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An ecological-thermodynamic approach to urban metabolism: Measuring resource utilization with open system network effectiveness analysis

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HIGHLIGHTS

- A new method, open system network effectiveness analysis, is introduced.
- Two performance metrics, effectiveness of utilization and conversion are developed.
- Effectiveness measures the ability of a city to maximize the resource available.
- The case study of Singapore shows the trajectory of effectiveness for 2005–2014.

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ABSTRACT

Cities have evolved as centers of economic growth and often described as open systems where the intake of resources is heavily dependent on flows imported from the external environment. The question is, how much of the resource available in cities is effectively utilized? In response, this paper develops an ecological-thermo-dynamic approach to assess the ability of a system to make full use of the resources available and reduce the demand for new resources. In this work, open system network effectiveness analysis is introduced as a novel assessment method to investigate the cities' producer and consumer behaviors by studying the resource flow connections and the interactions between the socio-economic sectors. Investigation on the urban flows network evaluates the ability of the system to utilize the resource imported through the effectiveness of utilization in-dicator and the ability to convert the resource imported to useful products through the effectiveness of con-version indicator. The effectiveness indicators, utilization and conversion, represent the consumption and pro-duction characteristics of the system respectively. This is tested through a case study conducted for Singapore city over the time period 2005–2014. The effectiveness results show that the city, on average, has utilized 45% of the maximum extractable usefulness from the resources imported throughout the years, with the lowest effec-tiveness, 39%, and the highest effectiveness, 50%, in the years 2007 and 2014 respectively. The trajectory of effectiveness results throughout the years suggests a trade-off relationship between the producers and consumers to balance the production and consumption of resources in the city.

1. Introduction

In 2014, urban economies generated 80% of the global Gross Domestic Product (GDP) but also contributed 70% of the global energy consumption and greenhouse gases (GHG) emissions [1]. Projections show 91% of global consumption growth from 2015 to 2030 will be generated by people living in cities due to increasing household in-comes and consumer spending [2]. Urban lifestyle and rapid disposal of fast-moving consumer goods also accelerated municipal waste generation [3]. Meeting the Sustainable Development Goals (SDGs), more specifically, SDG 11 for sustainable cities and communities and SDG 12 for responsible production and consumption [4], is challenged by these consumption patterns and the trends of global urbanization. Strategic resource management and waste reduction can be achieved by incorporating circular economy to harness useful materials from the waste streams through a regenerative system. Urban dwellers are urged to address the challenges by reformulating their sustainability objec-tives in order to decouple economic growth from resource-intensive
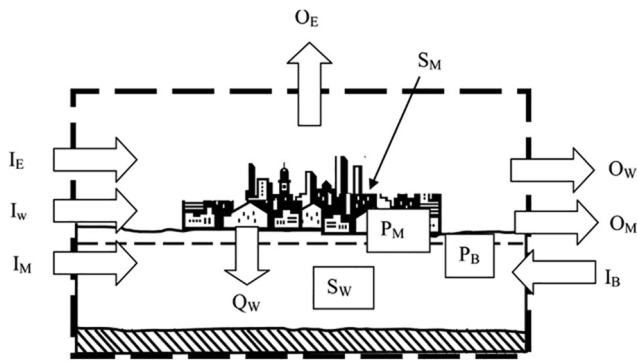
Fig. 1. Urban Metabolism framework: The boundary of an urban system showing inflows (I), outflows (O), internal flows (Q), storage (S), and production (P) of biomass (B), minerals (M), water (W), and energy (E) [17].

economic activities in cities. New tools and methods are imperative to ensure decision-making drives society towards these goals.

1.1. Review of urban metabolism framework

The concept of urban metabolism (UM) was introduced by Wolman in 1965 as an analogy between industrialized systems and biological metabolic systems in a hypothetical model to assess resource flows and waste produced from urban activities [5], as illustrated in Fig. 1. Adaptations of industrial ecology with the UM framework emphasized the importance of ecological and environmental management to sustain a growing system [6]. Further works on urban ecology revealed a strong link between UM and urban ecosystem by modelling the hierarchical metabolism of energy and material flows in cities [7–9]. In addition, reviews of the concept demonstrated broad and impactful applications of UM in sustainable resource management, environmental assessment and urban planning [10,11] highlighting the role of cities as driver of global energy use and waste generation [12]. Despite the abundance of UM case studies covering several locations worldwide, the applications of UM resource accounting are often incomparable and intended as flow-specific or case-specific to the methods implemented due to the distinctive characteristics of each city. For example, the case studies on Hong Kong [13], Toronto [14,15] and Paris [16] are unique in terms of the types of flow, socio-economic structures, climate conditions, and the energy supplies.

Metabolic flow analysis, in which the accounting methods fundamentally comprise of energy and material flow analyses, has made significant contributions to understanding UM by tracking the supply and use of resources in cities. To account for societal metabolism, exergy-based resource accounting methods have emerged as a convenient tool to model urban resource distribution by using exergy as a unified measure inclusive of both quantity and quality of the resource flows [18–20]. In relation to the concepts of irreversibility and work availability in thermodynamics, exergy is generally defined as the maximum physical work that can be extracted in a given process [21,22] which reflects the true level of resource availability. In a systems approach to the UM framework, urban systems are appropriately represented as inter-connected networks in many studies to investigate the functionality of urban processes and services [23,24]. For complex urban metabolic systems, network approaches have been adopted to assess resource distribution within urban ecosystems [25,26]. The formation of internal linkages, in the form of a weighted bi-directional network, is achieved by connecting smaller entities in the system, sharing a similar hierarchical setting with a natural ecosystem [27]. See Table 1 for the literature review of existing UM methods and indicators.

1.2. Cities as open system networks

Cities are often described as complex open systems where the intake of resources is heavily dependent on flows imported from regions outside cities [46], consequently causing high concentration of energy footprint [47,48] and carbon emissions in urban areas [49]. For a bounded urban system, resource inputs from outside the system and outputs to other systems can be considered as inter-city or international imports and exports, whereas waste emissions are treated as wasteful losses ejected from the system. These imports and exports, together with the input-output flows between the inner components, would fulfil the conditions of constructing an ecological flow network [50] which can then be used to describe the distribution and utilization of metabolic flows in the system with an open system network approach. Understanding the utilization and conversion of exergy in urban processes would provide transparency to the transformation pathways of resources circulating among the components within the urban systems and the interactions between the systems and the environment.

The second law of thermodynamics states that in an irreversible process, entropy is produced when energy is being converted to work done. This means not all energy can be converted into work because of their quality (usefulness) differences [51]. In terms of exergy, quality degradation occurs as exergy is being destroyed in a dissipative transformation process. Applying thermodynamics laws to ecosystem, when a system is being forced away from its equilibrium due to external inputs (applied gradient), it will grow and evolve by developing more structures and processes to increase its total dissipation in order to maximize the use of resources, as demonstrated in Kay's non-equilibrium thermodynamic framework for ecosystem integrity [52,53]. For an open system, the greater the inflow captured from outside, the greater the potential for degradation and dissipation [54]. These are known as self-organizational behaviors in ecosystem, at which the rates of entropy production and exergy destruction increase with higher resource intakes into the system [53]. According to Kay's observation, the rates of resource utilization and exergy destruction act as evaluating criteria for growth and development in ecosystems [55]. As such, in metabolic flow networks, linkages are internally organized to create flow pathways that are in favor of maximizing dissipation and exergy destruction [56]. Hence, a developed network with higher structural density and flow activity has a higher capacity to dissipate and destroy more exergy, and is more effective in terms of resource utilization.

