Hybrid Emergy-LCA (HEML) based metabolic evaluation of urban residential areas: The case of Beijing, China

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1. Introduction

The global trends of urbanization have made urban regions the central factor in how resources are metabolized within the human society. According to the UN statistics (2006), the world urbanized rate has exceeded 45%. This figure will continue growing to 61% around 2030. The world's urban population lives within geographic areas covering 2% of the Earth's surface only. Many metabolic processes and functions are mainly located in urban configurations, such as, the production and consumption of large amount of non-renewable energy, excessive exploitation of raw materials, heavy pressures on surrounding environment to the point of exhaustion and high amounts and rates of waste discharged. Influenced by the seminal book, Our Common Future, cities have become an integral scale in the struggle to define and achieve sustainability (Clark, 2003).

One of the most uncertain terms in the pursuit of urban sustainability is how to measure the status or the progress at different spatial scales (Ryan et al., 2007). Due to the intimate relationship of environmental impacts, analysis on the direct and indirect impacts of cities requires further development of methodological techniques for assessing the societal metabolism of energy and materials (Bai, 2007). Combing with the existing social complexity (Tainter, 2006), studies in urban metabolism have become an important instrument of sustainability since the groundbreaking work of Wolman (1965). Researches that followed began to focus on metabolic flows throughout the urban ecosystem (Decker et al., 2000; Zhang et al., 2006). In their cases, quantitative assessments were highlighted to present the total impacts derived from the socio-economic and technical progresses. All together, results from these studies clearly indicated that metabolic flows had remarkable influences on the urban sustainability (Kennedy et al., 2007).

The urban sustainability requires a way to evaluate the metabolic effects of urban residential areas (URAs). Investigating the sustainable performance of a specific URA will assist in understanding the urban metabolism dynamics and its implications for broader impacts. Herein two sub-topics exist. One is to evaluate the residential services occupied by the residents; another is to evaluate the gross environmental impact of the residential activities. For the first one, Quality of Life (QoL) of communities has been adopted in previous studies in the U.S.A., in the U.K. as well as in other E.U. countries (Costanza, 2007; Distaso, 2007; McMahon, 2002). The idea of QoL mainly focused on the social aspect of sustainability by surveying and measuring the subjective and psychological satisfaction of residents in URAs. For the aspect of gross environmental impact, some approaches have been developed to reveal the broader contents, such as Materials...
Flow Analysis (MFA) (Ritthoff et al., 2002), embodied energy analysis for buildings (Reddy and Jagadish, 2003; Thormark, 2002), and the modified Ecological Footprint (Ferng, 2005), etc. However, there is still much potential for improving metabolic indicators of “services” and “pressures” in URAs.

From the views of ecologists, negative impacts to ecosystems will not be alleviated unless a new energy budget of the biosphere and civilization is reestablished (Makarieva et al., 2008). By simplifying the complexity of the whole biosphere–human system, the Emergy Theory comes close as an appropriate tool for discussing the ecosystems services and pressures (Odum, 1996). Inherited from the food web theory, the core concept of Emergy Theory is to evaluate the natural and the man-made components (e.g. resources, commodities and services) and their metabolic flows (e.g. renewable and/or non-renewable energy flows) in terms of a common unit solar enjoule (sej). All the components in the metabolic system are accounted by tracing the renewable and non-renewable inputs during their production and procession, where the ultimate primary input of biosphere is solar energy. Emergy is usually referred to “energy memory” (Scienceeman, 1997), for its feature of tracing the work done by the natural ecosystems. In this manner, Emergy Analysis (EMA) could be employed to look into the fundamental flows, which is pivotal to urban ecosystem studies.

