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Research article

Sustainability accounting of neighborhood metabolism and its applications for urban renewal based on emergy analysis and SBM-DEA

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ABSTRACT

Rapid urbanization exacerbates urban metabolic activities associated with irreversible environmental degradation. Evaluating urban metabolic performance is an effective method to meet targets for sustainable development in contemporary urban areas. Neighborhoods, which are regarded as the basic parts of cities, can detail the metabolic structure and interactions from a bottom-up perspective. In consequence, this study proposed an eco-efficiency model which combined emergy synthesis and slack-based measure data envelopment analysis. A case study with questionnaire and statistical data for eight communities in Chongqing, China was used to shed a light on the properties of emergy metabolic flows and eco-efficiency. The results showed that the study communities heavily depended on external resources. Intense communal activities within relatively small geographic areas caused immediate surroundings to suffer from enhanced environmental pressures. Eco-efficiency performances were mostly invalid, and a significant heterogeneity existed among communities. Enhancing the performance of renewable and non-renewable resources whilst also reducing the production of wastes was essential to improve the overall eco-efficiency of local communities. To assist with this, a neighbor-level sustainable renewal framework was proposed which took account of metabolic flows and communal renewal operations. The findings of this study can provide a paradigmatic example for urban renewal projects elsewhere that embed metabolic performance in neighborhood redevelopment.

1. Introduction

Along with rapid urbanization over the past few decades, urban areas have evolved as centers of population. Cities were home to more than 50% of the world's population in 2010; this ratio is projected to increase to 68% in the 21st midcentury (Bassolas et al., 2019; UNPD, 2018). Human-driven activities have subjected to severe metabolic pressure and evoked dramatically irreversible environmental degradation. For instance, nearly 75% of material resources and 80% of energy consumption is consumed to support human activities in urban areas (Pulido Barrera et al., 2018). This situation is especially prominent in China due to unsurpassed economic development and urban intensification. Massive resource depletion, poor living conditions, and mounting environmental pollution have exerted higher pressure on China's urban sustainable development. Therefore, processes of transformation that promise toward sustainable urban development have risen upon the research agenda.

1.1. Study scale and accounting methods of urban metabolism

Urban metabolism introduced by Wolman (1965) focuses on unveiling the mechanism of resources input and wastes output in urban socioeconomic activities on the basis of a biophysical framework (Codoban and Kennedy, 2008). Accordingly, urban metabolism has become a long-standing topic in studies of sustainable urban development, planning, and management (Kennedy et al., 2011). To date, urban metabolic studies covering a wide range of scales, including national level (Velasco-Fernández et al., 2015), regional level (Huang et al., 2018b; Rocco et al., 2018; Tan et al., 2018) and city level (Lei et al., 2018; Qi et al., 2017), have focused on critical metabolic flows, assessed resource distribution, and revealed metabolic mechanism at the macro- and mid-levels. Furthermore, small-scale urban metabolism indicated

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the compelling value of detailing metabolic structure and interactions by providing bottom-up insights (Ai et al., 2019; Codoban and Kennedy, 2008). Incorporating urban metabolism into small-scale urban socio-economic domains has also drawn increasing attention. Household metabolism allows environmental impact at the individual household level to be contextualized. It was regarded as the sources of causing urban metabolic activities (Harder et al., 2017). Some studies have focused on metabolic flows types and household-based metabolism structures (Dombi et al., 2018). Another topic that has been addressed was the unveiling the driving forces of metabolic behaviors for households (Leray et al., 2016). In addition, investigations relevant to the environmental influences of household metabolism as well as its impact on social inequality household metabolism have been conducted (Chancel, 2014; Yang et al., 2012). The neighborhood, as the nexus between urban system and household settlements, is an appropriate unit unraveling intra-urban characteristics and intrinsic drivers of interrelations among cities, households and surrounding environment (Chen and Chen, 2017). Neighborhoods' metabolism provides a valuable insight to design sustainable urban neighborhoods (Codoban and Kennedy, 2008). To date, few studies of neighborhood metabolism have published. Codoban and Kennedy (2008) captured neighborhood-level metabolism properties with the help of four representative neighborhoods. Li and Wang (2009) evaluated the contributions of metabolism in a suburban residential area via the Hybrid Emergy-LCA approach. Luederitz et al. (2013) pointed out that the urban metabolism is one of the principles for developing sustainable neighborhood. Hall (2011) compared the socio-ecological metabolism performance of three neighborhoods to understand the potential for green infrastructure within a rust belt city. Lu et al. (2017) assessed the processes and structure of communal carbon metabolism based on a conceptual carbon metabolic model. Schandl et al. (2020) proposed a three-dimensional urban metabolism model to evaluate environmental performance of the construction activities at the suburb scale. Enrique Vega-Azamar et al. (2017) analyzed the emergy consumption of five typical housing units during the dwelling operational stage. Most of the community-led publications captured the metabolic performance at the small-scale, however, how to merge neighborhood metabolism into neighborhood design has yet to materialize. This could be the main issue when urbanization transfers its role from quantity-led mode into quality-oriented mode.

Metabolic flows, as bridges connecting to the metabolic system, allow reflecting the supply of resources and output to the neighboring environment (Haberl et al., 2019). To account for metabolic flows, material flow analysis (MFA), and energy flow analysis (EFA) are normally used (Zhang, 2013). MFA focuses on calculating multiple material flows and the stocks in a specific system on the basis of the law of the conservation of mass (Kennedy et al., 2011). However, this accounting method fails to portray the quality differences that exist among a set of materials and suffers from weaknesses in depicting the performance of energy flows from a system-oriented aspect (Zhang, 2013). To address this issue, energy flow analysis in accordance with the thermodynamics focuses upon uncovering the sustainable level of urbanization and living standards of urban dwellers through combining different forms of flows from a bottom-up perspective (Facchini et al., 2017). Emergy evaluation, as one of the most important accounting forms in EFA, aims to describe embodied energy (direct and indirect energy) during the process of primary solar radiation to final activities in the forms of renewable and nonrenewable inflows and indirect services (Peng et al., 2018; Zhong et al., 2018). Previous studies have applied emergy theory to investigate the sustainability of ecological systems (Liu et al., 2019b; Qi et al., 2017), resource expenditure distributions and management (Arden et al., 2019), urban metabolic factors (Yu et al., 2016) and biogas project management (Zhang and Chen, 2017) from numerous perspectives. Applying emergy analysis to measure the properties of metabolic inflows and outflows could be an effective way to investigate systematic performance and manifest sustainable goals.

