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Ecological network analysis on intra-city metabolism of functional urban areas in England and Wales

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ABSTRACT

The UK has one of the world's most urbanised societies where nearly 83% of the total population lives in cities. The continuing population growth could lead to increases in environmental pollutions and congestion within cities. The framework of urban metabolism uses an analogy between cities and ecosystems to study the metabolic processes within complex urban systems akin to natural biological systems. It remains as a challenge to fully understand the complicated distribution of resource flows within an urban network. In this paper, Ecological Network Analysis was applied to study the intra-city flows between economic sectors in 35 functional urban areas in order to investigate their respective metabolic relationships. The intra-city flows network of each area was also supplemented with the geographical distance between the workplace zones to study the impacts of spatial distribution on the density of resource flows. The metabolic systems were dominated by 64% of exploitative relationships with an average mutualism index of 0.93 and synergism index of 3.56 across all 35 areas. The consumption-control and production-dependency relationships revealed the hierarchical orders among the sectors resembling the pyramidal structure of an urban ecosystem. Network community classification emphasized the importance of inter-relationship within the organisation of each community class. The producer-type and consumer-type communities showed the tendencies of those sectors to cluster based on their respective hierarchical roles in the ecosystem. This work provides an insight into the wide range of intra-city ecological metabolic characteristics which can potentially expand to a multi-scale assessment of urban metabolism across the country.

1. Introduction

Urban population which made up to 55% of total population worldwide in 2016 is undergoing fastest growth in history, from 34% in 1960 and is projected to increase to 66% by 2050 (Department of Economic and Social Affairs (DESA, 2016). The UK has one of the world's most urbanised societies where nearly 83% of the total population lives in cities (World Bank, 2014). The continuing trend of rapid urbanisation presents a challenge for national and local governments to maintain the economic growth and standards of living in cities while ensuring the rates of resource consumption return to being within planetary limits.

The concept of urban metabolism by Wolman (Wolman, 1965) proposes an analogy between cities and ecosystems to study the metabolic processes within complex urban systems akin to a natural biological system using a hypothetical model. Since Wolman's pioneering study, research efforts have been invested to explore and expand the conceptual model by applying real data from various cities (Huang and Chen, 2009; Huang and Hsu, 2003; Newcombe et al., 2017; Warren-Rhodes and Koenig, 2001; Zucchetto, 1975). Despite the wide range of analytical frameworks developed to account for various types of material flows entering and leaving the cities (Cencic and Rechberger, 2008; Hunt et al., 2014; Page et al., 2008), it remains a challenge to fully understand the complicated distribution of resource flows within the urban network. Material flow analysis applies mass balance to quantify in- and out-flows of resources and evaluate the remaining stocks in cities. This accounting technique is useful in tracking circulations of material and to optimise disposal of waste generated from urban activities through recycling. However, it does not address the spatial distribution and resource flows within the internal

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organisation of a complex urban ecosystem (Ravalde and Keirstead, 2015). For energy flow analysis, emergy approach is proposed based on the concept of *embodied energy* in the flows of certain materials, which was developed by Odum (Odum, 1976, 1996) in his theory on the functioning of ecological system. In theory, the emergy approach addresses and rectifies the problem of incomparable flows between different subsystems and improves consistency for the losses and efficiencies of different transformations taking place within the system. The concern for such approach lies on the use of an appropriate measurement in converting the units of energy and must be determined for all flows to ensure a unified standard.

From the perspective of ecological networks (Bai, 2016; Huang, 1998; Newman, 1999), urban ecosystem is governed by the complex interactions among its components which lead to a unique mechanism in the shaping of ecological structure and social communities of a city. The Ecological Network Analysis (ENA) approach dissects the problems of urban ecosystem at each hierarchical level of the system based on its respective functioning roles and the rates of resource consumption. The concept of ENA was formed by connecting the smaller individual entities in the system as an ecological network to understand the existing direct and indirect linkages among the components, sharing a similar concept with a natural ecosystem. The work of ENA integrated with Input-Output techniques from Leontief's model to study the structural distribution of different components in an ecosystem (Hannon, 1973; Leontief, 1986), hence its impact on the interrelations between different trophic levels based on the hierarchical structure of an ecological pyramid. ENA was further improved and refined by incorporating with flow analysis (to address the total system throughflow, average pathlength and cycling index) and hence, the concept of "environ" was generated to study the behaviours of an ecological network with the pre-determined input and output flows at each component (Fath and Killian, 2007; Finn, 1976; Patten, 1982). From ENA, the energy and material flows through an ecosystem were simulated to investigate the structural distributions and functionality of the system (Jørgensen, 2000; Szyrmer and Ulanowicz, 1987). ENA provides an analytical tool for various applications to study metabolism in cities from different perspectives i.e. ecological hierarchy relationship, spatial variation, energy flows in previous scholarly researches (Chen and Chen, 2015; Fan et al., 2017; Fath and Borrett, 2006; Fath et al., 2010; Zhang et al., 2010, 2016). The technique of ENA is not limited to intra-system flows scaled on a single level such as city, region or country but also applied to study interregional energy flows between connected cities at combined levels, as demonstrated in the case study of Beijing-Tianjin-Hebei in China (Zheng et al., 2018).

To understand the requirements on resource management and examine the metabolic characteristics of an urban system, application of ENA on 35 functional urban areas in England and Wales was implemented in this study. ENA linked the socio-economic sectors in the urban area in an inter-connected network and investigated the pairwise metabolic relationships through the intra-city monetary transactions, reflecting the dependencies of the urban ecological network in terms of its resources flows and consumptions. The study was further extended with the estimated geographical distance between the sectors from the respective workplace zones classifications to address the spatial impact of urban network. For city planning and policymaking, this work demonstrates a better understanding of different resource demands and circulations within the local flow network, enabling the regulation of the needs and wastes of each sector in the city. Strategic resource management should improve the efficiency of the urban metabolism and lead to long-term benefits for the society.

The goals of this paper are twofold, firstly, it presents a novel attempt to conduct an in-depth inspection of intra-city metabolism across all urban areas in England and Wales at an aggregated level, highlighting the ecological interactions between the components of the urban ecosystem as a whole. Secondly, this paper addresses the spatial characteristics of urban network community structure and discusses the impact on community classification based on flow densities.

The rest of the paper is organised as follows. The next section in this paper explains the methodology adopted in the process of data sourcing and preparation, followed by the ecological methodologies and the functional analysis implemented in this work. Furthermore, the result of metabolic relationships and network community structures are also included. The final section concludes the study with the potential implications and future investigations on intra-city metabolism.