The aforementioned self-organizing behavior of ecosystems appears in order for the system to counteract the gradient applied through the inputs by dissipating more exergy in response to any movement away from its equilibrium. Thus, development of organizational levels and exergy dissipating capabilities of such a system are closely related to the fundamental UM analogy. As such, an urban ecosystem can be seen as a self-organizing open system network formed by connecting exergy dissipating entities of the functioning socio-economic sectors in the city [55]. Structural circularity and continuity in a network prolong the cycles of resource flow enabling increased energy transformation and exergy destruction through cascading processes. The system capacity increases by developing longer pathways to circulate metabolic flows in the system, which allows passing on of useful resources to other sectors in the network to enhance intra-system flow activity [57]. From a thermodynamic perspective, cities grow as dissipative structures with increasing exergy destruction and organizational development of the ecosystem [58]. In the interests of minimizing the supply chain footprint, the approach of open system network is coherent with the principles of circular economy to retain useful materials in the system for as long as possible. This maximizes the use of resources imported into cities and ultimately reduces the demands for extracting new resources [59,60].

Table 1
Summary of literature review of existing urban metabolism methods and indicators.

Method	Description	Indicator
Material flow analysis (MFA)	• Quantifies material input-output across the boundary • Overly simplified and linear nature, ignoring the differential in qualities [28]	• Material inputs and emissions [29] • Material consumption and production [30]
Emergy analysis	• Converts the energy embodied in different energy carriers into their equivalent solar energy [31]	• Emergy use [32]
Life cycle assessment (LCA)	• Includes all direct and indirect resources consumed and impact in all life associated with the product, also known as "cradle-to-grave" analysis	• Life cycle impact assessment indicators [33]
Input-output analysis (IO)	• Accounts for all direct and indirect inputs as embodied energy in the products and waste • Hybrid models account for embodied carbon and energy [34]	• Sectoral flows and consumption [35,36] • Embodied energy in national final demand [37] • Consumption of world economies [38]
Exergy analysis, Extended-exergy accounting (EEA)	• Useful in resource budgeting based on the embodied energetic content in the conversion processes • EEA method includes the non-energetic externalities such as labor, capital and environmental remediation costs associated with the processes [39]. • Lacks unified conversion method for waste	• Exergy inputs and outputs [40] • Exergy conversion [41]
Ecological network analysis (ENA)	• Incorporates flow analysis by tabulating the inter-compartmental transactions as an input-output matrix • Monetary transactions data is often used to estimate the weight of flows so may not represent the actual amount of resources.	• Total system throughflow [42] • Network and environ properties [43] • Spatial variations [44]
Ecological footprint (EF)	• Compares the land area required to sustain a population's resource consumption to the bio-capacity of the land available • Has a high degree of applicability and flexibility on spatial scale	• Ecological footprint [45]

1.3. Urban sustainability assessment

The importance of sustainability assessment at city-level was addressed by Musango et al. [61] in their report to United Nations (UN) Environment in leading a global shift towards increased resource efficiency. Having a robust assessment tool can assist urban planners in gauging the system sustainability performance and setting a carbon budget to restrict resource demands and in long-term, to decouple consumption from economic growth.

In recent literatures, sustainability assessment methods emerge as dedicated inter- and transdisciplinary approaches from different academic disciplines to develop solutions for sustainable futures [62,63]. Other than conventional monetary evaluation, socio-economic performance is closely related to public welfare in terms of infrastructure provision and social equality, highlighting the interrelations between environmental, economic and social issues. A multi-layered indicator set introduced by Kennedy et al. [64] presents a collection of standardized parameters for UM investigations in megacities, however the framework presents a challenge in data acquisition especially in some of the middle- and low-income developing countries with fast growing populations [17]. For these reasons, among the UM accounting tools, many were developed in a data-scarce environment, nonetheless, developments and implementation of UM research are often subjected to assumptions limited by data availability and accessibility [65].

For the purpose of investigation and quantification the metabolism of cities, comparative studies of energy utilization has revealed that exergy analysis is better suited in detecting inefficiencies of resource flows through an economy and hence a more suitable technique than energy analysis [66]. Exergy-based assessment is a powerful tool to identify the factors limiting resource utilization such as technology constraints and consumer behaviors of different sectors due to their respective hierarchical characteristics and ecological roles in the socio-economic system [67,68]. Coupling exergy with input-output analysis, as an environmental extension, provides a convenient and proven method to evaluate the availability of energetic resources and characterize the energy transformation processes within an economy [69,70]. Comparing to black-box metrics which lack of information regarding the differential resource quality and functional diversity is the system, grey-box metrics such as such as IO and ENA offer higher

transparencies showing the internal structure and transformation processes, presenting more precise indicators to assess the performance of complex urban systems [71].

1.4. A new approach for cities: Open system network effectiveness analysis (OSNEA)

The review in previous sections has discussed different UM methods, together with the applications to cities as open systems, and bringing these together demonstrates the frontier of urban sustainability assessment. However, a framework that considers the differential in energy and material flows to evaluate the utilization of resources imported into urban systems is absent from the existing assessments. Previous work by the authors [72] already highlights a number of shortcomings in ENA including the debated use of input-output monetary transactions as resource supply and use to account for the metabolic activities in cities. The current work builds on this by developing a new framework for accounting resource flows and introducing a set of new indicators to describe the metabolic performances of an urban system.

By taking an ecological-thermodynamic approach, this work presents a novel assessment method, the open system network effectiveness analysis (OSNEA), to investigate resource utilization in cities by evaluating the ability of the system to extract maximum work done from resources available in cities and reduce the needs of extracting new resources. The methodology of OSNEA essentially utilizes the techniques of ENA and IO to provide new insights of urban sustainability beyond the existing UM methods. OSNEA is unique not only because it presents a combination of thermodynamics and ecological approaches to study open economy, but also because the effectiveness analysis includes an investigation on the dynamics of internal linkages between individual components of the network. The advantage of incorporating ENA in OSNEA is to provide a network interpretation to the economic structure of a city allowing the framework to characterize the relationship between sectors based on the integral of all direct and indirect flows and to describe the inter-dependencies within the economy from an ecological perspective.