EMA was founded on the principles of the second law of thermodynamics, system theory and systems ecology (Brown and Herendeen, 1996). A similar philosophy was also used to explore other problems in urban systems, such as economic process (Raine et al., 2006). By bridging the human behaviors and natural properties from a biophysical foundation, rather than the traditional monetary based methods or subjective value based methods, EMA evaluates the benefits and costs together. For the more Emergy inflows are utilized, the higher level of products/services output is obtained, with correlative ecological pressures in return. Based on EMA, different issues in cities were investigated using the EMA framework, including:

2.1. Emergy Analysis (EMA)

The general framework of EMA has been explained in the series of handbook by Odum et al. (2000) and was further elaborated in a variety of other publications (Bargigl and Raugei, 2004; Brown and Ulgiati, 2002). Here is a brief summary of major steps in applying the EMA framework, including:

- Defining the system boundary, is primarily required. Particularly, to obtain a well integrated result, the boundary of EMA should be set accordingly with the LCA scope (see Fig. 1). For the cases of URAs, buildings, appliances and vehicles are covered, as well as their phases of producing, processing and discharging. The targeted URAs are monitored for the flows of energy and material of each component’s inputs and outputs. The indirect output,
environmental impacts of major pollutants, are discussed in Section 4.2.

- Drawing a systems flow chart, allows for organizing relationships between components and pathways of resource flows. Within the rectangular frame of the system, the sources, components, and flows are drawn with the Emergy language symbols (Table 1). The left–right order expresses a hierarchy of energy quality (containing more sej per unit). For URAs, the main streams include local renewable inputs, purchased energy (feedback from economy system), total input (utilization, where $U = F + R$) and waste. All the Emergy flows are defined as a product of their actual energy and transformities (a specific Emergy rate of energy or materials).

- Calculating annual Emergy (empower) tables, the aggregative table is structured from the flows chart, where each input flow becomes a row in the table to be evaluated. The references of Transformities and percentages are also listed in columns.

- Emergy indicators are evaluated, using the indicators for systematically investigating the output and the pressures of the targeted URAs (Table 2).

2.2. Life Cycle Assessment (LCA)

The LCA method is mainly used for studying the total resources needed and the total emissions output of producing processes. However, by enlarging the scope of LCA, the use phase of

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Table 1
Major system symbols and their short descriptions.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Energy circuit" /></td>
<td>Energy circuit: A pathway to the storage or upstream source</td>
</tr>
<tr>
<td><img src="image" alt="Source" /></td>
<td>Source: Outside source of energy delivering forces, any input that crosses the system boundary is a source, including pure energy and materials</td>
</tr>
<tr>
<td><img src="image" alt="Tank" /></td>
<td>Tank: A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows</td>
</tr>
<tr>
<td><img src="image" alt="Heat sink" /></td>
<td>Heat sink: Dispersion of potential energy into heat that accompanies all real transformation processes and storages, loss of potential energy from further use by the system</td>
</tr>
<tr>
<td><img src="image" alt="Interaction" /></td>
<td>Interaction: Interactive intersection of two or more pathways coupled to produce an outflow</td>
</tr>
<tr>
<td><img src="image" alt="Consumer" /></td>
<td>Consumer: A unit that transforms energy quality, stores it and feeds it back autocatalytically to improve systems inflow</td>
</tr>
<tr>
<td><img src="image" alt="Sensors" /></td>
<td>Sensors: Means the storages is controlled by some other flows</td>
</tr>
<tr>
<td><img src="image" alt="Box" /></td>
<td>Box: Miscellaneous symbol to use for whatever unit or function is labeled</td>
</tr>
</tbody>
</table>
production could also be covered. It is important to construct a uniform system boundary similar as that of EMA.

The detailed instruction of LCA could be found from SETAC (Kotaji and Schuurmans, 2003), EPA (USEPA, 2006) and the ISO standards (ISO 14040, 1997). Usually, the LCA methodology can be synthesized in the following phases:

- **Phase 1:** Life Cycle Scoping, during this phase, in addition to defining the boundary of LCA, the Functional Unit (F.U.) also needs to be identified and confirmed. The F.U. is offering a reference unit to which the inputs and outputs of the metabolic system can be correlated. Thus the F.U. of URAs is considered to be affiliated with the EMA indicator of household empower (Table 2). This is another guarantee for constructing a uniform boundary.
- **Phase 2:** Life Cycle Inventory, details computing the relevant inputs and outputs of a producing system, including the required energy and materials as well as the discharged emissions. The production system is modeled as assemblage of single operations from cradle to grave. The amounts of the resources and the emissions are objectively expressed in units of mass.
- **Phase 3:** Life Cycle Assessment and interpretation, requires that the calculated inventory results be classified into specific impact categories for representing their significance of potential environmental impacts. The level of depth, the choice of evaluating methods (e.g. reference choosing, weighing and so on) are both dependent on the scope and goal set up at phase 1. One of the criticisms of the LCA is derived from the subjectivity existing at phase 3 (Bakshi, 2002). The changes of technology, the broader environmental quality and the LCA scoping are all affecting, while the physical amounts of pollutants are much more comparable among different research cases. Nevertheless, after normalization, the integrated result helps judging the order of pollution migrating acts and visualizing them to decision-makers. It also makes sense for comparing cases within a similar spatio-temporal range. Thus, in HEML, we balanced the different demands. These two approaches are both adopted: the masses of major pollutants from inventory analysis and their emissions are objectively expressed in units of mass.

### Table 2

<table>
<thead>
<tr>
<th>Expression</th>
<th>Unit</th>
<th>Explanations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household empower</td>
<td>U/households</td>
<td>Average Emergy inflow per household, an objective indicator of residential living quality</td>
</tr>
<tr>
<td>URA environmental load ratio (ELR)</td>
<td>F/R</td>
<td>The ratio of purchased non-renewable resources to local supporting capability, an inflow indicator of the URA system pressure on local ecosystem</td>
</tr>
<tr>
<td>URA waste ratio (WR)</td>
<td>W/R</td>
<td>The ratio of direct discharging wastes to local supporting capability, an outflow indicator of the URA system pressure on local ecosystem</td>
</tr>
</tbody>
</table>

### 2.3. Hybrid Emergy-LCA (HEML) index

As discussed in Section 1, 5 aspects of the URA metabolic system are inspected besides a synthesized one. They are: (1) Emergy inflow per household provided from the URA system and even from the broader urban ecosystems, (2) the upstream and (3) the downstream impacts of the URA system and (4) the annual gross emission impact per household, and the (5) synthesized indicator, Emergy margin environmental impact for checking the household metabolic sustainability. It is defined as the household annual received Emergy (empower) per unit of household emission impacts (Table 4).

### 3. Study area and data preparation

#### 3.1. The targeted URA in Beijing

Tian Tongyuan (TTY) residential area is located in the northern part of Beijing City, in a distance of 17.6 km away from the inner part (Fig. 2). The construction of this area began in the late 1990s. About 70% of the buildings are high-rises, while the rest consist of 6–8 stories. One of the major purposes of TTY was to provide more low-price apartments for local citizens. Now a population of 150,000 people is living in four sub-zones now (Table 5), which is expected to reach 300,000 in next 10 years.

#### 3.2. Data collection and development

The social-economic and technical conditions of metabolic system in TTY are used for preparing primary data for the HEML method. The metabolic flow $M_h$ of the household $h$ is defined as:

$$M_h = \sum_j \sum_k \text{life style}_{j,k} \times \text{product parameters}_{j,k}$$

$$= \sum_j \sum_k \left( \text{own rate}_{j,k} \times \text{use intensity}_{j,k} \right) \times \text{product parameters}_{j,k}$$

where $j =$ (buildings, appliances, vehicles) and $k$ means the major energy using products (EuP), such as air conditionings, water heaters and private cars, etc. A survey was carried out to collect the necessary life style information in 2005 (Li et al., 2009). The data of building materials in TTY was calculated from the local planning report and previous literature (Liu and Hu, 2006).

Beside the high-density settlement, the residents in TTY were also suffering from bad traffic planning in this area. Though most of

### Table 3

Classification of household life cycle inventory of URAs.