1.2. Eco-efficiency assessment

Eco-efficiency reflects the metabolism capacity to produce more goods and services with less resource depletion and environmental pollution during the urban metabolic process (Schaltegger and Sturm, 1990; WBCSD, 2000). This concept provides a quantitative angle for systemic sustainable evaluations in urban metabolism by considering social, economic and environmental interactions (Zhang and Yang, 2007). To date, ratio approach and frontier approach are the two main analytical methods in eco-efficiency related studies (Robaina-Alves et al., 2015; Wang et al., 2011). The former method determines indicators weights involving subject factors, which may decrease the accuracy of results (Liu et al., 2019c). Data envelopment analysis (DEA) as a frontier approach is capable of embedding multiple indicators into a compatible and encompassing framework (Rashidi and Farzipoor Saen, 2015). This method can automatically determine indicators weights that enable the incorporation of interactions between input and output indicators. DEA method has been widely applied to assess eco-efficiency in existent studies. Specifically, some studies focused on eco-efficiency and its sub-efficiencies to analyze the sustainability of a specific system based on a total-factor analysis framework (Sun et al., 2017; Wang et al., 2016; Yu et al., 2019). Other studies analyzed the spatial distribution of eco-efficiency and its driving forces (Lin and Tan, 2016). Furthermore, coupling emergy analysis with DEA has been employed to reveal the eco-efficiency of urban metabolic interactions in a more accurate manner. For example, Cao et al. (2019) combined emergy evaluation indicators and the DEA Malmquist productivity approach to elaborate on the changes of eco-efficiency in 30 Chinese regions with the aid of time-serious inventory data. Liu et al. (2019c) measured the eco-efficiency, economic efficiency, and environmental efficiency of a typical Chinese coal mining area based on the slack-based measure (SBM) undesirable model and emergy analysis. He et al. (2016), through the use of emergy ecological footprint analysis and DEA, evaluated the characteristics of Jiangsu's eco-efficiency from 1993 to 2012. Wu et al. (2018) conducted a historical analysis of the overall efficiency of urban metabolism and emergy indicators (including structural and functional indicators) at the urban scale by integrating DEA, emergy and principal component analysis. As illustrated above, the combination of emergy analysis and DEA can enable insights into the measurement of eco-efficiency in the context of the urban metabolic system. This is in favor of understanding the mechanism of system operation and achieving urban sustainable development. Unfortunately, the aforementioned studies hardly demonstrated desirable mechanisms by which to combine emergy analysis with DEA to assess eco-efficiency performance at the small-scale.

Traditional DEA models, the Charnes, Cooper, and Rhodes (CCR) and Banker, Charnes, and Cooper (BCC) models, are conducted in accordance with radial measurements that every change of inputs or outputs of need to change of the same proportions (Cecchini et al., 2018). These models fail to compare input slacks (input excesses) and output slacks (output shortfalls) that are important in determining the performance of DMUs (Põldaru and Roots, 2014; Zhou et al., 2019). To tackle this problem, SBM, as one of the most commonly employed non-radial DEA models, was proposed to analyze input and output slacks under the target function (Tone, 2001).

1.3. Urban renewal in Chongqing

Developed areas always confront with redevelopment or rehabilitation when cities growing older. Urban renewal provides a concept that revitalizes existing city fabric to satisfy the needs of urban dwellers with regard to issues of environmental protection (Riera Pérez et al., 2018). Existing research on urban renewal focused on analyzing various material components (eg. land use, housing policy, social infrastructure, and culture) of urban renewal (Doğan et al., 2020; Zheng et al., 2017), evaluating the sustainability of urban renewal projects (Riera Pérez et al., 2018), exploring the relationships of stakeholders (Ay, 2019), and so on.

Chongqing, a typical Chinese southwestern inland city (29.4316° N, 106.9123° E), is the decisive nexus of the Belt and Road and the Yangtze River Economic Zone. In the past three decades, Chongqing has experienced a rapid rural-urban transformation with an increase in its urbanization rate from 32.6% in 1998 to 65.5% in 2018 (CSB, 2018). This process has caused land supply shortages, and large resource consumption; environmental pollution has exerted substantial pressure on local sustainable development. Against this background, plenty of urban renewal researches have been conducted at multiple scales to improve urban rehabilitation and Chongqing's living environment. From the urban perspective, Liu et al. (2019a) investigated the land-use change of the urban area of Chongqing with the consideration of spatial, economic and policy factors. Zhuang et al. (2019) analyzed the characteristics of stakeholders in the local urban renewal decision-making in the Yuzhong District, Chongqing. The neighborhood scale is as a proper scale for triggering sustainable urban renewal planning (Riera Pérez et al., 2018). This is because it able to customize people- and place-based initiatives to meet residential requirements and achieve local sustainability goals. Liu et al. (2014) investigated the influencing factors of service life of demolished buildings in seven communities in Chongqing. Huang et al. (2020) proposed neighborhood-scale urban renewal strategies on the basis of the decision-making framework. However, most of these publications were conducted via social, economic, or environmental aspects for sustainable assessment, which failed to provide a biophysical perspective.

Against this background, this work used slack-based measure data envelopment analysis (SBM-DEA) and emergy flow analysis to diagnose the communal metabolic performance and further proposed a neighbor-level renewal framework. The main contributions of this analysis are as follows. Firstly, this study examined emergy metabolic properties by considering residential behavior. Through so doing, a bottom-up picture of the metabolic interactions among socio, economic, and environmental systems at the neighborhood scale was portrayed. Secondly, by dividing overall eco-efficiency into input and output efficiency it was possible to better highlight the requirements of a metabolic system for sustainable management. Thirdly, by proposing a neighborhood-scale renewal framework based on the communal metabolic performance provided a reference for urban renewal projects elsewhere for nexus of the small-scale urban metabolic performance and urban renewal.

The remainder of this paper is organized as follows: The next section provides an introduction of emergy analysis and SBM model used in the study. Section 3 introduces the properties of the study area and an overview of the data sources. The results of the study's emergy analysis and ecological efficiency (eco-efficiency) are presented in Section 4. Section 5 provides neighborhood renewal implications. The last section presents the conclusions of this study.

2. Methods

2.1. Emergy analysis

The concept of emergy provides a systematic standardized quantification method to reflect the invested energy use that is induced by direct and indirect production processes within the metabolic system (Chen et al., 2017; Odum, 1996). In comparison with other thermodynamic methods, emergy-based analysis calculates energy requirements based on the supply chain, which can capture resource consumption reasonably (Ukidwe and Bakshi, 2004; Yu et al., 2016). Emergy analysis assesses a vast body of material and energy flows by converting them into a unified unit, namely solar emergy joule (sej), which enables measurement of metabolic performance and sustainability based on emergy indicators. Transformity reflects the volume of emergy used in producing one unit of a product. Based on the transformity, raw data of metabolic flows can be converted into emergy value. The conversion can be expressed as:

$$EM = E\tau \tag{1}$$

Where EM is the solar emergy of a product, E is the available energy or mass of a product, and τ is the solar transformity of a product. The geobiosphere emergy baseline used in this study is 1.2E+24 sej/year proposed by Brown and Ulgiati (2016a), which was justified based on the work of (Odum, 2000) and Brown and Ulgiati (2010). The nomenclature of this study is presented in Table 1.

The sustainability evaluation of a system on the basis of emergy synthesis can be conducted by the following three steps:

Step 1 *Drawing an integrated system diagram.* A system diagram identifies the study's scope and reflects the complex relationships that exist in the emergy metabolic process. Fig. 1 shows the emergy-based system diagram of a specific neighborhood metabolism, in which resources inflows and outflows are analyzed.

Step 2 *Identifying the main metabolic flows.* When examining material, energy, and the monetary flows that support the operation of neighborhood metabolism, this study embedded the accounting framework of neighborhood metabolic flows in relative publications (Codoban and Kennedy, 2008; Enrique Vega-Azamar et al., 2017; Yang et al., 2012). The basic metabolic elements for satisfying households' daily necessities were calculated via three main metabolic processes, namely operation of buildings, food consumption, and transportation. Food, energy, water inflows, and services, along with wastes outflows, were applied to portray the properties of neighborhood emergy metabolism. Residential services represent the emergy produced by local inhabitants, which are exported to the outside in the form of salary (Liu et al., 2019c). Because the study neighborhood was already built, metabolic flows induced by local construction activities didn't take into consideration (Codoban and Kennedy, 2008). Furthermore, based on previous emergy metabolism researches (Li and Wang, 2009; Yang et al., 2012), this study categorized metabolic inflows into renewable resources (R), local non-renewable resources (N) and purchased resources (F); whilst outflows contained desirable and undesirable flows, including residential services (S) and wastes (W) (Table 2). In total, 21 categories of emergy flows were taken into consideration in this study.