The rest of the paper is structured as follows. Firstly, a step-by-step explanation of the methodology workflow to demonstrate OSNEA. This
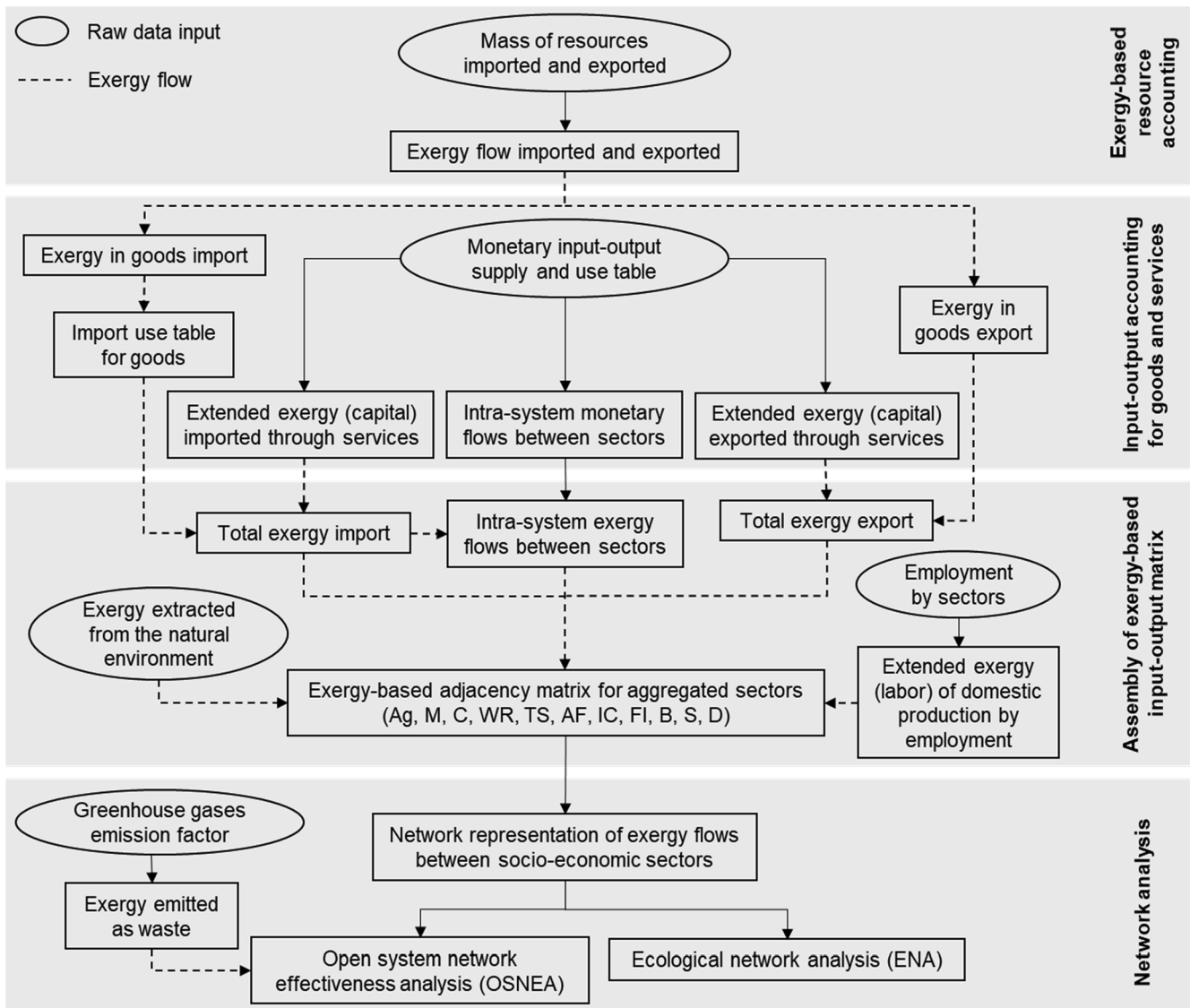
Fig. 2. Workflow diagram showing the key steps and data required to develop the OSNEA framework.

is followed by a showcase of the case study conducted for the city of Singapore, along with the results and discussion based on the observations. Finally, the paper concludes with the potential contributions of this study and future perspective in promoting global sustainability.

2. Method and data

This section explains the pioneering work on the development of OSNEA inspired by the idea of making full use of the resources available in cities. This paper is the first to introduce this method as a new approach to UM. The methodology of OSNEA consists of four key steps: (1) Acquisition of commodity mass flow data for exergy-based resource accounting; (2) Formulation of the input-output exchanges of goods and services between the socioeconomic sectors; (3) Assembly of exergy-based input-output adjacency matrix to construct the urban flows network; (4) Network analysis to investigate the performance of the system by conducting ENA and OSNEA, including the introduction of a set of *effectiveness* indicators for examining the resource utilization and conversion processes in the system. The workflow diagram showing the methodology development process is as illustrated in Fig. 2.

2.1. Exergy-based resource accounting

The concept of exergy provides a standardized quantification tool to measure the maximum usefulness of resource flows entering the system. Within the spatial boundaries defined, the total exergy imported and exported in physical goods can be estimated from UN Comtrade database which contains record of traded mass flows [73] and the specific exergetic content of materials. The reference conditions of surrounding temperature and pressure were assumed to be at 25 °C and 1 atm. The specific exergy values were mainly taken from the previous works on chemical exergies in elements [74] and other compounds [75], including the metal industries [76]. Exergy accounting of various types of material such as fossil fuels [77], plastics [78], building materials [79], household appliances [80], biomass [81,82], fertilizer and pesticides [83], food commodities [84] and municipal solid waste [85,86] were also considered in here.

2.2. Input-output accounting for goods and services

The network of intra-system resource flows between the economic sectors can be extracted from the monetary input-output supply and use table. Following Leontief's model [87], the input-output transactions

between the sectors form a network as a balanced square matrix. The table also includes the economic data pertaining to annual capital flows such as the gross value added (GVA), private expenditure consumption and gross fixed capital formation (GFCF) of the economy.

For an open economy, total exergy import is comprised of goods and services. The exergy contained in the form of goods are calculated from the equivalent exergetic content of the resource intakes. Also, the information of the types and amounts of goods imported by each sector can be obtained from the import use table to determine the resources inflow to each component of the network. The extended-exergy of services, in the units of Joule (J), is defined as the embodied exergy of the monetary capital invested to deliver the services recorded in the input-output table. For a single monetary unit, the *exergy equivalent of capital*, ee_K, can be computed as the ratio of the total incoming exergy flux, E_{in}, to the cumulative monetary circulation, $M2$, for that year. With reference to the econometric factors used in Sciubba's EEA method [88], ee_K is formulated as:

$$ee_K = \frac{\alpha \beta E_{in}}{M2} \tag{1}$$

where α is the first econometric factor representing the fraction of incoming exergy flux used to generate the cumulative labor work-hours of the whole population and β is the second econometric factor representing the amplification of wealth creation. Population, wages and employment data are required to determine α and β. The final extended-exergy of services is the product of ee_K, which is measured in J per monetary unit, and the cost of the services. See Appendix A for the supplementary material on the derivation of extended-exergy.

Similarly, goods exports are associated with the sectors handling the relevant products based on the mass of the exported goods recorded in the UN Comtrade database [73]. The equivalent extended-exergy of services exported can be calculated from ee_K in a similar manner to the imports.

2.3. Assembly of exergy-based input-output matrix

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

$$M_{ex} = [diag(F)][\widehat{M}_{ij}] \tag{2}$$

Distributing the vector of exergy import, f_{import_i}, based on $[\widehat{M}_{ij}]$ creates an exergy-based adjacency matrix, M_{ex}, for an open system network sustained by the incoming resources.

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

$$ee_L = \frac{\alpha E_{in}}{N_{wh}} \tag{3}$$

where N_{wh} is the total work-hours contributed by the entire labor workforce [88]. The extended-exergy of domestic labor received by the sectors, $f_{i,domestic} = EE_{Li}$ can be computed by multiplying ee_L by the total employed work-hours of each sector i. Resource consumed by the domestic sector, recorded as monetary private consumption expenditure in the input-output table, can be considered as the extended-exergy equivalent to the capital consumed calculated by using ee_K. Furthermore, exergy production in local activities such as agricultural, forestry and mining activities are treated as imports from the natural environment resulting from extraction of new resources.

The integration of thermodynamic and economic systems follows the principle of hybrid input-output analysis where exergy serves as an extension vector to the input-output matrix. The monetary transactions in the input-output matrix can be used as a proxy of resource flow. See Appendix A for the supplementary information of the resultant matrix assembly.

2.4. Network analysis

Network representation of an urban system is constructed by translating the adjacency input-output matrix to form a network with the size of m sectors. The nodes ($i, j = 1, 2, \cdots m$ and $i \neq j$) represent the socio-economic sectors including the domestic sector, while the edges, f_{ij}, represent exergy flows received by sector i from all other sectors j. The total flows to and from a sector, including the cross-boundary imports and exports, are denoted as T_i and T_j respectively.

