decision rooted in environmental and economic stewardship and resource-efficient cities.

CRediT authorship contribution statement

O. Galychyn: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **B.D. Fath:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation. **D. Wiedenhofer:** Writing – original draft, Supervision, Methodology, Investigation, Data curation, Conceptualization. **E. Buonocore:** Writing – review & editing, Supervision, Investigation. **P.P. Franzese:** Writing – review & editing, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clpl.2024.100058.

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6. CONCLUDING REMARKS

This thesis contributed to developing multi-criteria assessment frameworks capable of exploring the interplay of environment, economy, and resources taking place within the urban socio-ecological system by adopting an interdisciplinary and systems-based approach.

The integration of environmental accounting with multiple methods of network science proved to be helpful in overcoming the shortcomings of single criteria approaches when investigating complex environmental problems that manifest in the external characteristics of urban metabolic systems (resource consumption and environmental pollution).

The conceptual framework integrating environmental accounting and network science methodology highlighted three main windows of attention that can be identified when focusing on internal metabolic processes in cities: 1) environmental costs, 2) distribution of trophic levels and cost-benefit relationships among internal components and 3) generated environmental impacts.

Several metrics and evaluation methods of network science methodology were integrated and jointly used to investigate the structure, functions, and urban metabolic system footprints. Each evaluation method provided crucial parts of information describing different aspects of the overall resource efficiency and sustainability at different levels of aggregation.

However, further research should be carried out to quantitatively assess the multi-scale impacts of individual urban metabolic processes and how the activities at different spatial scales impact these processes. An optimal level of disaggregation for identifying environmental problems has not been determined. When several complementary methods are applied together to investigate environmental costs and impacts of production and consumption processes in cities, comprehensive socio-economic and ecological assessment of upstream and downstream requirements of urban metabolic activities can be fully understood and assessed.

The wastewater and waste treatment should also be included in future studies on urban metabolism. This information is highly relevant since waste recycling and reuse increase embodied solar emergy of the intermediate products in their transfer among industries in the urban economy and contribute to the energy use of source industries. Another appropriate use of this data would be to use ecological network analysis (ENA) to determine their contribution to other sectors' waste production and estimate their emergy acceptance and transfer efficiencies. Using these indices, the sectors constraining these two sectors' ability to induce waste production in other industries and the overall emergy utilisation efficiency can be identified.

Future research can be extended to incorporate energy and monetary losses into estimating transformities and in the construction process of the emergy input-output table. This data could be obtained through disaggregation of energy sector-related data for waste and wastewater treatment, through disaggregation of the final demand sector for the information on the production of wastes.

Lastly, using this data would allow us to analyse the effects of the implementation of the circular economy strategies in waste and wastewater treatment sectors to offset the carbon and emergy footprints of energy extraction industries. However, using these strategies as part of a more extensive intervention would be required to offset the impact on 'urban wealth' and include the consumers in footprint reduction measures by exploring emergy and carbon footprints from the consumer side (final users as a source of consumption and footprints). These directions will assist in guiding cities towards viability and sustainability.

Purging this data from energy and monetary use matrices allows us to account for actual emergy consumption. Applying this approach to estimating transformities will enable us to calculate them from complex non-square matrices, recognising the existence of the unequal process emergy efficiencies in ecological and economic systems. A less sophisticated approach would be to use the column totals in energy and monetary value-added matrices, which contain negative energy inputs (consumption) and positive energy outputs (production). These two approaches might generate different results because the first is based on the demand-side, and the second is based on the supply-side perspective. This direction should be explored considering the unsustainable and inefficient nature of urban metabolic processes in cities.

Moreover, advantages and disadvantages stemming from integrating network and footprint analysis with donor-side environmental accounting methods should be further investigated. While donor-side environmental accounting methods can assess the environmental costs of cities as a single organism, the network analysis can capture the impacts of these costs on internal metabolic activities in terms of production and consumption. Although the footprint analysis identifies environmental impacts associated with each production and consumption process in cities, it does not capture upstream environmental processes and indirect flows involved in production and exchange among sectors in cities.

The issues of how to combine system-level indicators, reflecting the system's resource efficiency and sustainability, with internal metabolism assessment to understand the processes affecting the state of the urban socio-ecological systems to improve its development in terms of efficiency and stability, and how to investigate the change of these properties over time to monitor urban metabolic system performance, and how to incorporate on donor-side oriented carbon footprint assessments into decision making to address low carbon economic development goals also need to be discussed further.

In conclusion, we maintain that a multi-criteria and system-based perspective on environmental accounting and urban metabolism could play an essential role in investigating the interactions between natural and human systems, allowing a broader understanding of the understanding the costs and benefits resulting from using raw and processed resources supplied from larger environmental systems in cities.

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