Step 3 *Constructing emergy-based indicators.* This study applied emergy indicators including emergy to money ratio (EM), emergy used per area (EP), the emergy self-sufficiency ratio (ESR), and environmental load ratios (ELR) to reflect the environmental performance (in Table 3).

2.2. The SBM model with undesirable output

Subsequently, DEA was adopted to investigate the eco-efficiency of this study's eight communities. The DEA model proposed by Charnes et al. (1978) is a non-parametric technique which utilizes a linear statistical method to assess the relative efficiency of homogenous decision-making units (DMUs) on the basis of various inputs and outputs. Due to the superiority of the automatic determination of weights,

Table 1
The nomenclature of this study.

Nomenclature			
SBM-DEA	slack-based measure data envelopment analysis	S	residential services
MFA	material flow analysis	W	wastes
EFA	energy flow analysis	EM	emergy to money ratio
sej	solar emergy joule	EP	emergy used per area
DEA	data envelopment analysis	ESR	emergy self-sufficiency ratio
R	renewable resources	ELR	environmental load ratio
N	local non-renewable resources	DMUs	decision-making units
F	purchased resources		

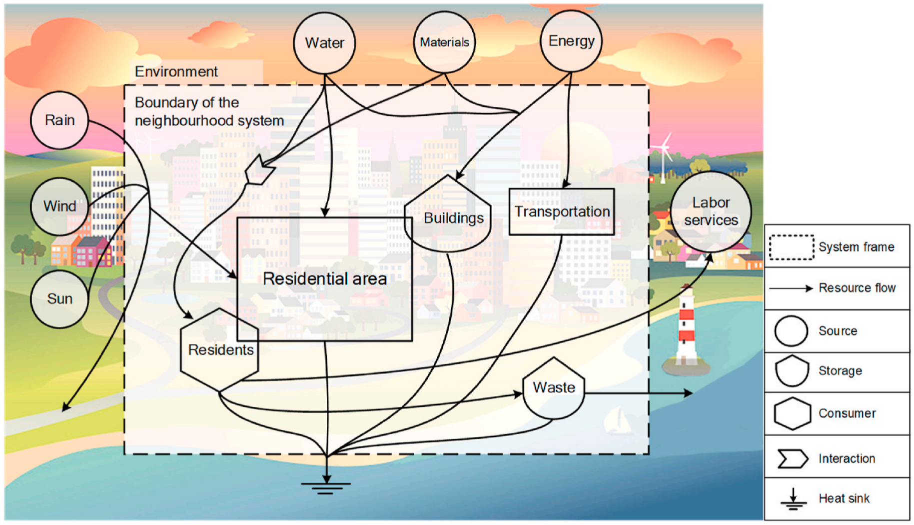

Fig. 1. System diagram of neighborhood metabolism.

this method can mitigate the subjectivity that may occur during the computational process (Kourtit et al., 2017). The SBM model with undesirable output was conducted to evaluate the eco-efficiency of the eight communities in this study.

Assuming that there were n DMUs ($j = 1,\ldots,n$), n was the number of communities in this study (eight communities). Each DUM had m inputs ($i = 1, \ldots, m$), k_1 desirable outputs ($r = 1,\ldots,k_1$) and k_2 undesirable outputs ($w = 1,\ldots,k_2$). The inputs in this study included renewable resources (R), local non-renewable resources (N) and purchased resources (F). The residential services (S) was selected as the desirable output, whilst wastes (W) was taken as the undesirable output. Then, the corresponding matrices can be indicated as $X = (x_1,\ldots,x_n) \in R^{m\times n}$, $Y^d = (y_1^d,\ldots,y_n^d) \in R^{k_1\times n}$, and $Y^u = (y_1^u,\ldots,y_n^u) \in R^{k_2\times n}$. The non-oriented SBM model with undesirable output is defined as follows:

$$\min\theta = \frac{1 - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}}}{1 + \frac{1}{k_1+k_2}\left(\sum_{r=1}^{k_1}\frac{s_r^d}{y_{r0}^d} + \sum_{w=1}^{k_2}\frac{s_w^u}{y_{w0}^u}\right)}$$

$$s.t$$

$$x_{i0} = \sum_{j=1}^{n}\lambda_j x_{ij} + s_i^- \qquad (2)$$

$$y_{r0}^d = \sum_{j=1}^{n}\lambda_j y_{rj}^d - s_r^d$$

$$y_{w0}^u = \sum_{j=1}^{n}\lambda_j y_{wj}^u + s_w^u$$

$$\sum\lambda_j = 1,\quad s_i^-, s_r^d, s_w^u, \lambda_j \geq 0$$

Where λ_j is the nonnegative multiplier vector, x_{ij} represents the vectors of input. s_i^- is the input slack variable denoting the potential reduction of the input indicators.s_r^d is the desirable output deficiency indicating the differences between the target output and actual output. s_w^u is the excess of undesirable outputs. The subscript 0 in x_{i0}, y_{r0}^d, and y_{w0}^u represents index of the DMU under estimation. θ is the value of eco-efficiency, indicating the overall ecological performance of a DMU taking emergy inflows and outflows into account. When $\theta = 1$ and $s_i^- = s_r^d = s_w^u = 0$, the DMU is efficient in terms of eco-efficiency, $\theta_j < 1$ implies that the DMU is inefficient and exhibits slacks.

3. Case study

3.1. Background of the study area

The Qixinggang (QXG) neighborhood is situated in the Yuzhong District which is the hotspots of urban renewal in Chongqing. QXG consists of eight communities with a combined resident population of 65,900. The spatial pattern and basic profile of the eight communities in QXG are presented in Fig. 2 and Table 4. In this study, the system boundary of each community coincided with its administrative boundary. The reasons for selecting the QXG neighborhood as a case study are as follows. Firstly, the QXG neighborhood is a major regeneration pilot area of urban renewal planning in Chongqing. This area involves a cluster of old and high-density residential buildings in poor physical conditions which are, therefore, ripe for urban renewal. Secondly, this neighborhood is heterogeneous in terms of its layout and functions which include residential, commercial and cultural premises. Thirdly, the basic properties (land-use area, and the density of population) of the eight communities in the QXG neighborhood provide differential and comparable patterns for conducting urban metabolism analysis at a small scale. These make the QXG neighborhood a representative case for studying neighborhood metabolism.

3.2. Data collection

The basic dataset used in this study was derived from questionnaire surveys and the statistical data released by government authorities. Table 2 summarizes emergy flows with raw data sources from the perspective of input and output flows. The raw data of renewable resources, local non-renewable resources, electricity used by transportation and waste water services were mainly obtained from the Chongqing Statistical Yearbook 2018, the China Statistical Yearbook on Environment 2018, the Chongqing Transport Annual Report 2017, and the Chongqing Water Resources Bulletins of 2017. With regard to purchased resources, residential services and solid wastes were collected according to a survey of inhabitants in January and February 2018. This survey was conducted via face-to-face semi-structured interviews with inhabitants living in the QXG neighborhood. During the survey, interviewees were randomly sampled within the eight communities. In order to gain detailed information about the interviewees, demographic and domestic consumption information was collected by questionnaire surveys covering family structure and income characteristics, household food consumption, energy consumption (including natural gas, electricity and gasoline), and generated solid wastes (see supplementary

Table 2
Emergy flows accounting of neighborhood metabolism in QXG (C1's case).