Throughflow analysis organizes the input-output flow matrix into output-orientated or input-orientated flows such that the output-orientated flow matrix, $G = [g_{ij}] = f_{ij}/T_j$ and the input-orientated flow matrix $G' = [g'_{ij}] = f_{ij}/T_i$. Using Leontief's [89] and Ghosh's [90] inverse functions, integral flow intensity matrices are given as, $N = [n_{ij}] = (I - G)^{-1}$ and $N' = [n'_{ij}] = (I - G')^{-1}$. These are used in network control analysis to study the degree of control and dependency relationships between pairwise sectors [91,92]. The control allocation, CA matrix indicates to what extent the supplying sectors control the consumption of the receiving sectors whereas the dependency allocation, DA matrix indicates to what extent the receiving sectors rely on the production of the supplying sectors. A dimensionless representation of CA and DA is used to provide pairwise comparison across different sectors and highlight the ecological role of the sectors based on their consumption and production patterns [93]. This helps to characterize the sectors to describe *effectiveness* of producing and consuming sectors in the urban system.

In utility analysis [94], the ecological relationships between the sectors can be characterized as mutualism, exploitation or competition based on the sign combinations of the pair (u_{ij}, u_{ji}) where $U = [u_{ij}] = (I - D)^{-1}$ is the integral utility intensity matrix and $D = [d_{ij}]$ is the direct utility intensity matrix. See Appendix A for the supplementary material on ENA formulations.

2.5. Open system network effectiveness analysis (OSNEA)

This section will introduce OSNEA as a novel ecological-thermodynamic approach, a complementary addition to the network analysis demonstrated in Section 2.4. OSNEA is an exergy-based method that accounts for the use of resources through urban processes in an open system network.

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

$$\eta_{ideal} = \left(1 - \frac{T_l}{T_h}\right) \times 100\% \tag{4}$$

where the ratio of the temperature at the cold sink, T_l to the temperature at hot source, T_h, acts as the limiting factor to the maximum achievable efficiency. Expressing the equation (4) in terms of rate of
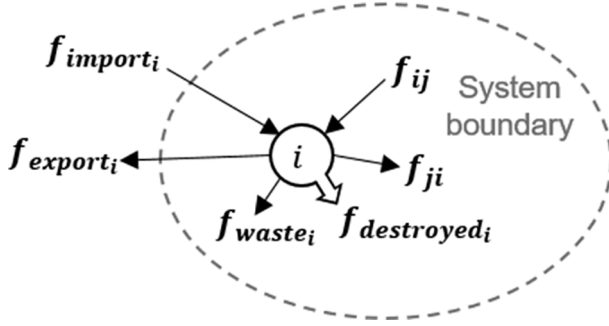
Fig. 3. The conceptual diagram showing the flow balance at node i.

work, $\dot{W}$, and heat energy input, $\dot{Q}_{in}$, gives:

$$\dot{W}_{ideal} = \dot{Q}_{in}\eta_{ideal} \tag{5}$$

Applying the same principles on urban socio-economic activities, the maximum outputs from the sectors and their processes are limited by the infrastructure facilities, technology available and operational efficiencies. If all the sectors are operating under their ideal conditions, assuming zero waste emission, the net difference between the input and output exergies is assumed to be inevitably destroyed when the resource flow is utilized in order to maintain the processes at their maximum efficiencies. Developments of inter-connected pathways between the sectors to circulate resource flows in the network allow more exergy transformation and destruction through cascading processes, as the system grows with increasing resource inflow [50].

To examine the use of the resources imported, exergy destruction serves as a measure of the exergy dissipation capability of a system in converting energy available to produce useful work done. The conceptual diagram in Fig. 3 shows the flow exchanges at a single node i.

As shown in Fig. 3, inputs to i, $\sum f_{input_i}$ are: import to i from the external environment, f_{import_i} and the total intra-system flow from other nodes, f_{ij}; outputs from i, $\sum f_{output_i}$ are: export from i to the external environment, f_{export_i} and the total intra-system flow to other nodes, f_{ji}, as well as the waste emitted, f_{waste_i} from the system (for example, GHG emission). From these, the net flow at i is the exergy destroyed in node i, $f_{destroyed_i}$, as resources are being utilized locally. Thus, the exergy balance at i is:

$$\sum f_{input_i} = \sum f_{output_i} + f_{destroyed_i} \tag{6}$$

$$f_{import_i} + f_{ij} = f_{export_i} + f_{ji} + f_{waste_i} + f_{destroyed_i} \tag{7}$$

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

$$\sum_{i=1}^{m} f_{import_i} = \sum_{i=1}^{m} f_{export_i} + \sum_{i=1}^{m} f_{waste_i} + \sum_{i=1}^{m} f_{destroyed_i} \tag{8}$$

$$\sum_{i=1}^{m} f_{import_i} = \sum_{i=1}^{m} f_{export_i} + \sum_{i=1}^{m} f_{waste_i} + \sum_{i=1}^{m} f_{input_i} - \sum_{i=1}^{m} f_{output_i} \tag{9}$$

For OSNEA implementation, Table 2 shows the metrics considered to examine the performance of the system in the contexts of resource flows and environmental sustainability.

It is worth clarifying that the new indicator introduced in Table 2, *effectiveness of utilization* ($Eff_{utilization}$), is different to the terminology of utilization efficiency used in other analyzing methods [66,95]. These often refer energy utilization as reflection of resource consumption and evaluate utilization efficiency based on the total resource input. In the current work, utilization results from the energy transformation processes that cause quality degradation and exergy destruction. The metric of *effectiveness*, with a denominator of exergy import, refers to the ability of the system to utilize or convert the high-quality resources imported to work done or other useful products. In contrast to the

description of *effectiveness of conversion* ($Eff_{conversion}$) introduced in Table 2, Sciubba [96] defines *conversion effectiveness* as the ratio of extended-exergy output to the equivalent exergy input. $Eff_{conversion}$ defined here is a system-wide indicator to measure how much of the resources imported is converted to products that are exported in exchange for monetary income or contributed to the local stock inventory.

In OSNEA, $Eff_{utilization}$ and $Eff_{conversion}$ are expressed as a fraction of exergy import and have an upper limit of 1 but the sum of $Eff_{utilization}$ and $Eff_{conversion}$ does not necessarily sum to unity. This is because of the potential withdrawal of goods from local stock inventories and generation of extended-exergy equivalent to GFCF added to the capital reserve in the city, as recorded in the input-output table, in which case both are not counted as import and export of the system therefore would result in a sum greater than 1. The idea of OSNEA is to describe the producer and consumer behaviors of urban ecosystem based on the *effectiveness* results to indicate how much of the high-quality resources imported to cities is effectively utilized and converted to useful work. The arguments are:

- For producing sectors, higher $Eff_{conversion}$ and defficiencies are preferred to improve the system transformation processes for minimal costs and waste;
- For consuming sectors, the meaningful measure of $Eff_{utilization}$ is the ability of the system to maximize the use of the resources available and reduce the needs for new extraction or import.

From these arguments, the results provide new insights in assessing system performance based on the ecological behaviors exhibited through the *effectiveness* indicators.

2.6. Data requirements

The OSNEA framework is designed and developed to study the metabolism of cities as open economies. From the workflow illustrated in Fig. 2 (raw data inputs are in circle), the types of data are:

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

Official statistics usually hold yearly records of the required data, though these may vary with different cities. In the OSNEA framework, the rates of resource flows and exergy destruction are calculated based on the annual figures.

The constraints of data availability depend on the chosen spatial location. Firstly, inter-city imports and exports data is unavailable and hence excluded in the current study. This could be an area for improvement to account for inter-city energy footprint in future investigation. Secondly, the availability of city-level input-output data is subject to the granularity of the data source. Scaling from a national-level to city-level will maintain the same economic structure and aggregated sectors across different scales [97].