<table>
<thead>
<tr>
<th>Environmental impacts</th>
<th>Unit</th>
<th>Scale</th>
<th>Normalization and weighting parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Warming Potentials (GWP)</td>
<td>gCO₂ eq./yr</td>
<td>Global</td>
<td>Reference values in Beijing: 87000000 g CO₂ eq./cap/yr, Weighting factors: 0.83</td>
</tr>
<tr>
<td>Acidification potentials (AP)</td>
<td>gSO₂ eq./yr</td>
<td>Regional</td>
<td>Reference values in Beijing: 35000 g SO₂ eq./cap/yr, Weighting factors: 0.73</td>
</tr>
<tr>
<td>Nutrient and eutrophication potentials (NEP)</td>
<td>gNO₃ eq./yr</td>
<td>Regional</td>
<td>Reference values in Beijing: 59000 g NO₃ eq./cap/yr, Weighting factors: 0.73</td>
</tr>
<tr>
<td>Photochemical oxidant creation potentials (POCP)</td>
<td>gethane eq./yr</td>
<td>Regional</td>
<td>Reference values in Beijing: 650 g ethane eq./cap/yr, Weighting factors: 0.61</td>
</tr>
<tr>
<td>Solid waste (SW)</td>
<td>g/yr</td>
<td>Local</td>
<td>Reference values in Beijing: 291000 g/cap/yr, Weighting factors: 0.62</td>
</tr>
</tbody>
</table>
their jobs were located in the inner city, the current roads and public transport lines were far behind in meeting the increasing demands of commuting. Costly time delays, air pollution, and other issues were induced by serious congestion. The transportation behavior of residents was also given significant attention in this study.

4. Result

4.1. EMA

After the survey, the basic energy and materials is accounted (column “input” in Table 6). The dynamic metabolism in real life is expressed by a year-by-year steady process. With the equation in Section 3.2, the energy and the materials used for every equipment are calculated and allotted within their life-spans averagely. Related Emergy values of metabolic flows are obtained by their input and transformities.

Table 6 shows the annual Emergy flow chart in TTY. The renewable and non-renewable inputs were 8.49E+18 and 1.05E+21 sej/yr respectively. Hereinto, a flow of 9.93E+20 sej/yr Emergy was used for the parts of buildings and public, including 2.32E+20 sej/yr for the home appliances. The rest of 9.79E+19 sej/yr Emergy was used for the part of transportation. A sum of 1.09E+21 sej/yr Emergy was offered by the URA metabolic system to more than 60,000 households living in TTY.

Table 6 describes the breakdown Emergy flows supporting the local residents. Among these are the flows of renewable and non-renewable inputs. The renewable inputs only account for 0.78% of total Emergy input, which is an obvious characteristic of an area relying on the external resources instead of products procured locally. Among the major non-renewable inputs, 41.20% are raw materials and 58.17% are fuel-bearing materials. Among the non-renewable inflows, 68.46% is occupied by building and space heating, 22.06% for appliances and 9.48% for vehicles. For the use phase, the largest single Emergy inflow is coal for TTY URA’s regional space heating use, 33.28% of the total utilized Emergy. Following that is electricity, 14.87%, which is mainly used for the appliances and public facilities.

4.2. LCA

The LCA inventory of household consumption is listed as the indicator X4i in Table 7. The normalized result in Fig. 4 indicates that the largest environmental impact is derived from the POCP pollutants. The amount of Household POCP is 4.67E+05 g ethane eq./yr. The products manufacturing and fuels using are major