2. Methodology

2.1. Data preparation

The UK National Input-Output Supply and Use Table 2011 published by Official National Statistics (Office for National Statistics (ONS, 2017a) was used in this study. In order to examine the flow at a local scale, the data for Gross Value Added (GVA) 2011 (Office for National Statistics (ONS, 2017b) of different sectors for each functional urban area were used to scale down the national flow data accordingly, assuming the same ratio for local production and consumption of goods and services compared to the national figures. This could result in erroneous estimations of import and export since international cross-boundary flow does not scale with the local GVA. The resultant format of the input-output data for all industrial sectors must comply with Leontief's model (Leontief, 1986). The input-output monetary flows within the city were tabulated in the form of a balanced square matrix. This was then used as the adjacency matrix was to construct the resource flow network. In this paper, 35 case studies were identified based on the boundary of functional urban areas in England and Wales. Table 1 shows the abbreviation and name for all 35 functional urban areas, in a decreasing order of their total population. The urban audit boundary was set to define the scope of the study for 35 functional urban areas in England and Wales, which includes the core central city of each area and its commuting zones (Eurostat, 2017). In this case, the wider functional urban areas might consist of multiple local authorities (the lowest administrative level of local governing councils) as data collecting units. The resultant data of urban population and GVA of the urban areas were obtained by combining all the local authorities within the respective boundaries.

The sectors in the National Input-Output Supply and Use Table at intermediate product level were categorised according to UK Standard Industrial Classification of Economic Activities (SIC2007) (Office for National Statistics (ONS, 2017d) to allocate the 105 sectors to 11 categories of the GVA data provided by the local authorities based on the types of economic activity, as shown in Table 2. This was to reduce the resolution of economic activities in order to obtain the input-output flow data at urban level through GVA scaling. See Supplementary Tables S1 and S2 for the national input-output data of 105 and 11 sectors respectively. See Supplementary Table S3 for local intra-city input-output table for 35 urban areas, scaled to local GVA.

Workplace zones classification data based on the workforce populations (Cockings et al., 2015) were applied to investigate the spatial distribution of the local community structure and its impact on resource consumption. Sector allocations were carried out based on the employment data documented by ONS (2012) in each workplace zone and two sectors with the two highest workforce populations were selected. There were two exceptional cases of special condition in this part: first, if the employment number for multiple sectors are similar, the zone is allocated under multiple sectors simultaneously; second, if one sector only exists in a particular workplace zone, it is selected regardless of its population in that area. Geographic Information System (GIS) was used to measure the spatial distance between the sectors within the urban areas and to study the relationship between the spatial connection among the sectors and their monetary flows. The "spatial join" function combined the workplace zones with each urban audit function area of the 35 cases (Office for National Statistics (ONS, 2017c) inspected in

Table 1
Name and abbreviation of 35 functional urban areas in England and Wales.

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

[a] Combined regional data based on Local Authority in the UK (2011) (Office for National Statistics (ONS, 2017c).

this study. The centroid, or geometrical centre of each polygon in the workplace zone area was identified using GIS to represent the location of the respective sector, as shown in Fig. 1. A distance matrix (11 × 11) was generated to tabulate the average pairwise distance between all 11 sectors for each area.

2.2. Ecological network analysis

The conceptual ecological network model in Fig. 1b shows that each node represents a sector, located at the centroid of each workplace zone on the map of an urban area and the arrow connection between the nodes represents the resources flow. In this study, the network had bi-directional flows with different weights, corresponded to the monetary value of the flows. For steady-state operation, the input-output flow system was assumed to be in equilibrium, where the sum of inflows equals to the sum of outflows, $T_i^{(in)} = T_i^{(out)}$. Given that f_{ij} represents flows from compartment j to compartment i and vice versa, the formulae for total inflow and outflow at compartment i are

$$T_i^{(in)} = T_i = \sum\nolimits_{j=1}^{n} f_{ij} + z_i \tag{1}$$

Table 2
Industrial classification.

Sector Number	Sector Code	Contents
1	A	Agriculture, Forestry and Fishing
2	BDE	Production other than manufacturing: Mining and quarrying Electricity, gas, steam and air conditioning supply Water supply, sewerage, waste management, remediation activities
3	C	Manufacturing
4	F	Construction
5	GHI	Distribution: Wholesale and retail trade; repair of motor vehicles and motorcycles. Transport and storage Accommodation and food service activities
6	J	Information and Communication
7	K	Finance and Insurance Activities
8	L	Real Estate Activities
9	MN	Business Service Activities: Professional, scientific and technical activities Administrative and support service activities
10	OPQ	Public Administration and defence; compulsory social security Education Human health and social work activities
11	RST	Arts entertainment and recreation Other service activities Household activities for own use.

$$T_i^{(out)} = T_j = \sum\nolimits_{j=1}^{n} f_{ji} + y_i \tag{2}$$

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

However, the initial regional input-output table was not in equilibrium. Inter-city flows were not accounted when scaling down the input-output flows according to local *GVA* data. Only the national import and export were taken as cross-boundary flow into and out of the city. To balance the local intra-city input-output table, any computed difference between the initial $T_i^{(in)}$ and $T_i^{(out)}$ was treated as addition to the total cross-boundary flows around each urban area, regardless of inter-city or international flows.

With the balanced flow matrix, the Ecological Network Analysis (ENA) method (Chen and Chen, 2015; Fan et al., 2017; Fath and Borrett, 2006; Fath et al., 2010; Jørgensen, 2000; Zhang et al., 2010, 2016; Zheng et al., 2018) was employed to study the metabolic relationships between the sectors within an urban area with each sector being treated as a compartment in the urban network. The functional analysis frameworks of ENA are as demonstrated in the next section.

2.2.1. Throughflow analysis

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

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

$$g'_{ij} = \frac{f_{ij}}{T_i} \tag{4}$$

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

$$N = G^0 + G^1 + G^2 + G^3 + \ldots + G^n = (I - G)^{-1} \tag{5}$$

$$N' = (G')^0 + (G')^1 + G(G')^2 + (G')^3 + \ldots + (G')^n = (I - G')^{-1} \tag{6}$$