3. Results and discussion: A case study of Singapore

Singapore is an island city-state which has limited reserves of natural resources. As such, the inflow of resources is drawn into the city through foreign imports, resembling an open system. The maritime border of the city automatically draws a distinct and intuitive boundary distinguishing foreign imports from intra-system flows in the urban scale economy. For these reasons, Singapore is perfectly suitable as a case study with its own entry of input-output supply and use data.

Table 2
Description and equations for the metrics used in OSNEA.

Metric	Equation	Description
Exergy import [J]	f_{import_i}	The total exergetic content of cross-boundary resources entering the system at city limits received by each sector, including the extraction of natural resources, calculated from mass flows.
Effectiveness of Utilization, Eff$_{Utilization}$ [%], $0 < Eff_{utilization} < 1$	$\frac{\sum_{i=1}^{m} f_{destroyed_i}}{\sum_{i=1}^{m} f_{import_i}}$	A new dimensionless system-wide performance metric based on the ratio of exergy destruction to total exergy import, representing a fraction of the total resources imported that is utilized in the system to produce work done.
Effectiveness of Conversion, Eff$_{Conversion}$ [%], $0 < Eff_{Conversion} < 1$	$\frac{\sum_{i=1}^{m} f_{export_i}}{\sum_{i=1}^{m} f_{import_i}}$	A new dimensionless system-wide performance metric based on the ratio of exergy export (including capital generation and output to inventory) to total exergy import, representing a fraction of the total resources imported that is converted to useful products for exporting purposes.
Exergetic efficiency [%]	$\frac{\sum f_{output_i} - f_{waste_i}}{\sum f_{input_i}}$	A dimensionless ratio of total useful output (except f_{waste_i}) to the total input of a sector, representing the useful work produced with a given resource intake.
Exergy intensity [J/monetary unit]	$\frac{f_{import_i}}{GDP_i}$	Exergy imported to generate per unit GDP of a sector.

Earlier UM studies of Singapore have demonstrated a wide variety of methods performed to study this city, including the applications of MFA to evaluate domestic material consumption [98], LCA to investigate embodied emissions [99] and a non-equilibrium thermodynamics framework to explore urban growth [58].

3.1. Urban system network representation

In this case study, OSNEA was undertaken for the socio-economic system of Singapore to examine the functionality of the city and resource use in the economy. According to Singapore Standard Industrial Classification (SSIC) [100], the sectors (nodes) and flow connections (edges) of the open system network can be categorized as illustrated in Fig. 4. See Appendix A for the supplementary material of intra-sectoral classification based on economic activities.

3.2. Exergy imports

Data were retrieved from Singapore Department of Statistics for the economy and employment data [100], Energy Market Authority for data regarding resource use and GHG emission factors [101], Agri-Food and Veterinary Authority for local production accounting data [102]. From the sources available, data for 2005, 2007, 2010, 2012, 2013 and 2014 were extracted. Fig. 5 shows the comparison between the exergy and mass imported by the sectors in those six years.

The results show the highest mass import (36%) by the manufacturing sector (M) due to a large quantity of resources imported to be used as the raw materials for local manufacturing activities. The highest exergy import (55%) by the production sector (P) as the sector largely imports high-quality energy carriers such as coal, natural gas and petroleum to power utility services. It is expected that the construction sectors (C) and M would have higher mass import due to the large quantity and weight of building materials, while the transportation and storage sector (TS) would have high exergy import due to high fossil fuel consumption. From the exergy import data, the trends of exergy and monetary intensities of Singapore's economy, relative to the year 2005, are shown in Fig. 6.

Although the exergy and monetary intensities of all sectors (including the domestic sector with no GDP contribution) have changed steadily since 2005, a wide variation was observed across the sectors.
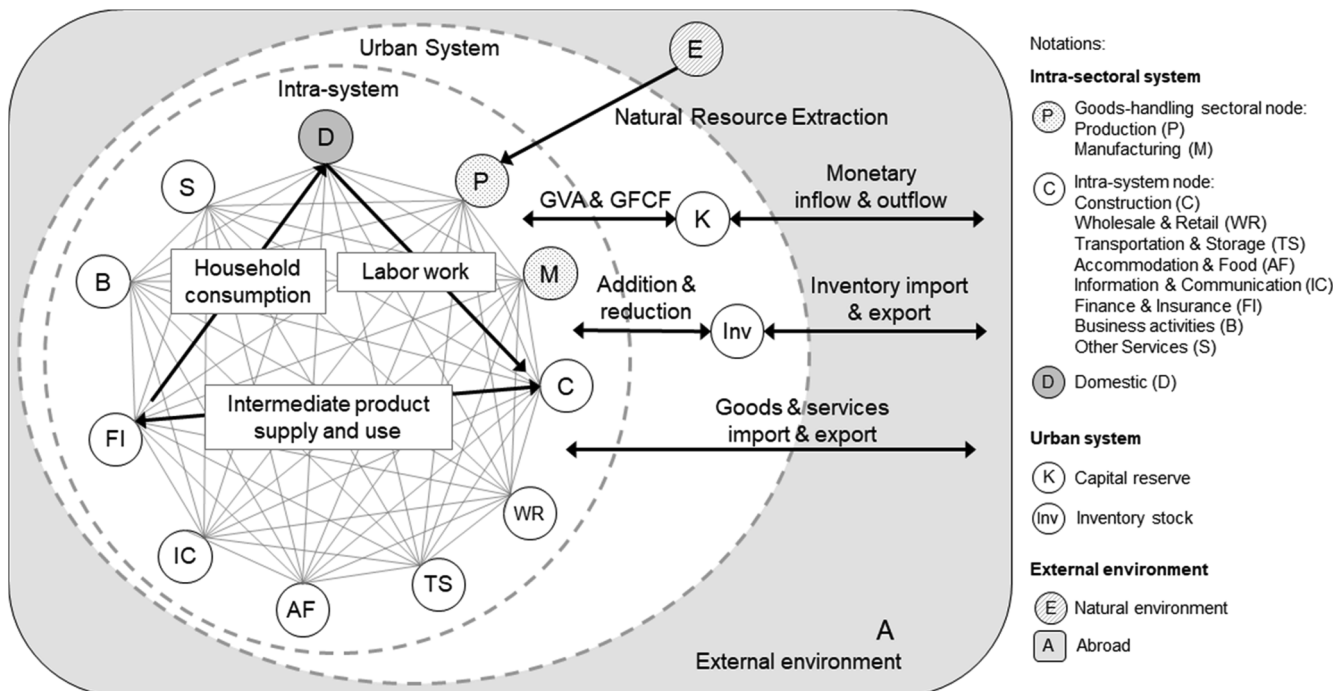