Note	Item	Basic data of C1[a]	Unit/year	Transformity (sej/unit)	Reference	Emergy (sej/year)	Data source
Renewable resources (R)							
1	Sunlight	6.69E+14	J	1.00E+00	Odum (1996)	6.69E+14	China Statistical Yearbook on Environment 2018, Chongqing Statistical Yearbook 2018
2	Wind	3.94E+11	J	8.00E+02	Brown and Ulgiati (2016b)	3.15E+14	Chongqing Statistical Yearbook 2018
3	Rain (chemical potential energy)	1.18E+12	J	7.00E+03	Brown and Ulgiati (2016b)	8.27E+15	Chongqing Statistical Yearbook 2018
4	Rain (geopotential energy)	1.43E+11	J	1.28E+04	Brown and Ulgiati (2016b)	3.65E+14	China Statistical Yearbook on Environment 2018
Local non-renewable resources (N)							
5	Topsoil loss	9.10E+10	g	1.71E+03	Odum (2000)	1.56E+14	China Statistical Yearbook on Environment 2018, Chongqing Statistical Yearbook 2018
Purchased resources (F)							
6	Cereals	1.16E+09	g	1.48E+05	Odum (1996)	1.72E+14	Questionnaire surveys
7	Meat	3.36E+08	g	3.36E+06	Zhu (2002)	1.13E+15	Questionnaire surveys
8	Aquatic products	8.83E+07	g	2.00E+07	Odum (1996)	1.77E+15	Questionnaire surveys
9	Vegetables	1.20E+09	g	8.30E+04	Odum (1996)	9.99E+13	Questionnaire surveys
10	Fruits	3.60E+08	g	8.90E+04	Zhu (2002)	3.20E+13	Questionnaire surveys
11	Eggs	8.30E+07	g	3.36E+06	Zhu (2002)	2.79E+14	Questionnaire surveys
12	Milk and other diaries	1.45E+08	g	2.00E+07	Odum (1996)	2.90E+15	Questionnaire surveys
13	Drink	9.38E+07	g	3.36E+06	Zhu (2002)	3.15E+14	Questionnaire surveys
14	Plant oil	1.25E+08	g	1.16E+06	Zhu (2002)	1.45E+14	Questionnaire surveys
15	Water	4.18E+08	g	8.06E+04	Odum (2000)	3.37E+13	Chongqing Water Resources Bulletins in 2017, questionnaire surveys
16	Natural gas	1.78E+08	J	1.78E+05	Brown et al. (2011)	3.16E+13	Questionnaire surveys
17	Electricity	1.02E+08	J	1.6E+05	Odum (1996)	1.63E+13	Chongqing Transport Annual Report 2017, questionnaire surveys
18	Gasoline	3.18E+08	J	1.11E+05	Odum (1996)	3.53E+13	China Energy Statistical Yearbook 2018, questionnaire surveys
Residential services (S)							
19	Salary	7.63E+08	Yuan	9.27E+13	Meillaud et al. (2005)	7.07E+22	Questionnaire surveys
Wastes (W)							
20	Waste water	4.33E+06	g	6.39E+05	Huang and Chen (2005)	2.77E+12	Chongqing Water Resources Bulletins in 2017
21	Solid wastes	1.41E+09	g	1.73E+06	Huang and Chen (2005)	2.43E+15	Questionnaire surveys

Note: * The emergy baseline used in this study was 1.2E+24 sej/year proposed by Brown and Ulgiati (2016a).
* The raw metabolic data calculation of C1: [1] Sunlight = (the average radiation of Chongqing)×(area) = (3.34E+09 J/m^2/year)×(2.00E+05 m^2) = 6.69E+14 J/year; [2] Wind = (area)×(air density)×(drag coefficient)×(geostrophic wind)^3×(time frame) = (2.00E+05 m^2)×(1.23 kg/m^3)×(3.00E-03)×(3.17 m/s)^3×(seconds/year) = 3.94E+11 J/year (Campbell and Ohrt, 2009); [3] Rain (chemical potential energy) = (area)×(average rainfall)×(water density)×(Gibbs free energy of water) = (2.00E+05 m^2)×(1.12 m)×(1.00E+03 kg/m^3)×(4.94E+03 J/kg) = 1.18E+12 J/year (Odum, 2000); [4] Rain (geopotential energy) = (area)×(elevation)×(Average ratio)×(average rainfall)×(ratio)×(water density)×(gravity) = (2.00E+05 m^2)×(304 m)×(0.2)×(1.12 m)×(1.00E+03 kg/m^3)×(9.8 m/s^2) = 1.43E+11 J/year; [5] Topsoil loss = (Area)×(Topsoil loss energy) = (2.00E+05 m^2)×(4.55E+05 J/m^2) = 9.10E+10 J/year. The calculation process of [6-21] = (the average usage of per household/per person)×(the number of household/person in the study area) ×(1 year/12 months/365 days). For instance, [6]Cereals = (the cereals consumption per household)×(the number of household)×(12 months) = (3.45E+04 g/household)×(2.81E+03 person/household)×12 = 1.16E+09 g/year. The calculation processes of other communities are the same as C1.

Table 3
Emergy-based indicators.

Indicator	Description	Unit	Explanation
Total emergy used (U)	U = R + N + F	sej/year	Total emergy inputs of the urban neighborhood metabolism system
Emergy to money ratio (EM)	EM = U/income of the neighborhood unit	sej/Yuan	Communal purchasing ability of emergy in the form of money
Emergy used per area (EP)	EP = U/area	sej/m^2·year	Emergy metabolic density imposed by a community on its environment
Emergy self-sufficiency ratio (ESR)	ESR=(R + N)/U	–	The level of communal metabolic dependence on the surrounding environment
Environmental load ratio (ELR)	ELR=(F + N)/R	–	Environmental stress of a communal system

material). To ensure the robustness of the sample size, this study determined a 5% attrition rate from the total communal population of 65,900 persons. 400 questionnaires were distributed, after eliminating invalid questionnaires, 374 surveys were valid; a response rate of 93.5%.

4. Results

4.1. Emergy accounting results

The input and output of emergy streams in the case neighborhood are presented in Figs. 3 and 4. Overall, the total emergy inputs of the study area during the study period were 1.08E+17 sej with renewable resources at 4.43E+16 sej, non-renewable resources at 1.25E+15 sej and purchased resources at 6.21E+16 sej. It is noteworthy that purchased resources were responsible for more than 55% of total emergy inflows; indicating that the QXG Neighborhood depends heavily on external resources rather than local products. Of the total required emergy inflows, milk and other diaries, seafoods and meat had the largest proportion. This signifies that food consumption is the major input form in the