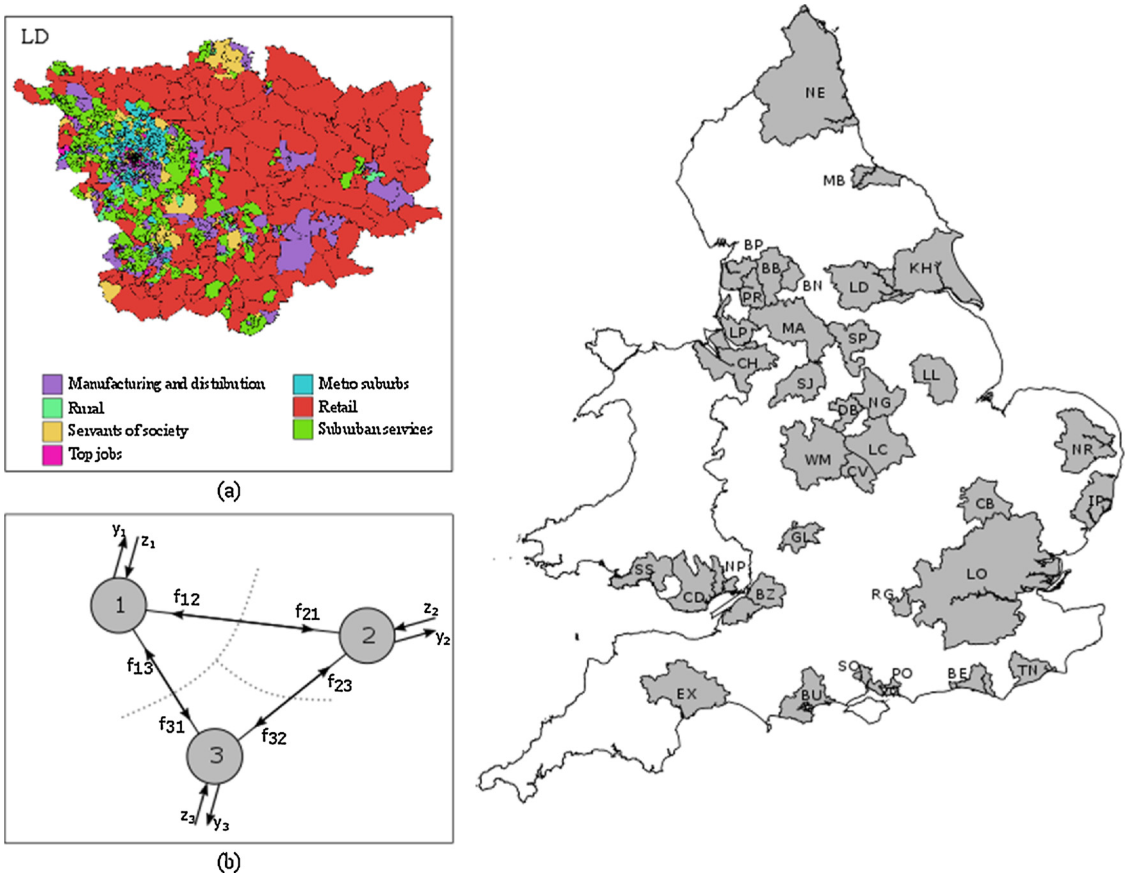


Fig. 1. Map showing the geographical location of 35 functional urban areas including (a) the workplace zones in Leeds with its respective classification based on industrial type and (b) the conceptual schematic diagram of Leeds to demonstrate the network model with multiple sector nodes and connecting flows between them.

The identity matrix G^0 and $(G')^0$ represent the self-flow of the compartments, G^1 and $(G')^1$ represent any one-step, direct flow between 2 compartments, G^2 and $(G')^2$ represents any two-step, indirect flow between 2 compartments and G^n and $(G')^n$ represents the n -step, indirect flow between 2 compartments in the network. This enables the integral throughflow across multiple path-lengths to be considered in ENA.

2.2.2. Control analysis

Control Analysis (Schramski et al., 2006) was conducted to quantify control and dependency relationships between the compartments. Control Allocation (CA) matrix reflects how the receiving sector controls the supplying sector, while Dependence Allocation (DA) Matrix reflects how the supplying sector depends on the receiving sector. The equations for CA and DA:

$$CA = [ca_{ij}] = \begin{cases} n_{ij} - n'_{ji} > 0, & ca_{ij} = \frac{n_{ij} - n'_{ji}}{\sum_{i=1}^{m} n_{ij} - n'_{ji}} \\ n_{ij} - n'_{ji} \leq 0, & ca_{ij} = 0 \end{cases} \tag{7}$$

$$DA = [da_{ij}] = \begin{cases} n_{ij} - n'_{ji} > 0, & da_{ij} = \frac{n_{ij} - n'_{ji}}{\sum_{j=1}^{m} n_{ij} - n'_{ji}} \\ n_{ij} - n'_{ji} \leq 0, & da_{ij} = 0 \end{cases} \tag{8}$$

The results control and dependency relationships are expressed on a scale of 0 to 1 based on to what extent the sectors are in control or dependent on one another.

2.2.3. Utility analysis

In Utility Analysis (Patten, 1991; Fath and Patten, 1998), the type of the inter-compartment relationships can be characterised by using the dimensionless integral utility intensity matrix, U, which is formulated as

$$U = D^0 + D^1 + D^2 + D^3 + \ldots + D^n = (I-D)^{-1} \tag{9}$$

where D is the direct utility intensity matrix, in which the elements d_{ij} can be calculated as

$$d_{ij} = \frac{(f_{ij} - f_{ji})}{T_i} \tag{10}$$

From the positive or negative signs of the pair (u_{ij}, u_{ji}) in U matrix, the types of ecological relationship between compartments i and j can be determined, as summarised in Table 3.

- If the signs of u_{ij} and u_{ji} are both positive (+, +), both compartments benefit from each other and hence have a mutual relationship.
- If both u_{ij} and u_{ji} are negative (−, −), it means the two compartments are negatively influenced by each other and compete for resources available so there is a competitive relationship.
- If u_{ij} is positive while u_{ji} is negative, then compartment i receives positive benefit from compartment j while compartment j receives negative impact from compartment i, in which case, compartment j is the prey and is being exploited, while compartment i is the

Table 3
Ecological relationship between two compartments based on sign pairs from U matrix.

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

predator and exploits compartment j. Hence, it is an exploitation relationship when u_{ij} and u_{ji} have different signs $(+, -)$, or vice versa.

To identify the overall inter-compartment relationships of the network, two dimensionless quantities, namely, mutualism index, M, and synergism index, S, were computed from U. M is defined as ratio of the total number of utilities with positives signs to the total number of utilities with negative signs in the U matrix.

$$M = \frac{S_+}{S_-} = \frac{\sum \max[sgn(u_{ij}),\ 0]}{-\sum \min[sgn(u_{ij}),\ 0]} \tag{11}$$

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

$$S = \frac{\sum \max(u_{ij},\ 0)}{-\sum \min(u_{ij},\ 0)} \tag{12}$$

Hence, the overall benefit gained by a system is proportional to the S value which depends on the signs of the utility elements, u_{ij} computed from the flow amount between the sectors. High S value indicates more benefits at lower cost.

2.2.4. Network community detection

Networks are divided into modules or grouped in smaller clusters when the nodes of the same cluster have denser connections compared to other nodes. In this study, clusters of economic sectors were treated as communities and modularity measures the strength of these communities. Modularity of a network can be computed using a community detection algorithm (Blondel et al., 2008) to study the clustering properties of the nodes and classification of the community groups based on the flow weights. The algorithm determines the community classification by unfolding the hierarchical structure of the system and calculates the optimised modularity based on the clustering properties of the network. It by-passes the resolution limit (Fortunato and Barthélemy, 2006) to detect smaller communities in the given network of small number of nodes.