Fig. 4. Network representation of open system network for the case study of Singapore.
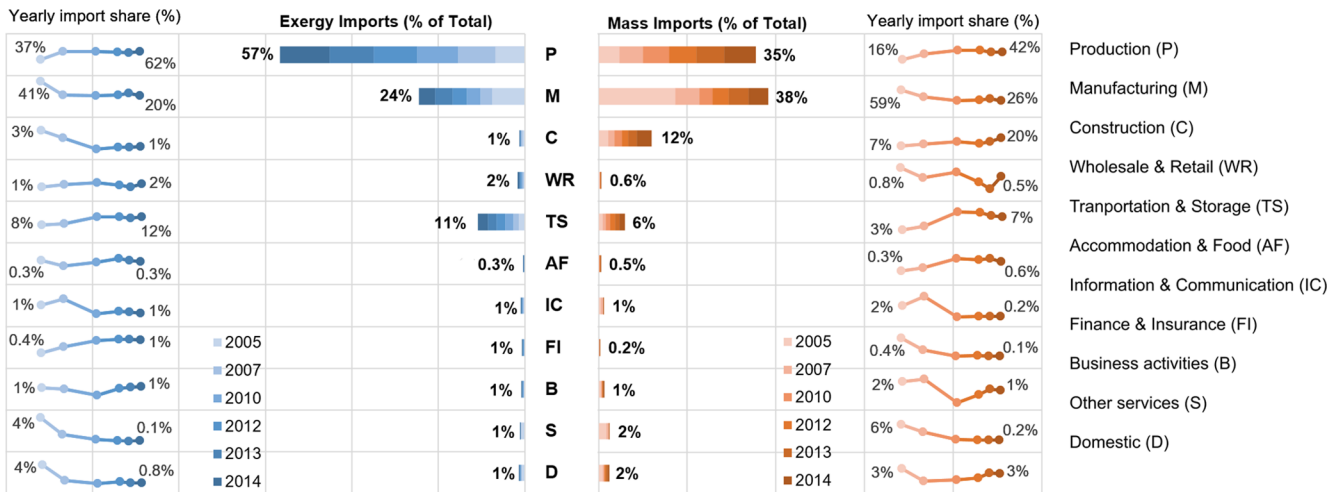
Fig. 5. The comparison between the sum of exergy (left) and mass (right) imports by each sector, as a percentage of total resource import by all sectors across the years as well as the trends of yearly import share by each sector, as a percentage of resource import by each sector in that year.

For instances, TS and the business sector (B) had lower exergy intensity in early years but eventually required more exergy import for further GDP generation in later years. Comparing the monetary intensities among the sectors, the importing cost per unit GDP has increased enormously (up to 6 times) from 2005 except for the services sector (S) with declining monetary intensity. It is worth noting that M was one of the high-income sectors and managed to maintain low intensities throughout the years.

3.3. Ecological network analysis results

ENA was applied to both monetary and exergy-based input-output flow matrices to study the metabolism of Singapore based on the exchanges between sectors. Fig. 7 shows the results of control and utility analyses between the sectors, for the year 2010 with both exergy and monetary flows. See Appendix A for the supplementary material of all ENA results.

Fig. 7(a) reveals the differences between the controlling sectors when comparing the analyses of monetary values and exergy resources. With monetary flows, tertiary sectors (FI and IC) were in stronger control whereas in the case of exergy flows, TS had substantially high control over the resources consumed by most of the other sectors. This

highlights the role of TS systems as resource distributor. In Fig. 7(b), for exergy flows, concentrated dependencies were observed at the domestic sector (D) as one would expect for domestic households to be the main consumers in the ecosystem. Therefore, household consumption is heavily dependent on the production of other sectors to deliver the products or services required by the end-users. The ecological relationships mapped in Fig. 7(c) shows mutualism across the diagonal due to self-promotion and competition between accommodation and food (AF) and other tertiary sectors (FI, B and S) as they compete for the same resources. For exergy flows, the side above the diagonal is dominated by light-grey patches (X exploits Y) while the side below has more dark-grey patches (Y exploits X) because the importers (P, M and TS) were exploited as they are losing resources to support others' benefits through imports from abroad. In comparison, the monetary results show an inverted pattern across the diagonal due to high monetary flows at the consuming sectors but have low energetic values. This emphasizes that exergy is a better suited than monetary units in describing the behavior of the ecosystem.

From Fig. 7, the individual sectors fit well with the respective ecological roles based on the types of economic activities. According the hierarchical structure of an ecosystem, the producing sector on the lowest level is the main supplier for the upper-level consumers hence, P
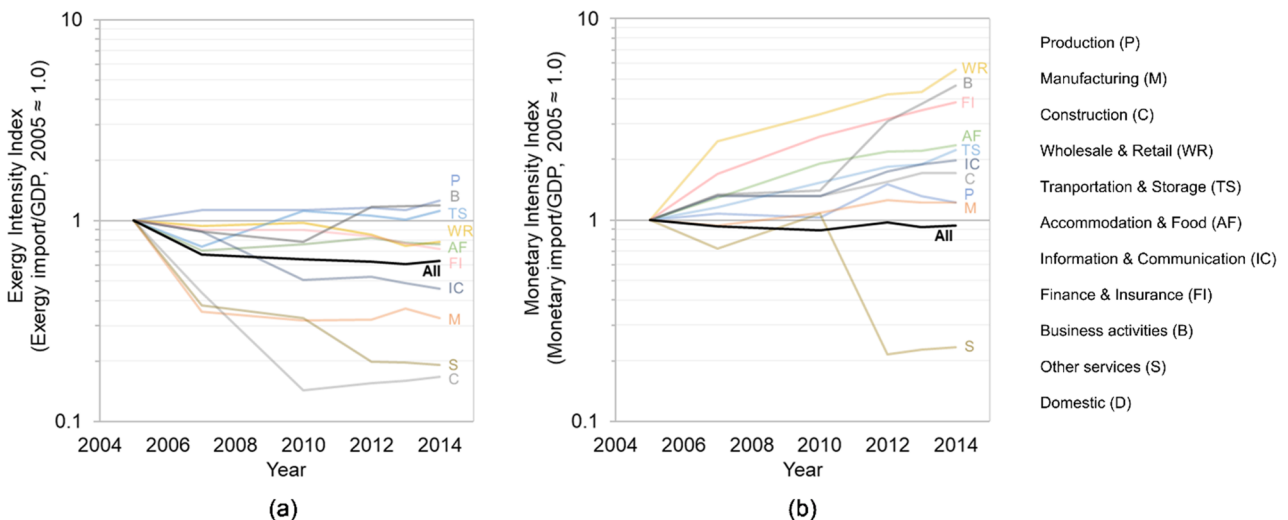

Fig. 6. Change in (a) exergy intensity (exergy import per unit GDP generated), (b) monetary intensity (monetary equivalence to the import per unit GDP) relative to the year 2005.
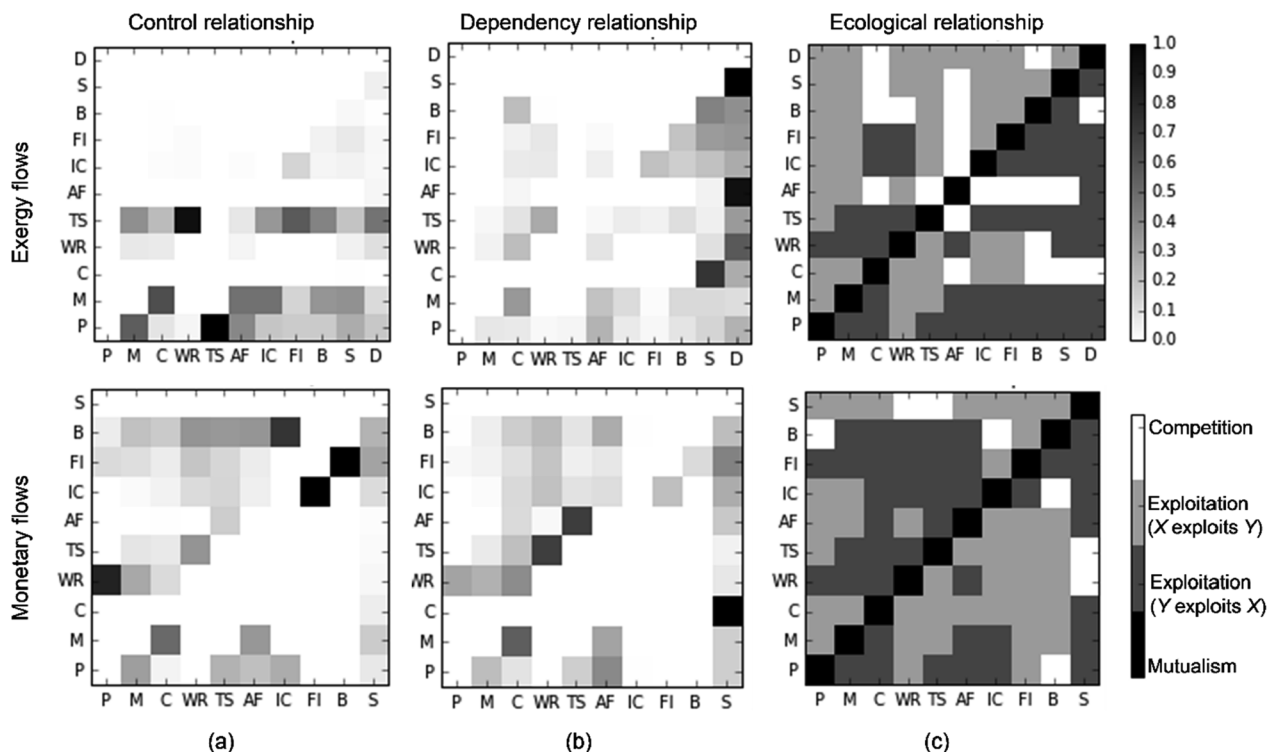
Fig. 7. ENA results for the year 2010, showing (a) control relationship, (b) dependency relationship and (c) ecological relationships between the sectors based on exergy (top) and monetary (bottom) flows.