**Fig. 2.** Location and configuration of Tian Tongyuan (TTY).
Table 6
Aggregated Emergy flow table of TTY.

<table>
<thead>
<tr>
<th>Item</th>
<th>Input Unit</th>
<th>Transformity (sej/unit)</th>
<th>Emergy flow (sej/yr)</th>
<th>Fraction (%)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Renewable inputs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Sunlight</td>
<td>2.35E+16 J</td>
<td>1.00E+00</td>
<td>2.35E+16</td>
<td>0.002</td>
<td>Def.</td>
</tr>
<tr>
<td>2 Wind</td>
<td>3.32E+15 J</td>
<td>2.45E+03</td>
<td>8.14E+18</td>
<td>0.771</td>
<td>a.</td>
</tr>
<tr>
<td>3 Rain</td>
<td>1.04E+13 J</td>
<td>3.10E+04</td>
<td>3.23E+17</td>
<td>0.031</td>
<td>a.</td>
</tr>
<tr>
<td><strong>Purchased non-renewable input</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Water</td>
<td>3.16E+13 J</td>
<td>8.06E+04</td>
<td>2.55E+18</td>
<td>0.241</td>
<td>a.</td>
</tr>
<tr>
<td>5 Wood</td>
<td>2.05E+03 t</td>
<td>1.48E+15</td>
<td>2.88E+18</td>
<td>0.273</td>
<td>b.</td>
</tr>
<tr>
<td>6 Sand</td>
<td>5.03E+04 t</td>
<td>1.12E+15</td>
<td>5.37E+19</td>
<td>0.508</td>
<td>a.</td>
</tr>
<tr>
<td>7 Stone</td>
<td>9.01E+04 t</td>
<td>1.68E+15</td>
<td>1.44E+20</td>
<td>13.637</td>
<td>a.</td>
</tr>
<tr>
<td>8 Iron</td>
<td>1.76E+03 t</td>
<td>4.75E+15</td>
<td>8.38E+18</td>
<td>0.793</td>
<td>c.</td>
</tr>
<tr>
<td>10 Aluminum</td>
<td>3.40E+02 t</td>
<td>2.11E+16</td>
<td>7.16E+18</td>
<td>0.678</td>
<td>b.</td>
</tr>
<tr>
<td>11 Copper</td>
<td>2.49E+02 t</td>
<td>1.14E+17</td>
<td>2.83E+19</td>
<td>2.675</td>
<td>d.</td>
</tr>
<tr>
<td>12 Cement</td>
<td>2.12E+04 t</td>
<td>3.48E+15</td>
<td>7.03E+19</td>
<td>6.656</td>
<td>c.</td>
</tr>
<tr>
<td>13 Brick</td>
<td>1.06E+04 t</td>
<td>3.90E+15</td>
<td>3.93E+19</td>
<td>3.719</td>
<td>c.</td>
</tr>
<tr>
<td>14 Plastic</td>
<td>9.50E+02 t</td>
<td>9.83E+15</td>
<td>9.34E+18</td>
<td>0.884</td>
<td>c.</td>
</tr>
<tr>
<td>15 Rubber</td>
<td>2.31E+02 t</td>
<td>5.38E+15</td>
<td>1.24E+18</td>
<td>0.118</td>
<td>a.</td>
</tr>
<tr>
<td>16 Glass</td>
<td>9.66E+02 t</td>
<td>3.63E+15</td>
<td>3.88E+18</td>
<td>0.368</td>
<td>c.</td>
</tr>
<tr>
<td><strong>Energy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 Coal</td>
<td>5.49E+15 J</td>
<td>6.72E+04</td>
<td>3.52E+20</td>
<td>33.278</td>
<td>e.</td>
</tr>
<tr>
<td>18 Gasoline</td>
<td>4.70E+14 J</td>
<td>1.11E+05</td>
<td>5.21E+19</td>
<td>4.929</td>
<td>e.</td>
</tr>
<tr>
<td>19 Diesel oil</td>
<td>8.39E+13 J</td>
<td>8.90E+04</td>
<td>7.47E+18</td>
<td>0.707</td>
<td>a.</td>
</tr>
<tr>
<td>20 Electricity</td>
<td>6.04E+14 J</td>
<td>2.69E+05</td>
<td>1.62E+20</td>
<td>15.361</td>
<td>a.</td>
</tr>
<tr>
<td>21 Natural gas</td>
<td>5.11E+14 J</td>
<td>8.06E+04</td>
<td>4.12E+19</td>
<td>3.897</td>
<td>a.</td>
</tr>
<tr>
<td><strong>Wastes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22 Waste water</td>
<td>2.48E+13 J</td>
<td>1.12E+06</td>
<td>2.65E+19</td>
<td>f.</td>
<td></td>
</tr>
<tr>
<td>23 Construction waste</td>
<td>3.96E+03 t</td>
<td>3.01E+15</td>
<td>2.67E+20</td>
<td>f.</td>
<td></td>
</tr>
<tr>
<td>24 Other waste</td>
<td>6.19E+03 t</td>
<td>4.69E+15</td>
<td>2.90E+19</td>
<td>a.</td>
<td></td>
</tr>
</tbody>
</table>


Fig. 3. Annual metabolic flow chart of TTY (E+17 sej/yr).
contributors to the POCP scores. The next significant impact is solid waste, whose amount in mass is 1.20E + 08 g/yr and the normalized value is 101.94. Following in degrees of significance are the impacts from the greenhouse gas (GWP) and the acidification matters (AP), while the NEP pollutants have the least impact.