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

3. Results and discussion

Across all 35 functional urban areas in England and Wales listed in Table 1, Leeds, one of the major cities in the UK, was used as the example to represent the common case observed in the results, unless stated otherwise. This is because Leeds showed average performance and exhibited the urban structure commonly found in other areas through in-depth investigations at different perspectives.

3.1. Intra-city metabolism

From an ecological perspective, intra-city metabolism resembles a natural ecosystem consists of multiple hierarchical levels. Individual units in different levels are connected through interactions with each other in the form of a pyramidal structure based on the ecological characteristics (producer or consumer) of the units, as shown in Fig. 2.

Those units represent different roles in the ecosystem to maintain the functionality of the system and promote organisational growth as a whole. From the lowest level, the producer supplies resources to the units in upper levels to fulfil their needs or in other words, the upper levels survive on sufficient inputs from the lower levels. These form unique paired relationships among the units in different hierarchical levels and the types of existing relationship can be explored through ENA.

Fig. 2. Pyramidal structure showing the different hierarchical of an ecosystem.

Control Analysis identifies the degrees of control relationship based on consumption-input and dependence relationship based on production-output between the 11 sectors. Fig. 3 shows the results of network control (CA) and network dependency (DA) relationships for the urban ecological network with a normalized scale from 0 to 1.

Network control result in Fig. 3a shows that *Business* was not controlled by any other sectors but it controlled the consumption-input of all 10 other sectors in Leeds network. The highest degree of control relationship was 74% over *Production*, followed by 68% control over *Finance and Insurance*. In terms of dependency relationship in Fig. 3b, *Business* was completely independent while the *Public Administration* was found to be highly dependent on the production-output of other sectors, in which it fully dependent on *Distribution* and not been depended on by any other sector in Leeds.

Furthermore, the average of CA and DA matrices across all 35 cases were computed to investigate the overall network control and dependency relationships in all 35 urban areas. From the average network control results in Fig. 3c, *Business* remained as the key controlling sector of resources consumption-input in those urban areas. In this context, identifying the significant control relationship in the urban ecological network helps in understanding the functions of each economic sector and the impacts on other sectors. For the case in Fig. 3c, the network control relationship between *Business*, *Production*, *Manufacturing*, *Construction* formed a structured ecological pyramid to demonstrate the resources supply chain from the producer at the lowest level to the top-levelled consumers, as shown in Fig. 4a. The chained relationship between these sectors formed a control hierarchy as the resources supply from the lower level controls the consumption of the level above it, and affects all the subsequent levels, under the same principle as the natural ecosystem pyramid shown in Fig. 2. To connect the producers to consumers, processes of material transformation at the intermediate levels were being controlled by the producers while it also had control over the consumers. However, due to the high population densities and intensive business activities in the urban areas, the *Business* sector remained in strong control over all other sectors, hence it was placed at the lowest level of the pyramid to show its dominance over the consumption of all the upper sectors despite of being a resources consumer in nature. This presents a challenge in regulating the supply and demand for resources in urban development planning to ensure sustainable consumptions with adequate production flows within the network.

From the average network dependency results shown in Fig. 3d, dependency relationship was identified between *Finance and Insurance*, *Real Estate*, *Distribution* and *Public Administration (PA)*. On the highest level of the pyramid shown in Fig. 4b, PA activities such as education, social security and defence depended on the production of *Distribution* sector, including the services provided by the local transportation system and goods delivery. On the second highest level, *Distribution* was dependent on *Real Estate* on the lower level which in turn relied on the production of *Finance and Insurance* on the lowest level of the pyramid.

Further analysis on stable metabolic relationship identified the repetitive characteristics in the pairwise relationships which the 35 urban

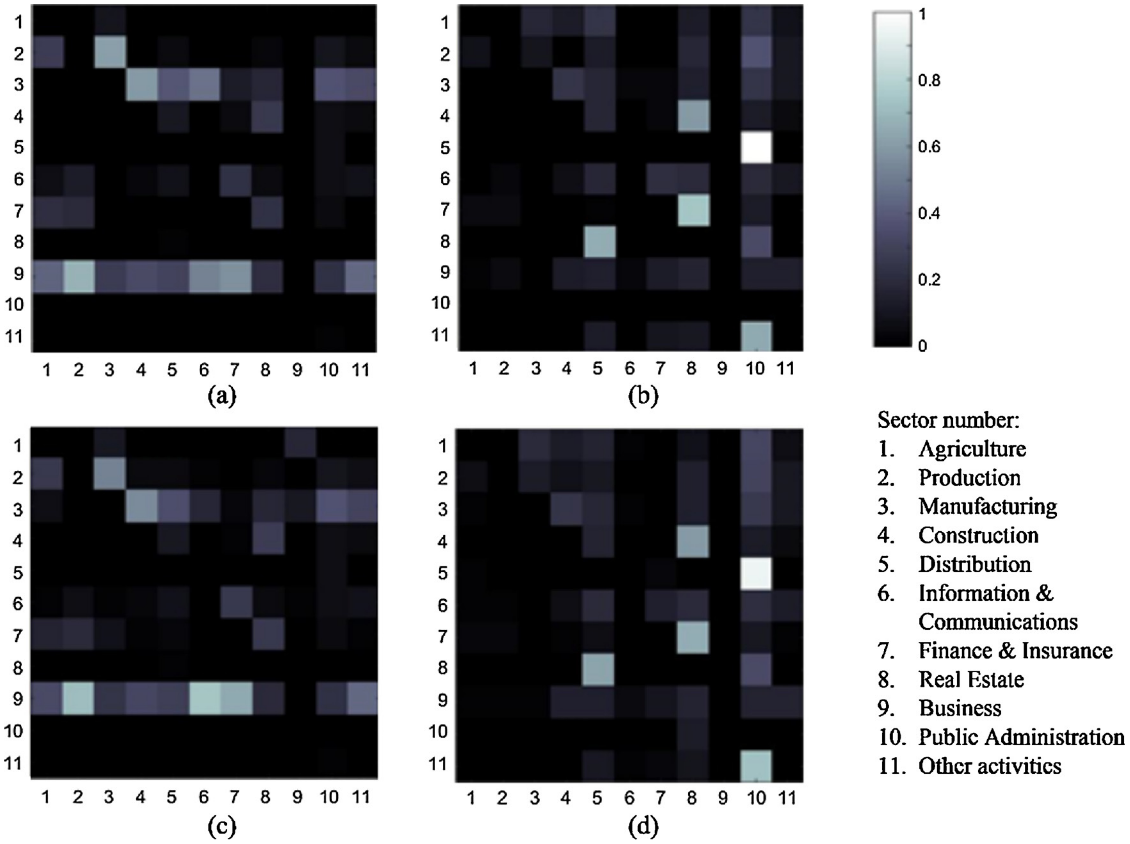


Fig. 3. Results of (a) network control (sector number in column controlled by row sector) and (b) network dependency (sector in column depended on row sector) of Leeds, and the average results of (c) network control (sector in column controlled by row sector) and (d) network dependency (sector in column depended on row sector) of all 35 functional urban areas.

areas have in common. This was done by intersecting 35 sets of relationship matrices of all areas to find the common relationships. The results are tabulated in Fig. 5 as a symmetrical square matrix along the diagonal based on the types of relationship. Moreover, the exploitative relationship is directed to tell which sector is being exploited by the others. See Supplementary Table S4 for tabulated relationship matrices of 35 urban areas.