is being exploited. On the intermediate level, the distributing sector acts as the primary consumer that connects the resource supply chain between the lower and upper levels hence, TS controls the consumption of other sectors. The final consumer at the highest level relies on the lower-level suppliers hence, D is highly dependent on the production of other sectors. Therefore, it can be deduced that the ecosystem is balanced and supported mainly by the resources imported to maintain the city's metabolism.

3.4. Sector efficiencies and system effectiveness results

Efficiency reflects the productivity of each sector based on the aggregated inputs from all sources regardless of the flow destinations or sources. At optimum processing efficiency, resource intakes through local supplies would increase flow circulations within the system and reduce the demands for importing new resources. The scatter plot of efficiencies and exergy imports is as shown in Fig. 8.
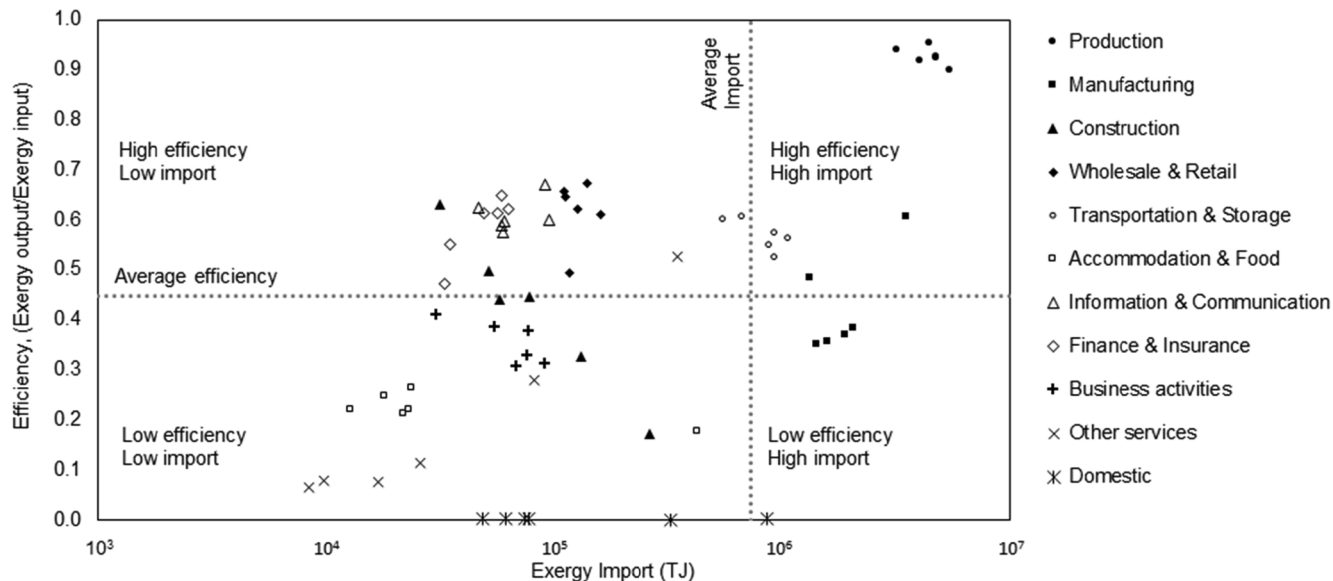

Fig. 8. The efficiency and exergy import (log-scale) of each sector distributed over four quadrants bounded by the system-wide average values (each point represents a year).
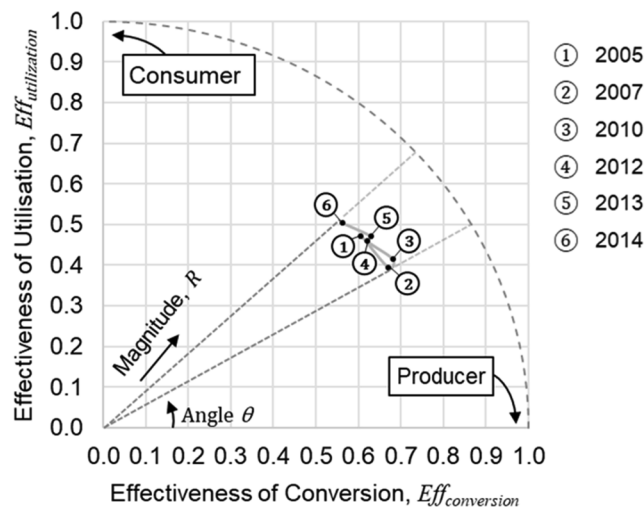
Fig. 9. The trajectory of $Eff_{utilization}$ versus $Eff_{conversion}$ (in the ascending order from number ① to ⑥) and the schematic frontier of the thermodynamic limit at magnitude equal to 1, as both axes are bounded by a maximum value of 1.

As shown in Fig. 8, the sectors fitted within the range of high efficiency and low import (in the top-left quadrant) are finance and insurance (FI), information and communication (IC) and wholesale and retail (WR). FI and IC belong to the group of tertiary sectors which only require minimal resource import (mainly services) to sustain their activities. WR manages the distribution of resources among different sectors to deliver resources from producers or importers to consumers and retain local resources in order to maintain high efficiency and low import. Among the sectors with high import, P has the highest efficiencies as the main importer of primary energy acting the role of producer in the ecosystem. Although M is inefficient and has high import, the sector also has low exergy intensity due to high GDP contribution for economic benefits. Furthermore, the essential consumers, D, has the lowest efficiency because is the only output from household activities. These observations justify the balanced ecosystem deduced from ENA results.

OSNEA evaluates $Eff_{utilization}$ and $Eff_{conversion}$ based on limited resources available in the imports. Fig. 9 shows the *effectiveness* trajectory of Singapore through time.