For different sectors, Fig. 5 presents an overall picture of environmental impacts allocation among the three sectors of buildings, appliances and vehicles. Due to the large amount of resources used, the building sector consequently is a central source of pollutants. All of the largest environmental impact of every category is caused by construction. The vehicles bring the second largest impacts. The full result of HEML on TTY is summarized in Table 7.

5. Discussion

5.1. Comparison

To further demonstrate using HEML based metabolic evaluation on URAs, another sample URA, Zhongxin Sushe (ZXSS) near the inner city and of the average status of URAs in Beijing Municipality (BJ) were added for comparison. The data were collected through a similar survey and pulled from the Beijing Municipal Statistical Yearbook (2007) respectively.

The major differences between TTY and ZXSS lay on: (1) the distances to the city center; the distance from ZXSS to the city center is about 7.2 km; (2) the volumes; the floor area of ZXSS is about 1/300 of that of TTY; (3) the building types; the ZXSS was finished in two decades ago. Most of the buildings are lower than 6 stories; and (4) the space heating systems; a natural gas boiler is used in ZXSS instead of the regional coal-burning one in the TTY area. These differences brought on the dissimilarity of density and the behaviors of residents. The population per household in ZXSS is more than that of TTY because more percentage of old or retired people are living in ZXSS, while the density of buildings in ZXSS is less. Residents in ZXSS also drive less and use more public transportation.

Calculating results of these URAs are listed in Table 8. For easier understanding the comparison, the average status of BJ is chosen as a reference benchmark. Deviations of the ELR and the pollutions of individual URA are expressed by their benchmark values, which reduces the rage of $X_j$ to a standard one. The benchmark of BJ is associated with 0. Thus, the deviations $D$ of individual URA reflect the “disadvantages or advantages” from the general local level.

$$D = \frac{X_{ji} - X_{Bi}}{X_{Bi}}$$

where $j = (TTY, ZXSS)$ and $i = (1, 2, 3, 4, 5)$.

A radar plot is used to interpret the deviations $D$ (Fig. 6). The range of radial axis is set from $[-50\%, 50\%]$. The ELR and the six kinds of pollutions of TTY, ZXSS and Beijing city average are mapped to offer a general picture of their eco-environmental pressures. The value of Beijing city as benchmark is indicated at the middle circle. The calculated indicators of targeted URAs will fall near the benchmark circle. The external ones are worse and the internal ones are better than the local average. Additionally, the benchmark could be changed. For example, a current “best practice” URA could be used as benchmark for studying the mitigating alternatives of targeted URAs.

Considering the structure of emissions helps to better known of the differences among these URAs (Fig. 7). For the building sector, the differences of environmental impacts are caused by the various materials required for different building height. There are many more high-rise apartments in TTY, whereas the lowest building existing in the ZXSS. The planning regulation on height of URA contribute to this distinctness. This kind of scheme also influences the vehicles sector, as the residents in TTY have more requirements on mobility, which leading to the relatively higher owning rate of private cars in TTY and catalyzed by the longer distance to the inner city. The lack of public transportation accesses, such as metro stations or public buses lines around TTY further aggravates the ownership of private cars, which makes the impact of vehicles in TTY become more than two times as large as in ZXSS. For the appliances sector, the deviations are the smallest. For there are more aged people living in ZXSS, the owning rates and the using

![Fig. 4. Normalized result of environmental impacts.](image)

![Fig. 5. Breakdown chart of pollutants from the buildings, appliances and vehicles.](image)
intensity of appliances in ZXSS makes its environmental impacts be less than that of TTY and BJ average.

5.2. The synthesized indicator

From the above discussion, a general rule can be found, that the more raw materials and energy is used, the higher level of residential services is obtained, with heavier environmental loads and ecological pressures introduced to local and broader surroundings. Thus, the last indicator of HEML, Emergy margin environmental impact, could be adopted to determine the performance of household metabolic sustainability and providing a way for comparison among different URA systems.