Excluding self-flow at each sector for internal promotions (Patten, 1991), no stable mutualistic relationship was found in all 35 cases. Three pairs of competitive relationship were observed in six different sectors. Exploitative relationship dominated the overall network as fifteen pairs were observed, with the highest occurrence at the *Distribution* sector for exploiting others while the *Business* sector was mostly exploited by others. For instances, *Distribution* exploited *Production*, *Manufacturing*, *Real Estate* and *Business*. On the other hand, *Business* was being exploited by *Construction, Distribution*, *Public Administration* and *Other Activities*.

Fig. 6 shows the results of M and S indices from Utility Analysis on all 35 urban areas, in a decreasing order of the index values from left to right on the horizontal axes. Box plots are used to show the data distribution across all cases.

From Fig. 6a, only ten cases, which corresponded to seven urban areas in the ten highest populated areas and also Reading (Rank 27), Brighton and Hove (Rank 21), and Portsmouth (Rank 14) have mutualism index value greater than 1, indicating a healthy urban metabolic system. The average M across all 35 cases was 0.93 which implies only 48% of all utilities were positive, in which London had the highest mutualism index of 1.20 and Blackburn had the lowest, 0.70. It is worth noting that these areas have comparative synergism indices as shown in Fig. 7 and were both above the average value. In term of S, Leeds (Rank 6) lied at the average value of 3.56 with Derby (Rank 23) at the highest and Ipswich (Rank 30) was the lowest. With larger population in major urban areas, formation of a more diversified and matured economic structure strengthened the connections in the network to promote mutual benefits locally for growth.

By definition, M measures the overall system mutuality quantitatively by the number of positive or negative utility count observed while S takes into account of the numerical magnitude so it is affected by the quality of each count. From observation in Fig. 6a, M changed gradually from the highest value on the left to the lowest value on the right compared to the change in S which showed a larger difference in the values between two consecutive areas illustrated in Fig. 6b. The gap between the highest and the second highest S values was seven times larger than the gap between the second and third highest S values.

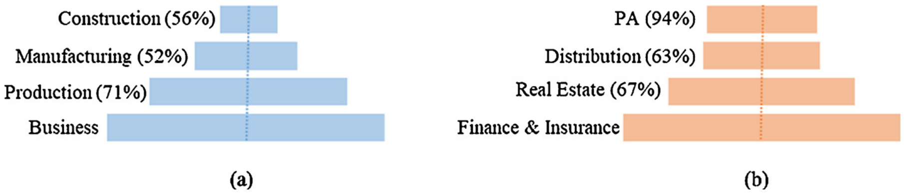
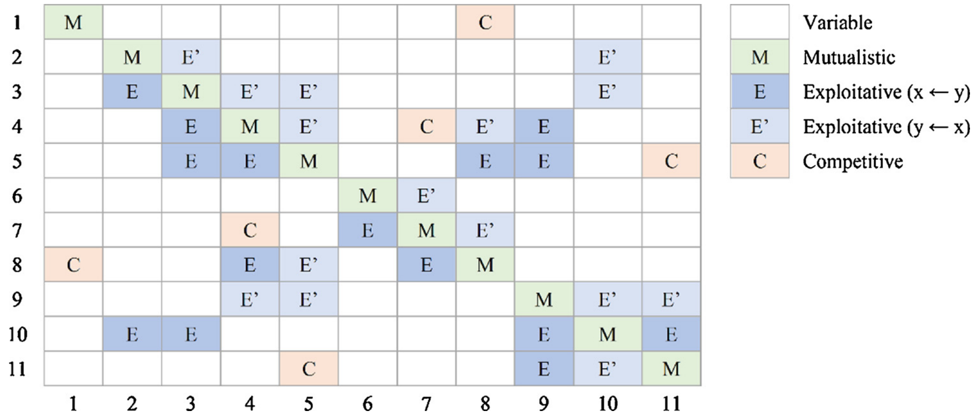


Fig. 4. Pyramidal structure of urban ecosystem based on (a) *CA* and (b) *DA* results. The width (shown in percentage) of each level reflects the degree of control or dependency relationships between the sector and the sectors the lower level.



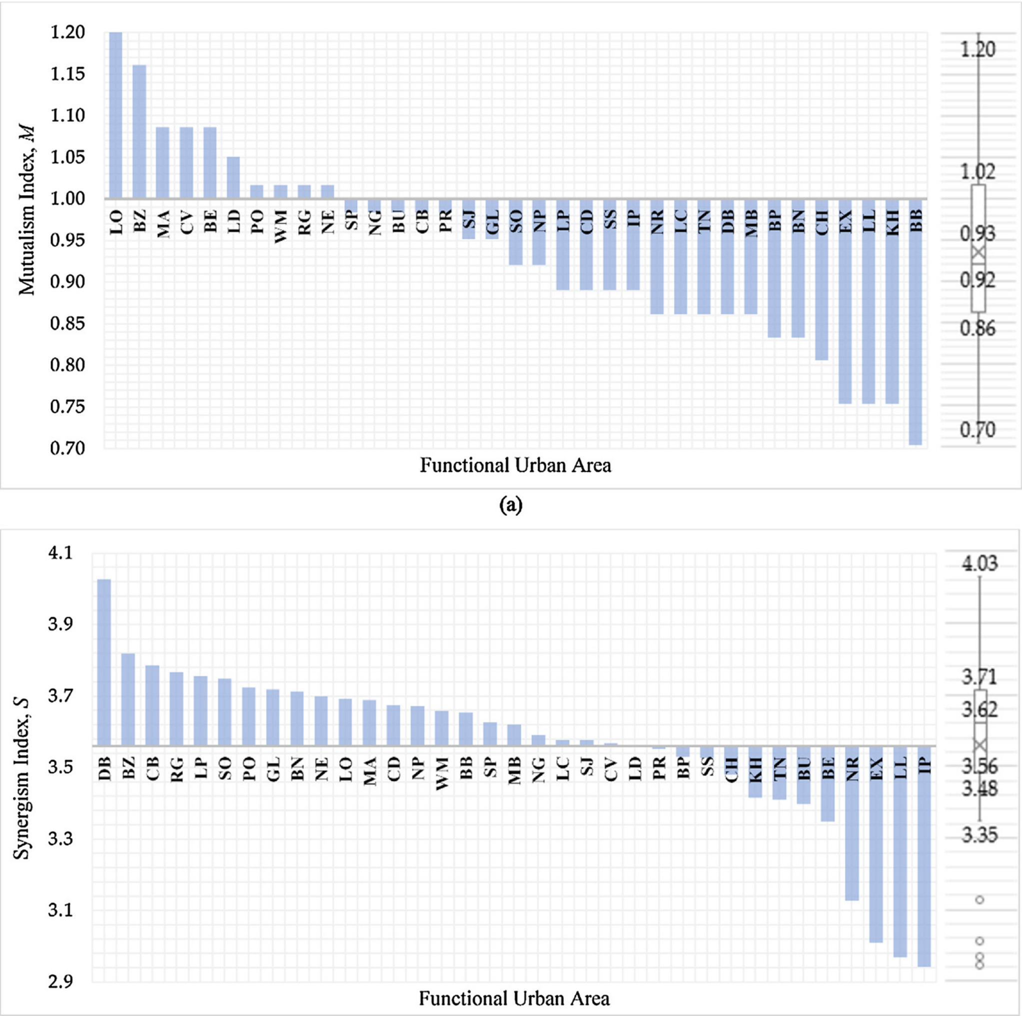
	1	2	3	4	5	6	7	8	9	10	11
1	M							C			
2		M	E’							E’	
3		E	M	E’	E’					E’	
4			E	M	E’		C	E’	E		
5			E	E	M			E	E		C
6						M	E’				
7				C		E	M	E’			
8	C			E	E’		E	M			
9				E’	E’				M	E’	E’
10		E	E						E	M	E
11					C				E	E’	M