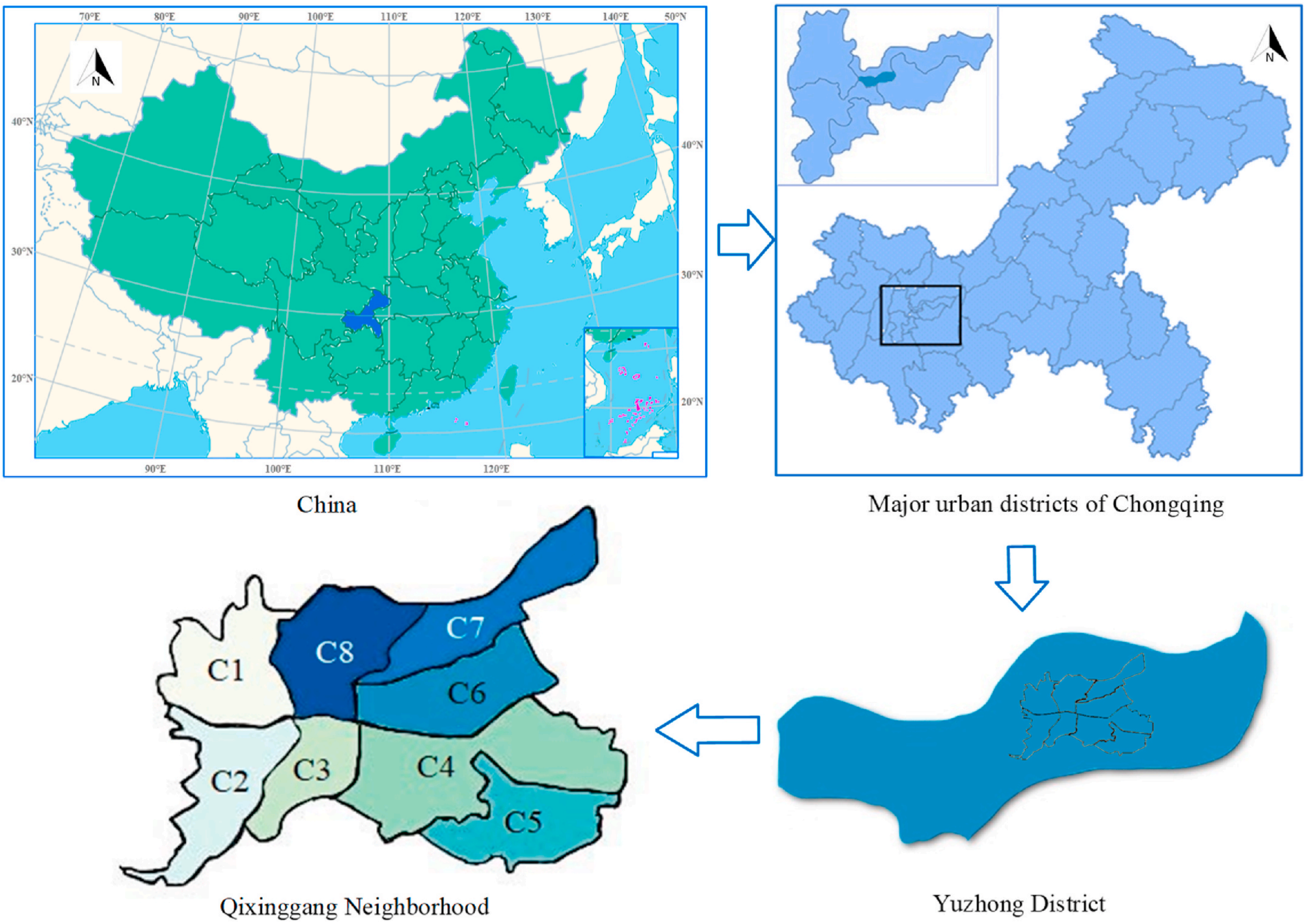

Fig. 2. Geographical location of Qixinggang neighborhood.

communal metabolism, which differs other forms of urban metabolism (such as industrial metabolism). Emergy from local energy consumption indicated that the requirement of gasoline (3.15E+14 sej/year) was higher than natural gas (3.05E+14 sej/year) and electricity (1.45E+14 sej/year). Water-related emergy flows (rain, water consumption, and waste water) were also important for supporting communal metabolic activities. However, the value of the water flows only occupied a small amount of the total emergy steams at 4.00E+16 sej/year. The main reason for this is that water resources are in a low hierarchy of substance, in other words, it can be directly obtained from or discharged to nature without further processing steps that lead to a lower transformity. In addition, emergy outflows within the study neighborhood were recorded as being 2.6E+23 sej/year by residential services and wastes. The metabolic processes induced by residential services played as the leading donor of the communal metabolic system, which accounted for more than 90% of the metabolic output magnitude. One explanation for this is that residential services comprise a vast body of human economic activities in the products production by local inhabitants, and thus have larger transformity than other outputs. The emergy from waste water (2.47E+13 sej/year) and solid waste (2.17E+16 sej/year) in the study neighborhood was the main source for increasing communal environmental pressure.

To shed light on the performance of communities in the total emergy consumption, the metabolism structures of the eight neighborhood units are further presented in Fig. 5.

The total emergy input of these eight neighborhoods demonstrated significant differences; C8 contributed the largest share (2.05E+16 sej/year) at nearly 20%, followed by C1 (1.67E+16 sej/year) at 15.55%, whilst C3 occupied the lowest position (4.23E+15 sej/year) with less than 4%. As for emergy metabolic flows, C1 occupied the highest position in terms of renewable resources. This is mainly because the landscaping and geographical area of this community are the largest compared and thus provide massive metabolic flows of natural resources. C8 had the highest emergy value of purchased resources than other communities due to having the largest population; nearly 20% of QXG residents live in C8. Further, by comparing residential services in each community, it is clear that the emergy value of C1, C4 and C6 occupied high positions (more than 60% of the total residential services) due to their frequent commercial activities. For instance, the economically prosperous area in C1 covers more than one-third of its total area. With regard to wastes, C8 was the major contributor for solid waste accounting for 19.58% of the total value.

4.2. Emergy-based indicators

Emergy-based indicators were selected to detail emergy metabolic properties in the eight communities. Emergy to money ratio (EM) makes it possible to reflect the relative ability of purchasing emergy from economic aspects (Huang and Chen, 2005; Huang et al., 2018b). As illustrated in Fig. 6a, EM in C2 with 1.44E+11 sej/Yuan was in the lowest positions, whilst C8 ranked at the high position with 8.19E+11 sej/Yuan in the investigation period. This demonstrated that C2 had a good performance of transforming input resources into economic value than others. In other words, C8 had the low-income level converting into the low emergy utilization rate. Given the fact that this community had the high emergy inflows in the study area while its income performance

Table 4
Characterization of study communities.

No.	Study community	Land area (km^2)	Population (person)	Density of buildings	Characteristics
C1	Linhua	0.200	8430	215	Have the commercial heart of the QXG neighborhood; flourish in community activities
C2	Kangjiantang	0.100	11,123	880	Poor accessibility to communal leisure facilities, high population densities
C3	Xinglong	0.043	2232	744	High mobility of population; the least populated in study neighborhood
C4	Jintang	0.161	10,680	329	Vibrant commercial activities
C5	Lingshixiang	0.060	7530	600	High population density; inadequate green public space; poor physical condition of buildings
C6	Guiyuansi	0.105	9248	248	Poor public transportation; frequent commercial activities
C7	Huayipo	0.080	11,047	438	Nearly 90% of residential buildings do not have an elevator; the latest retrofit activities can be traced back to the late 1990s; high population density; poor transportation conditions
C8	Hanwei	0.169	14730	639	Most populous among study communities

Note: The density of buildings is the ratio of the number of residential buildings and land areas.

ranked after. Its economic pattern needs to be transformed into an intensive model. Emergy used per area (EP) reflects the level of emergy metabolic pressure imposed by a community on its environment; a higher EP value implies a larger depletion of emergy to maintain system development (Qi et al., 2017; Zhang et al., 2011). C7 and C5 were the top communities of EP with respective values of 1.16E+11 sej/m^2 and 1.54E+11 sej/m^2. This phenomenon can be explained as that the relatively high population densities of these two communities (C7 and C5), thereby needing vast amounts of resources to maintain metabolic exchange. This suggests that intense metabolic activities within a relatively small geographic area are inclined to generate higher pressure on the local eco-environment. In contrast, C1 and C3 had notably lower scores with 8.37E+10 sej/m^2 and 9.84E+10 sej/m^2 during the study period. C1 occupies the largest land area (more than 20% of the QXG's total area) providing a huge potential for relieving environmental pressure. The metabolic exchanges of C3 were relatively weak due to its small population with only 3.23% of the total population.