The results show that the system has utilized 39% (2007) to 50% (2014) of the usefulness equivalent to the total resources imported ($0.39 < Eff_{utilization} < 0.50$) through exergy destruction. The conversion outputs have usefulness equivalent to 56% (2014) to 68% (2010) of the import ($0.56 < Eff_{conversion} < 0.68$) to generate capital inflows for economic growth. The increase in the radius magnitude, R, from 0.75 (2014) to 0.80 (2010), indicates an overall improved performance. The system shifted towards higher $Eff_{utilization}$ and lower $Eff_{conversion}$ in after a significant change in trajectory direction between 2007 and 2008, showing an increasing resource utilization by the consuming sectors. The back-and-forth trajectory, with fluctuating polar angle, θ, from 30° (2007) to 42° (2014), suggests a trade-off between $Eff_{utilization}$ and $Eff_{conversion}$. From Fig. 9, between 2005 and 2007, the $Eff_{conversion}$ increased but the $Eff_{utilization}$ decreased and an opposite behavior between 2010–2012 and 2013–2014. These movements can be interpreted as the system organized and compromised to achieve a balance (assumed 45° from the axes) between the producing and consuming sectors, although the results for the recent years are more inclined towards the consumers owing to the growing services and domestic sectors. The thermodynamic limit (dashed-curve-line) shown in Fig. 9 assumes the maximum magnitude is equal to 1, however, this requires further analytical work to estimate the theoretical limit of *effectiveness*.

3.5. Discussion: Insights and implications from the ecological-thermodynamic approach, OSNEA

In this study, OSNEA investigates the ecological behaviors of Singapore socio-economic system, through time, to provide insights of the system performance using *effectiveness* as a new indicator to assess urban sustainability by quantifying the ability of a system to extract the usefulness from resources. Comparing to other UM methods which merely focus on consumptions and emissions, OSNEA addresses an often-overlooked criterion of resource utilization in cities that should be understood in the global development agenda. Measuring resource utilization based on the rate of exergy destruction to the total imports of the city shapes a new dimension to understand UM with a novel method of quantifying resource use through new performance metrics. This approach requires more attention from global researchers and policy-makers to promote urban sustainability through effective use of high-quality city resources.

The introduction of the OSNEA framework sheds light on the issues concerning the state of resource utilization in urban systems based on total imports. The *effectiveness of utilization* indicates how much of the resources imported into the city have been utilized based on the rate of exergy destruction; the model indicates operations at higher utilization rates are more resource-effective. Furthermore, the *effectiveness of conversion* complements the assessment framework by considering the conversion rate for generating useful resource outputs based on the imports. High *effectiveness* indicates longer resource circulations within the flow network to achieve the maximum use and complete degradation through cascading processes. From a circular economy perspective, *effectiveness* serves as a measure of system circularity and flows transmission within the network to promote higher effectiveness through higher connectivity and longer use cycles. From the *effectiveness* results in Fig. 9, Singapore has, on average, utilized 45% of the maximum extractable usefulness from the resources imported over the years, showing a significant potential to achieve higher effectiveness by lowering the imports and wastes. The system has, on average, converted 63% of the imports to local stock additions and capital incomes through exports.

Exergy analysis is a convenient tool for accounting for the work extractable and transformations of resource flows across different urban processes in different sectors. In Fig. 7, the exergy-based ENA has captured the inter-dependencies between the sectors and revealed a spectrum of ecological roles within the economy structure. Furthermore, another advantage of exergy over monetary-based ENA is the expansion of the network beyond intra-sectoral system, meaning labor and capital flows are included.

The essence of OSNEA is the establishment of *effectiveness* indicators to describe the ecological behaviors of the system. In Section 2.5, the arguments relate *effectiveness* to the ecological roles of different sectors in the socioeconomic system. The results in Fig. 9 suggest a trade-off relationship between the producing and consuming sectors in the city, while the results in Fig. 6 show that the intensities of all sectors remained steady since 2007 compared to the changes in individual sectors. From the perspective of urban industrial ecology, maintaining the ecological balance between the producers and consumers in an ecosystem is important to ensure the coexistence of different sectors within the same environment and long-lasting organizational stability. Thus, the work on OSNEA is closely related to the urban ecosystem analogy and has similarities with Kay's discussion on self-organizing behaviors in dissipative open systems for better understanding of cities [55].

Confining the frontier limit of the trajectory would assist urban planners and resource managers to focus on the more practical objectives in their development agenda. This helps in performance optimization by identifying the potential for resource use improvements in the system. For instance, inducing trade tariffs that regulate the imports and exports to manage the distribution of resources among the producing and consuming sectors in the city and to maintain the balance by

closing the development gaps between sectors. This also applies to the relationship with the external environment as unregulated patterns such as consumption beyond planetary limits could disrupt the balance and lead to system collapse.

The findings inform decision makers of the potential leverage points for policy interventions as OSNEA provides insights integrated across the social, economic and environmental aspects. This case study adds to ongoing debate on decarbonizing urban activities through the quantification of the performance of resource-intensive sectors such as utilities provision, manufacturing and transportation due to high exergy imports, shown in Fig. 5. Switching to renewable energy sources or low-carbon alternatives can help to relieve the high concentration of energy footprint and reduce the demands for high exergy imports, improving the overall *effectiveness* performance with larger radius magnitude. New interventions should also consider the impacts on the socio-economic system concerning local businesses, labor employment and consumer prices. For example, employing advanced technologies can increase the efficiencies of the manufacturing sector which was found to have high imports but low processing efficiency in Fig. 8, however, this may cause unemployment due automation and result in rising living costs. The framework provides decision-makers with a tool to assess the system requirements and contemplate the necessities of compromising resource intakes and economic incomes for long-term environmental sustainability in future development.

3.6. Limitations

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

To improve the overall validity of the results, a sensitivity analysis was conducted based on the uncertainties of the input data to determine the degree to which the accuracy of material data would impact the final outcomes of the study. Preliminary observations from the sensitivity analysis for different resource types suggest the results are more sensitive to the uncertainties of exergy contents in fossil fuel products compared to other products. The exergy contents of fossil fuels were estimated from the calorific values [75,77] because accurate fossil fuel data is of higher significance to mitigate the loss in data accuracy for other materials. See Appendix A for the supplementary material on sensitivity analysis.

4. Conclusion

This work presents the application of a novel approach to tackle the global resource problem, a real-world challenge facing the whole population that is yet to be fully understood. The open system network effectiveness analysis is proposed as an ecological-thermodynamic approach to study the distribution and utilization of resources in cities. The importance of this work is to highlight the implications of how cities are organized as open systems when more and more resources are being imported into the system and to encourage effective operations to maximize the use of limited resources available. The results of *effectiveness* show the traits of consumer and producer behaviors exhibited by the system and provide new insights as a complementary measure in examining urban sustainability. From a broader perspective, strategies

to reduce the demand and consumption through better use of the existing resources available are the keys to sustainable development on a planet with finite carrying capacity.

In future work, suggestions for further development are: (1) Formulation of analytical proof to identify the frontier of *effectiveness* analysis for blueprinting the areas for potential improvement and to facilitate resource utilization while maintaining high processing efficiencies and output conversion rate to sustain economic growth. (2) Dynamical systems modelling to study the temporal changes of the system behaviors rather than a static snapshot to allow forecasting of future scenarios. (3) Exergy accounting of waste emissions to include all types of waste exiting the system. (4) Understanding policy adaptation strategies based on the producer or consumer behaviors observed and the impacts on the system to enhance resource management in urban environments for optimized performance. (5) Extending the applications of the open system network effectiveness analysis to different cities and at global scale to allow comparisons between different systems, including a system of the Earth limited by the planetary bio-capacity and finite supplies of natural resources from the environment.

Author contributions

LMT, HA and MM have designed the study. LMT has undertaken the study and wrote the manuscript. HA, PEB, DDT and MM contributed to the discussion and the manuscript. All authors have given approval to the final version of the manuscript.

Declaration of Competing Interest

None.

Acknowledgements

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.113618.

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