	Variable
M	Mutualistic
E	Exploitative (x ← y)
E’	Exploitative (y ← x)
C	Competitive

Fig. 5. Stable relationships between the 11 sectors across all 35 urban areas.

According to the distribution of S data shown in the box plot, the four lowest values were the outliers in this case. This was due to the large differences between the magnitudes of those positive utilities in the U matrix. The main contributor of those positive utilities was the self-flow of a sector for internal benefits and promotions, so these observations suggest that the inter-sectoral flows were less mutualistic than the internal flows and more prompted to exhibit an exploitative relationship with other sectors. This is supported by the domination of exploitative relationships (Fig. 5) which made up to 64% (Competitive 20; Mutualistic 16%) of the overall urban metabolic system across all 35 cases.

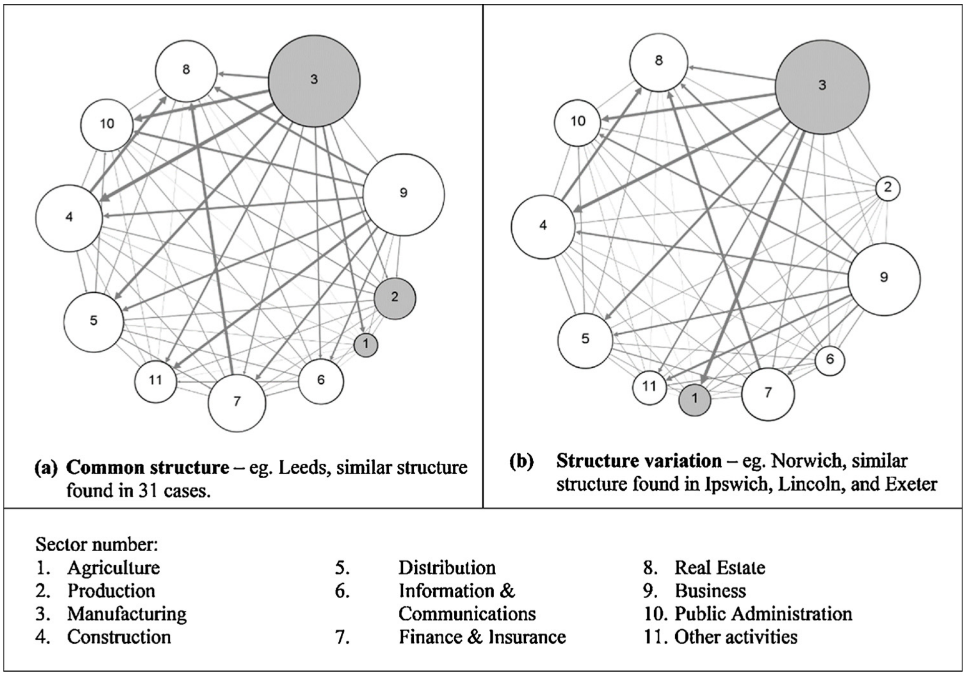
Findings from the Utility Analysis agreed with the pyramidal structure of the urban metabolic ecosystem constructed based on the network control and dependency results from the Control Analysis. *Business* sector was located at the lowest hierarchical level of the ecosystem as the limiting factor on the system's metabolism by controlling the consumption of other sectors and it is also mostly exploited by other



(a)

(b)

Fig. 6. Bar charts of (a) Mutualism index, M and (b) Synergism index, S of the 35 urban areas and the respective data distribution plot.



(a) **Common structure** – eg. Leeds, similar structure found in 31 cases.

(b) **Structure variation** – eg. Norwich, similar structure found in Ipswich, Lincoln, and Exeter

Fig. 7. Classification of community groups into two clusters based on throughflow network (white nodes for the large cluster and grey nodes for the small cluster) showing (a) the common structure in Leeds and (b) the variation observed in Norwich.

sectors as a consumer.

3.2. Network community structure

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

Visualisation software was used to demonstrate the classification of colour-coded community groups in all urban areas studied. The results of community groups classification based on throughflow network are as shown in Fig. 7. The common network community structure was illustrated using the example of Leeds in 2011, which shared the similar clustering structure with 30 other cases including some of the highly populated urban areas such as London, Birmingham Manchester, Liverpool, Newcastle as well as areas with smaller population in Burnley, Hastings and Cheltenham. The size of the nodes and edges are proportional to the overall degree and weight of the flow respectively. The placement of nodes was arranged in a circular layout with descending order of weighted in-degree to each node in counter-clockwise direction to show the consumption-input of resources at each sector.