Considering the substantial support and environmental loads together, when same volume of pollutants discharged, the URA with more Emergy inflows obtained by every household is more sustainable. Indeed, the margin value is the slope of URAs in the Emission-Emergy plot (Fig. 8). During the whole life cycles of production and consumption, although the households in TTY received more Emergy supporting their lives, they are also releasing greater gross pollutants than ZXSS and BJ. The Emergy margin environmental impact indicator is useful to identify a relevant ranking on the URA’s sustainability. This synthesized indicator can be used to evaluate a migrating measure which would introduce any changes of the Emergy inflows and the environmental pollutants. Future studies could

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**Table 8**

Results of HEML indicators among TTY, ZXSS and BJ households.

<table>
<thead>
<tr>
<th></th>
<th>Empower (sej/yr)</th>
<th>ELR (N/A)</th>
<th>WR (N/A)</th>
<th>GWP</th>
<th>AP</th>
<th>NEP</th>
<th>POCP</th>
<th>SW</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJ</td>
<td>1.06E+16</td>
<td>104.60</td>
<td>39.09</td>
<td>403.48</td>
<td>997.59</td>
<td>191.86</td>
<td>332.03</td>
<td>736.15</td>
</tr>
<tr>
<td>ZXSS</td>
<td>1.19E+16</td>
<td>122.59</td>
<td>36.53</td>
<td>328.25</td>
<td>811.51</td>
<td>156.32</td>
<td>274.70</td>
<td>598.32</td>
</tr>
<tr>
<td>TTY</td>
<td>1.72E+16</td>
<td>124.08</td>
<td>38.05</td>
<td>705.42</td>
<td>1744.15</td>
<td>335.39</td>
<td>578.59</td>
<td>1287.79</td>
</tr>
</tbody>
</table>

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![Fig. 6. Relative comparison, where the benchmark value of BJ = 0%.

![Fig. 7. Different composition of environmental impacts among TTY, ZXSS and BJ.

![Fig. 8. Emission-Emergy plot of TTY, ZXSS and BJ.](https://example.com/plot.png)
be carried out by selecting different benchmarks and marking off on this plot.

6. Conclusion

By reviewing and comparing different methodologies, we used the Hybrid Emergy-LCA (HEML) approach to assessing the conditions of metabolism in URAs. Based on the broader scope of the spatiality (regional and global) and the timeliness (full life cycles of products), the positive and the negative aspects of metabolism in URAs are investigated together and evaluated by objective values. Particularly, the emission impacts are recorded by their inventory masses, while their normalized values are also involved for the synthesized indicator Emergy margin environmental impact, which is representing the URAs' sustainability by their household metabolism states.

The HEML results of TTY in Beijing reveal that, the household Empower is 1.76E+16 sej/yr. The URA Environmental Loading Ratio and WR is 127.58 and 39.62 respectively. The gross household emissions are 1.64E+09 g CO₂ eq./yr, 6.32E+06 g SO₂ eq./yr, 4.84E+06 g NO₃⁻ eq./yr, 4.58E+05 g ethane eq./yr and 1.18E+05 g solid waste/yr. The prominent impact is a result of POCP matters. The Emergy margin environmental impact is 7.15E+13 sej/emission impacts, which is 57.14% and 98.80% of that of the ZXSS and BJ average respectively.

The evaluating results of these three kinds of URAs in Beijing reflect that, currently, the main environmental impacts are all from the building sectors, accounting for half of the total impact around. The impact of vehicles differs, depending on the distance to job locations and the abundance of public transportation supply. While the appliance sectors are much similar across all URAs.

Based on the metabolic evaluation results, mitigation policies for improving the quality of living environment and enhancing the sustainability of URAs should focus on the building issues, e.g. using alternative and environmental-friendly materials, or increasing the life span of structures. Accessible and sufficient public transportation can support cutting down the environmental impacts effectively. All of the measures and improvements can be monitored and evaluated by the HEML index quantitatively.

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