Fig. 6(b) presents a summary of the performance of emergy self-sufficiency ratio (ESR) and environmental load ratio (ELR) among the eight communities. ESR measures the level of metabolic dependence on the indigenous environment; a higher ratio implies a more sustainable way of communal emergy metabolism and a less metabolic load on the surrounding environment. The ESR value in C7 (0.31) was much lower than the corresponding value of other communities. This indicated that C7 depended heavily on external investments to satisfy daily demands. ELR is directly influenced by the inflows of renewable resources, which can be conducted to reflect the environmental load on a metabolic system. By analyzing the ELR, Fig. 6(b) reveals that significant differences in ELR values existed within these eight communities. C7 and C5 were the top two communities suffering from high environmental loads compared with others. In contrast, C1 had the lowest value of ELR with only 30% of the rate recorded by C7.

4.3. Eco-efficiency evaluation

Fig. 7 presents the eco-efficiency performance of the eight communities. Overall, a significant heterogeneity existed between them with regard to eco-efficiency values. To demonstrate disparities, the eight communities were categorized into four groups in accordance with their eco-efficiency performance. The first group included C1 and C8; these were the leading communities in terms of eco-efficiency. With a rating equal to 1 it can be concluded that these communities achieved full efficiency with no input redundancy and output slacks. The remaining communities had lower eco-efficiency values revealing that emergy metabolic processes were not entirely efficient. C4 belonged to the second group with an efficiency value more than 0.8. The third group includes C2 and C7 which had eco-efficiency values between 0.55 and 0.7. Finally, C3, C5 and C6 were in the fourth group and had eco-efficiency values ranging from 0.25 to 0.5. Although C3 and C6 had similarly poor eco-efficiency performance, the causes of this differed. The relatively small emergy metabolic shared among all metabolic categories due to the inner metabolism strength of C3. With respect to

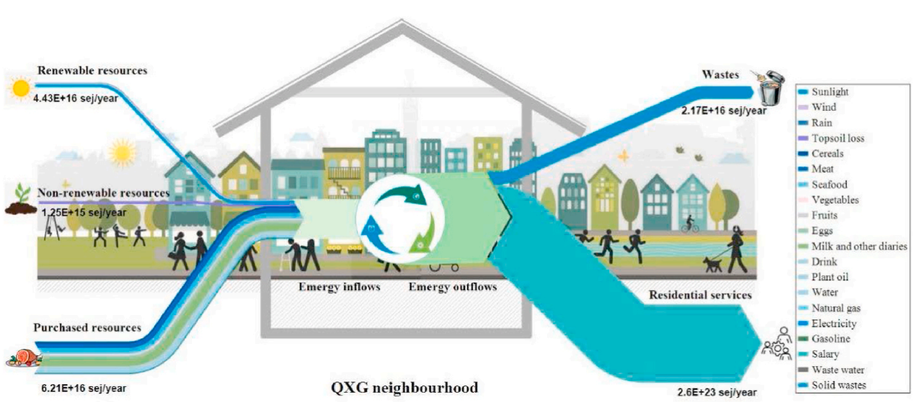

Fig. 3. Emergy flows for the study neighborhood.

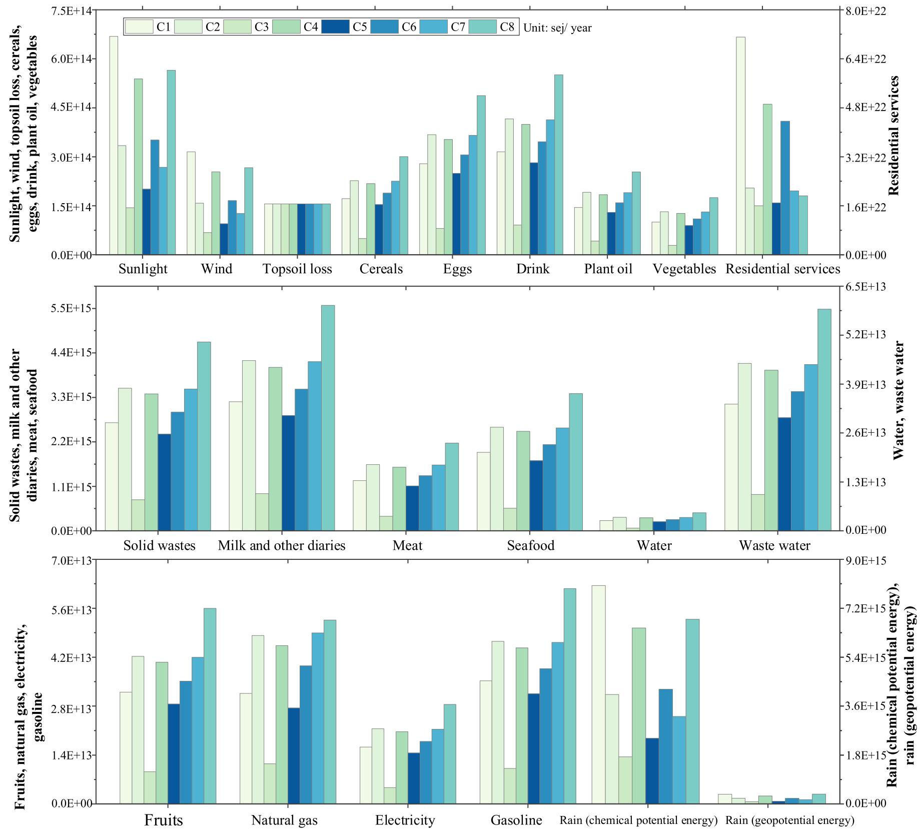

Fig. 4. The emergy metabolic flows of each neighborhood in the QXG community.

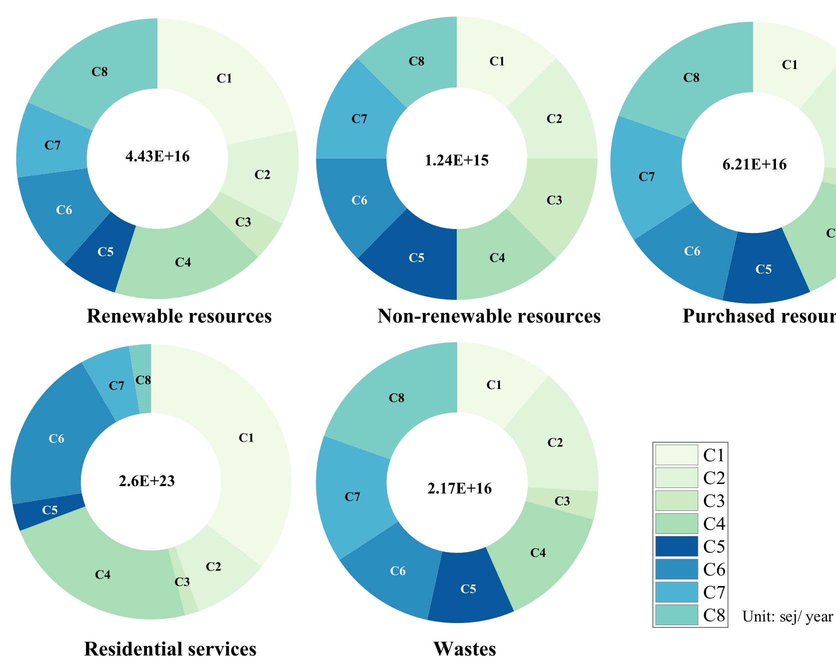

Fig. 5. The emergy metabolism structure among eight communities.