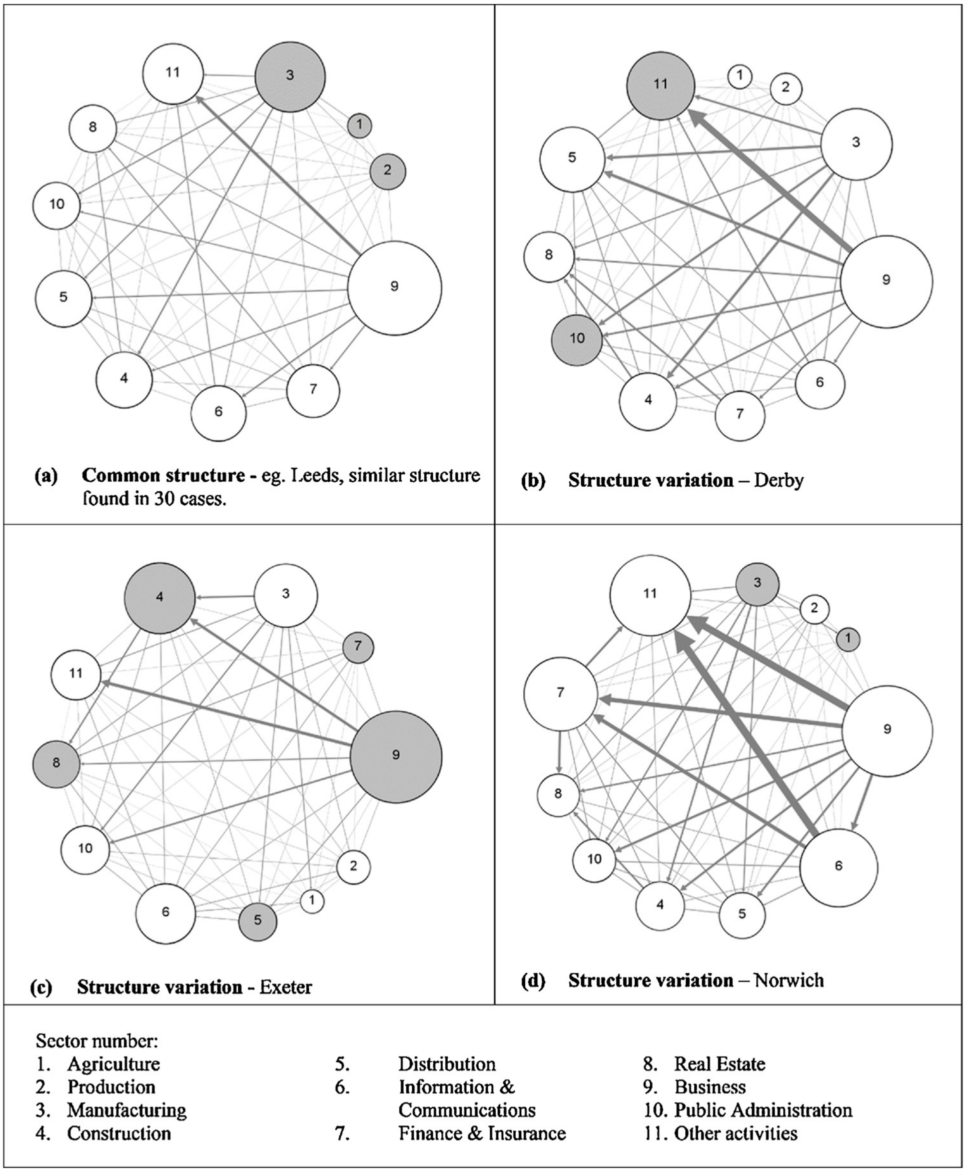
As in Fig. 7a, the largest node, *Manufacturing* had the highest weighted overall degree as it plays an important role in the processes of energy transformation as an intermediate consumer, connecting the producing sector to the final-users. However, according to the placement order of the nodes in counter-clockwise direction, *Manufacturing* had the lowest weighted in-degree of resources consumption flows into the sector, followed by *Business*, implying that *Manufacturing* and *Business* sectors were the main producers in the network with high output contributions and low input consumptions. In richer areas with fast growing business activities and higher GVA per capita, such as London and Reading, the *Business* sector overtook *Manufacturing* as the largest node within the intra-city network. An exceptional case is Kingston upon Hull where *Construction* was larger than *Business*. On the other hand, *Real Estate*, had relatively high consumptions as it was ranked as the lowest in terms of weighted in-degree among the 11 sectors although *Agriculture* was the smallest node with the lowest weighted degree in all cases.

In terms of community group classifications, two clusters were formed which consist of eight and three sectors respectively.

- Larger cluster: Business, Information and Communication, Finance and Insurance, Other Activities (including arts, entertainment and household activities), Distribution, Construction, Public Administration and Real Estate
- Smaller cluster: Manufacturing, Production and Agriculture

From the clustering structure, the producers and intermediate consumers in the small cluster had higher tendencies to form a cluster among those sectors with stronger economic connections. The larger cluster in the network consisted of mostly final consumers or end-use sectors in the ecosystem. The two largest nodes with the highest overall weighted degrees, *Manufacturing* and *Business*, belonged to two different community groups. Hence, the classification of the remaining nine sectors could be influenced and determined by the weightage of the flow connections between the remaining nodes and the two largest nodes, representing the two clusters. In Leeds, the eight sectors in larger cluster were mainly the consumer-type receivers from *Business* sector while the remaining three sectors in the smaller cluster act as the producer-type suppliers to *Business* with supportive role.

A different type of community structure, as shown in Fig. 7b was



(a) Common structure - eg. Leeds, similar structure found in 30 cases.

(b) Structure variation – Derby

(c) Structure variation - Exeter

(d) Structure variation – Norwich

Fig. 8. Classification of community groups into two clusters based on throughflow density network (white nodes for the large cluster and grey nodes for the small cluster) showing (a) the common structure in Leeds and the variation observed in (b) Derby, (c) Exeter and (d) Norwich.

observed in Norwich, Ipswich, Lincoln and Exeter. In these areas, the *Production* sector belonged to the large cluster dominated by *Business* and the smaller cluster consisted of two nodes: *Manufacturing* and *Agriculture* only. Comparing this result with the more common structure in Fig. 7a, the *Production* sector was more connected to consumer-type receivers in the larger cluster with more connections and increased its overall degree. This might be caused by overwhelming consumption of resources in these areas resulting in insufficient production to meet the high demand. Nonetheless, the types of economic activities (including mining, quarrying, electricity and water supplies) in *Production* sector indicates its fundamental role as a primary producer in an urban ecosystem. In this study, the analysis was limited to intra-city flows only hence, any inter-city supplies of resources such as export of local products to other regions was not considered. Further investigations on inter-city metabolism could explore the flows between different areas and their interactions with the external surroundings.