C6, a poor metabolic structure could be found; vast amounts of natural and purchased resources were used, few residential services were produced, and the community suffered from heavy environmental pressures.

To establish why some communities had poor efficiency performances and their potential for enhancement, the efficiency performance of inputs (renewable resources, non-renewable resources, and purchased resources) and outputs (residential services and wastes) were further analyzed (as shown in Fig. 7). Focusing on the efficiency of detailed input indicators, C1 and C8 were the highest ranked communities for efficiency performance. In contrast, the other six communities were not efficient in terms of renewable resources and purchased

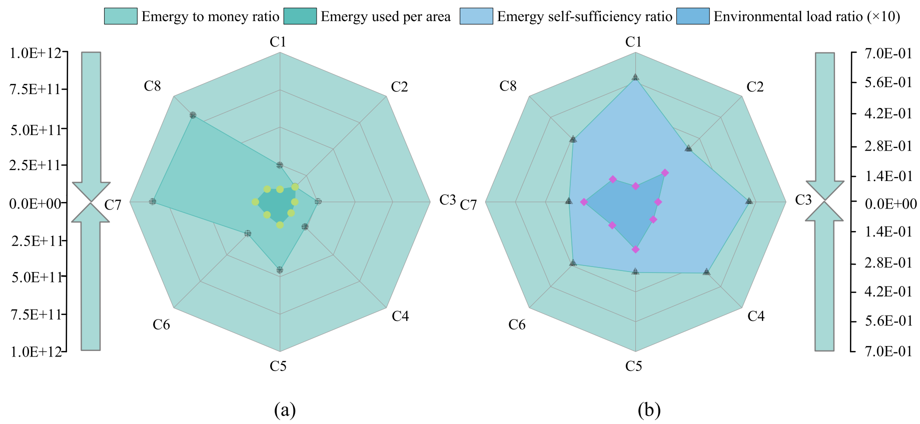

Fig. 6. Emergy intensities and metabolism pressures of eight communities.

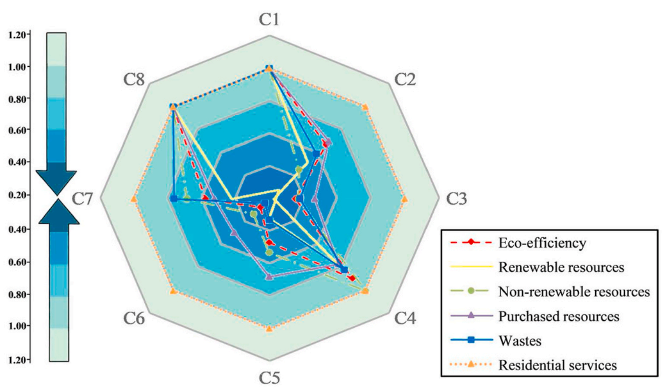

Fig. 7. Eco-efficiency and its optimization of eight communities in the QXG neighborhood.

resources with respective efficiency values between 0.128 and 0.811, between 0.466 and 0.698. Five communities suffered from inefficient input of local non-renewable resources with scores ranging from 0.335 to 0.687. It is worth noting that C6 implied significant efficiency margins of renewable resources and local non-renewable resources. This finding signified that this community was behind the others in natural resource efficiency. Furthermore, a detailed comparison of inflow efficiency showed that input efficiencies followed a sequence from renewable resources, through non-renewable resources, to purchased resources. This result implied that there was substantial room for enhancing the performance of renewable and non-renewable resources to improve the overall efficiency in local communities.

As far as the performance of outputs was concerned, all communities had the optimal efficiency in terms of residential services. With respect to wastes, non-SBM efficient communities evoked the environmental pressure with efficiency performance ranging from 0.237 to 0.824. More specifically, C6, C5 and C3 presented relatively high reduction potential of wastes, with respective values of 76.3%, 67.1% and 62.1%. This finding signified that more attention should be paid to the development of recycling technologies in these communities to achieve the optimal performance of inefficient neighborhoods.

5. Discussions

To link the results with small-scale dimensions of the urban renewal, a detailed neighborhood-scale renewal frame is advanced by this study from the perspectives of metabolism to trigger the local regeneration process (see Fig. 8).

Firstly, re-design strategies of the metabolic flows within systematic hinterlands are necessary in order to improve the performance of emergy flow system. First of all, water flows comprised of rain, household water consumption, and waste water played important roles in local communal emergy metabolic systems. Therefore, developing the water circulation system of a local neighborhood in accordance with demand management is essential to achieving water conservation, reuse and recycling. In addition, closed loops of water can not only save daily water for domestic use but also reconcile the flood. Moreover, the district governments of the study area should encourage investment to improve wastewater treatment technology and implement varying incentives and grants to construct integrated rainwater harvesting systems. Secondly, attention should simultaneously be focused on protecting existing ecological land. Ecological land is helpful in both mitigating local topsoil loss and improving the quality of surrounding environments for inhabitants. However, the protection of ecological land is still rare in local contexts. To change this situation, policy interventions need to be strengthened with mandatory targets for managing existing ecological land, slowing down the growth rate of other forms of land use, transforming underutilized communal areas into green ecological land, and coupling local development with ecological land conservation. Moreover, residential participatory approaches posited as a suitable route to protect common ecological land are also imperative within urban blocks. Thirdly, given the fact that the utilization of clean energy (natural gas and electricity) was lower than non-clean energy (gasoline) in the local neighborhoods, attention needs to be given to enhance energy conservation in the study area. Optimizing the structure of energy consumption from non-renewable energy to renewable energy (such as by developing photovoltaic and solar thermal systems), and providing taxation support for regional low-carbon technology should be initiated to achieve non-clean energy reduction. Meanwhile, efforts to improve energy efficiency are also urgently required with regard to household-based consumption. For example, strengthening the thermal insulation of buildings (especially old buildings) by fixing walls, doors and windows would be an effective method for saving energy communally. Lastly, a series of mandatory regulations in terms of solid wastes management should be established. The Implementation Plan on the Household Solid Waste Classification System promulgated by China's government has been undertaken in 46 Chinese cities to increase the recycling rate of household solid waste. Against this background, the local government in Chongqing should be well aware of comparatively long-lasting solid waste management mechanisms and play the role of executor, so waste management systems can be built efficiently. In addition, the efficiency of local waste recycling technical conversion should also be enhanced by developing waste separation and recycling systems. For instance, within the waste separation system, glass and wood can be reused as materials for communal redevelopment, and kitchen waste can be used as fertilizer for communal green spaces. A waste separation system based on source-separated collection can lead to waste minimization, which in turn can