Investigations of the spatial impact of geographical distance between the sectors on network community structure gives throughflow density networks, as shown in Fig. 8. Classification of community groups based on throughflow density network in Fig. 8a were similar to the throughflow network in most cases with the common structure shown in Fig. 7a. The sectors were grouped based on its economic activities and functioning roles in the urban ecosystem, either consumers-type in the large cluster or producer-type in the small cluster. However, sizes of the node differed in the throughflow density networks because the weighted degree changed with the average spatial distance between the sectors. In the density networks, *Business* had higher degree and denser connections than *Manufacturing* and the size of the *Manufacturing* node decreased with low density due to the larger distance between industrial zones for manufacturing activities and the other consumers in the same urban area. In contrast, the biggest node, *Business* sector processed higher density flows due to its proximity benefits from closer location and higher accessibility to the consumers in other sectors.

In some cases, the lower degree and reduced dominance of *Manufacturing* sector in the density network resulted in more complicated interactions in the urban ecosystem when the impacts of spatial characteristics were considered. For example, the throughflow density network of Derby in Fig. 8b shows both the producers and consumers were found in the large cluster while the small cluster consisted of

Public Administration and *Other Activities* only. The producer and consumer sectors are well spatially scattered and equally distributed across the area owing to the strategic geographical location of Derby in the Midlands, spanning the central region of England (Midlands Connect, 2017). Derby's highly connected resources network contributes to its highest synergism index ($S = 4.03$) and benefit-to-cost ratio across all 35 areas.

Another variation in Fig. 8c shows the different clustering properties in Exeter where the *Manufacturing* node was smaller than *Business* and *Construction*. In Norwich, classification of community groups based on throughflow density network shows a similar structure as its throughflow network except for the changes on the size of the nodes due to the spatial distribution of the sectors in the urban network, as shown in Fig. 8d.

There were insufficient spatial data on several sectors in Blackpool and Burnley, resulting in smaller sample sizes for the number of sector nodes in the network and therefore, Structural Analysis on clustering properties of the throughflow density network of these areas are excluded in this study.

3.3. Implications and limitations

The intra-city flow network, constructed with ENA and supplemented with the geographical distance between the workplace sectors, represents the inter-connected structure of an urban ecosystem. The flows between the sectors were projected in the network to study the distribution of resources within the boundary of a functional urban area. Understanding the ecological relationships between the sectors and the classification of the community groups in an urban network helps to identify the points of intervention for efficient policymaking with larger impact by targeting the dominating sector with the strongest influence on other sectors. This provides a foundation to build an effective resource network in urban areas through regulating the overall production and consumption of the sectors through the chained relationships in the intra-city ecosystem.

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

On intra-city level, granularity of data remains the main constraint since scaling to aggregated urban level from larger scales (eg. national and regional data) is required. Cross-boundary flows including imports, exports and inter-city flows are excluded from the analysis of network community structure due to the limitations of data available. The steady-state assumption was made to compensate for any unbalanced flows with external import or export. As such, the downside would be negligence of the differential between inter-city and international trade flows. Although the approach taken in this study managed to capture the interactions between the sectors at intra-city level, there will be space for improvement if more detailed data becomes available to future researchers.

In this study, monetary transactions of the Input-Output Supply and Use Table were used as material flows between the sectors within urban areas. Nonetheless, in reality, monetary and material flow accounts are non-equivalent. To counterbalance for any non-equivalences between the flow values, there is a need to explore the knowledge gaps in understanding of the correlation between monetary and material flows for different sectors in future research. Other suggestions for further investigations are: (1) data acquisition at local urban level for each urbanised area including inter-city flows to accurately account for all cross-boundary flows in and out of the area; (2) trends and temporal changes in the metabolic relationships and community structure between the sectors within the network; (3) the impacts of spatial distribution on the characteristics of metabolic relationships and the relevant numerical indices.

4. Conclusion

The ENA results in this study described the metabolic characteristics of the urban system in England and Wales as exploitative. The exploitative behaviour observed in the ecological network of 35 functional urban areas suggests that their metabolic systems are still in developing phase for further improvements. The *Business* sector was being exploited by others and also in control of the consumptions in most of the other sectors. The sector was exploited as it was at deficit in terms of the resultant throughflow with higher outflows than inflows passing through the *Business* node. As such, the sector also acted as the limiting node or the "gatekeeper" to control the amount of resources received and consumed by other sectors. Highly concentrated business related activities and services in cities have significant impact on urban metabolism. Mutualism and synergism indices generated prove that London has the most matured system among those cities. Economic diversity in the urban areas with larger population contributes to the development of healthy urban metabolic systems through balancing and regulating the distributions of resources among different sectors in the cities based on various types of activities and demands for different resources.

In terms of community structure, the classification of sectors shows the importance of the inter-relationship within the organisation of each community class. In most of the areas, formation of the producer-type and consumer-type clusters separated the economic sectors based on their respective hierarchical roles in the ecosystem. The producer-type cluster maintains the foundation of resources supply chain to different sectors in the cities while the consumer-type cluster focuses on the distribution of resources received by the consumer sectors for final expenditure. The throughflow density network emphasizes on the impact of spatial distance between the sectors within a functional urban area. The analysis considered the size of the city, proximity and accessibility of those sectors. In the case of Derby, the geographical location of a city could also affect the community structure of its ecological network. This result emphasises on the importance of addressing the impact of spatial distribution in planning resource management strategies.

Understanding the correlations between the economic activities and their spatial distribution assists policymakers in the decision-making process and implementation of sustainable resource management strategies. This study has considered the intra-city network of all functional urban areas in England and Wales to provide a better understanding for the characteristic sectoral exchange patterns in the overall urban system of England and Wales which facilitates development of national levers for change, rather than solutions isolated to a single city.

Author contributions

Ling Min Tan, Hadi Arbabi, Danielle Densley Tingley and Martin Mayfield have designed the study. Ling Min Tan, Hadi Arbabi, Qianqian Li and Yulan Sheng have undertaken the study. Ling Min Tan has critically analysed the results and wrote the manuscript. Danielle Densley Tingley, Martin Mayfield and Daniel Coca contributed to the discussion and the manuscript. All authors have given approval to the final version of the manuscript.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2018.06.010.

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Update

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Corrigendum

Corrigendum to "Ecological network analysis on intra-city metabolism of functional urban areas in England and Wales" [Resour. Conserv. Recycl. 138 (2018) 172–182]

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The authors regret to inform the readers on a phrasing mistake that could result in potential misinterpretation of the material. In the published paper, page 175, section 2.2.2, first paragraph, second sentence:

> "Control Allocation (CA) matrix reflects how the receiving sector controls the supplying sector, while Dependence Allocation (DA) Matrix reflects how the supplying sector depends on the receiving sector."

The receiving and supplying sectors are referenced incorrectly with respect to the control/dependence relationships. In this case, the correct sentence should be:

> "Control Allocation (CA) matrix reflects how the supplying sector controls the receiving sector, while Dependence Allocation (DA) Matrix reflects how the receiving sector depends on the supplying sector."

We can further confirm the mistake mentioned above does not affect the rest of our analysis and results featured in the paper.

The authors would like to apologise for any inconvenience caused.

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