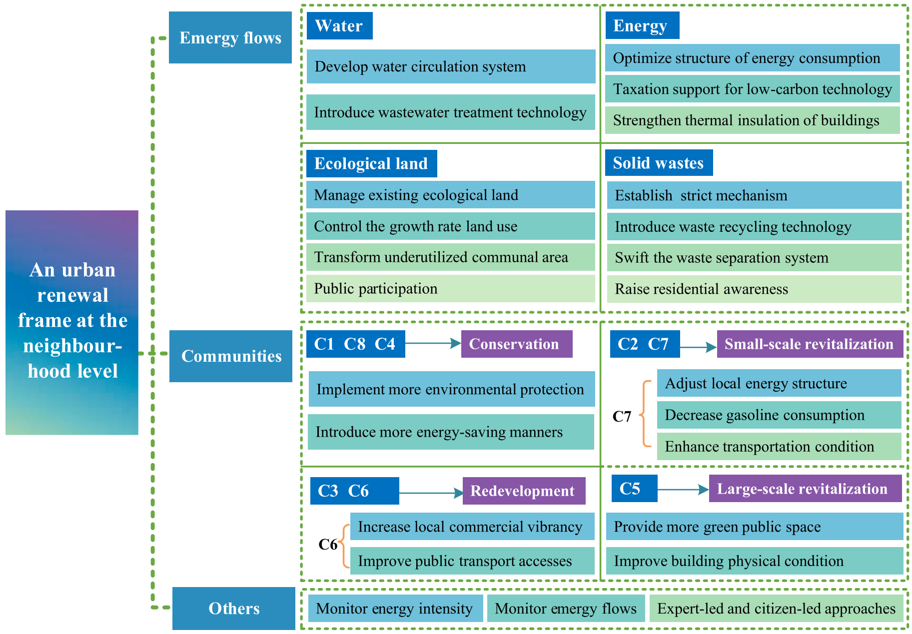

Fig. 8. A neighborhood-scale renewal framework.

relieve existent pressures on waste management. In addition, for the local residents, bottom up behavioral changes are needed with regard to garbage classification; this could be achieved by educational campaigns and media publicity raising residential awareness.

Given the multiple properties involved in communal renovation, this study further summarizes corresponding renewal operations of specific communities from the aspects of conservation, revitalization and redevelopment. C1, C8 and C4 are the best performers in terms of emergy-based indicators and eco-efficiency. It follows, that the conservation strategy could be implemented in these communities. While conservation, a series of more environmental protection and energy-saving strategies for retaining their current performance would be necessary. Considering the fact that C8 occupied the highest position in terms of waste production, greater efforts for waste management strategies are required to minimize the inner environmental pressure. Moreover, multiple measures of urban revitalization need to be conducted based on scrutinizing detailed problems. The small-scale revitalization strategy needs to be adopted in C2 and C7. In the latter, efficiency improvement for purchased inflows in C7 was deemed to be an attempt to reconcile the environmental load ratio given that gasoline consumption took the high position. Within this community, upgrading the energy structure and introducing clean energy should be a priority. Apart from improving the efficiency of gasoline use, efforts to improve existing poor transportation conditions such as enhancing the density of the road network should be considered in the revitalization strategy for C7. Large-scale revitalization strategies should also be conducted in C5 to address the problems that have arisen from the inner-communal shortfall of land area. Greater indigenous green public space with renewing the dilapidated area and roof garden could be considered for urban planners during the process of communal renewal. Meanwhile, attention should also be given to improve the current physical condition of buildings in this community. A series of redevelopment strategies should also be applied in the communities of C3 and C6. With respect to C6, the longer distance from residential area to the commercial center and poor public transportation inevitably aggravate the consumption of energy. Some actions can, thereafter, be conducted to increase commercial vibrancy (such as optimizing the layout of the commercial district and diversifying commercial functions) and public transportation access to it could be enhanced. More attention should be paid in C3 to increase residential awareness of energy conservation with a view to reduce metabolic pressure and improve eco-efficiency.

To better achieve the goal of small-scale urban renewal, pertinent management strategies from the aspects of emergy flows and specific communities also need to be taken into consideration. One way to do this is to monitor actual neighborhood-level energy consumption and the trajectories of critical emergy flows. This would allow decision-makers to capture metabolic information of emergy flows at a refined scale. Furthermore, expert-led and citizen-led approaches to the application of communal renewal are more resilient methods of enhancing residential satisfaction in the long-term especially with regard to green neighborhood development and, therefore, this approach should also be considered.

6. Conclusions

This work combined emergy synthesis and SBM-DEA model in DEA to construct an eco-efficiency model. A typical neighborhood with eight units was used as a case study to investigate communal emergy metabolic structure, emergy flows and eco-efficiency performance. The results indicated that the Qixinggang neighborhood heavily depended on external resources instead of local products. Emergy flows induced by residential services are the most dependent, followed by purchased resources, while local non-renewable resources were at the bottom. Concurrently, intense communal activities within a relatively small geographic area caused heavy environmental load. With regard to eco-efficiency performance, a significant heterogeneity existed amongst the eight communities. Only two communities had achieved full eco-efficiency during emergy metabolic processes. Enhancing the performance of renewable and non-renewable resources and reducing the production of wastes were essential measures to improve the overall efficiency in local communities; both those which form the focus of this study and more generally.

Given the communal disparities of emergy metabolism and eco-efficiency, a neighborhood-scale renewal framework had been put forward. Turning to emergy flows, water circulation systems and wastewater treatment, greater technology should be introduced into the local context. The strengthened policy interventions, creation of mandatory targets and enhancement of residential participatory approaches should be implemented to improve ecological efficiency. Furthermore, it is necessary to optimize the structure of energy and provide taxation support for regional low-carbon technology. To address solid waste management, a series of mandatory policies which raise residential awareness and introduce waste recycling technology should be adopted by local authorities. With respect to the renewal operations of specific communities, conservation, large-scale and small-scale revitalization and redevelopment had been put as approaches based on the actual performance of the eight communities that were the focus of this study.

The findings of this study can be regarded as potential references for urban renewal projects elsewhere that involve nexus urban renewal and urban metabolism at a refined scale. In addition, district governments can implement effective urban renewal strategies from the biophysical aspect to address the growing demand for local sustainability from the aspect of urban metabolism.

However, a few gaps in this study should be further improved in the future. First, with regard to the accounting of neighborhood metabolic flows, the current study aimed at evaluating emergy performance induced by households' daily activities. Emergy metabolic flows caused by local building construction activities didn't take into consideration. Due to the raw materials and energy consumed in the construction phase, heavier environmental impact and ecological pressure would be introduced to the metabolic system. Future research should detail accounting of neighborhood-scale emergy metabolic flows in a more comprehensive manner. Secondly, the sample size must be enlarged in the following studies. The limited study communities could affect the accuracy of efficient frontier estimation and further lead to the precision of eco-efficiency value. Therefore, enlarging the sample size of evaluating the efficiency performance should be meaningful. In addition, social activities have an increasing influence on communal metabolism, which should be taken into consideration with environmental and economic factors. However, how to effectively quantify social factors in the eco-efficiency analysis is regarded as the main question (Huang et al., 2018a; Liu et al., 2019c). Future researches thus require to be covered and quantified social parameters in the eco-efficiency accounting process. Lastly, the neighborhood-scale renewal framework of this study provides an idea for the following research that nexus of the small-scale urban metabolic performance and urban renewal. The practical renewal framework may need to adjust according to the actual conditions of a specific neighborhood.

CRediT authorship contribution statement

Miaohan Tang: Methodology, Investigation, Writing - original draft. **Jingke Hong:** Conceptualization, Writing - review & editing. **Xianzhu Wang:** Software, Visualization. **Rongxiao He:** Writing - review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.111177.

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