Overcoming the “black box” approach of urban metabolism

Aristide Athanassiadis\textsuperscript{1,2,3}, Robert H. Crawford\textsuperscript{3} and Philippe Bouillard\textsuperscript{2}
\textsuperscript{1}Belgian Fund for Scientific Research (F.R.S.-FNRS), Brussels, Belgium
\textsuperscript{2}Université Libre de Bruxelles, Brussels, Belgium
\textsuperscript{3}The University of Melbourne, Melbourne, Australia
\texttt{aathanassiad@student.unimelb.edu.au, rhcr@unimelb.edu.au, philippe.bouillard@ulb.ac.be}

Abstract: Urban areas cover 2\% of the Earth’s land surface, while hosting more than half of the global population and are estimated to account for around three quarters of CO\textsubscript{2} emissions from global energy use. In order to mitigate existing and future direct and indirect environmental pressures resulting from urban resource use, it is necessary to investigate and better understand resource and pollution flows associated with urban systems. Urban Metabolism (UM) is an urban environmental assessment framework that measures resource and pollution flows that enter and exit urban systems. However, UM presents an important shortcoming, namely its “black box” approach. Indeed, standalone, UM figures are not enough to explain why they are specific and exclusive to a city and whether this city is heading towards a more sustainable state. In this study, four transversal aspects that attempt to overcome this “black box” approach are presented. These additional layers of understanding include temporal evolution, spatialisation and disaggregation, identification of resource use and pollution drivers and finally the indirect resource use and pollution emissions that occur outside of the urban boundaries.

Keywords: Urban metabolism; temporal evolution; spatialisation; embodied impacts.

1. Introduction

While urban areas cover only 2\% of the Earth’s land surface (Balk et al., 2005), they now host more than 50\% of the global population and are estimated to account for 71-76\% of CO\textsubscript{2} emissions from global final energy use and between 67-76\% of global energy use (Seto et al., 2014). In fact, cities can be seen as the complex expression of a global-local articulation in an ever globalising world and economy. Cities are the nexus of global and local challenges ranging on the one hand from climate change, degradation of ecosystem services, global financial crises and global conflicts due to resource scarcity; to unemployment, city cleanliness, and housing affordability on the other hand. In environmental terms, cities or urban systems are hotspots of resource consumption, that mobilise material and energy flows from around the world in order to match its inhabitants’ needs. Considering that the urban population is likely to continue to increase, especially in developing countries, it can be expected that cities will continue to be created and expanded to host this additional population. The creation and expansion of
cities in the near future will require a considerable amount of new urban infrastructure, resulting in significant demand for natural resources and further exacerbating existing environmental pressures.

In order to mitigate existing and future direct and indirect environmental pressures resulting from the functioning of cities, it is necessary to investigate and better understand how resource flows are associated with the urban system. Urban Metabolism (UM) is an urban environmental assessment framework that measures resource and pollution flows that enter and exit the urban system. While the urban metabolism field is now well established and is continuously evolving either with new accounting developments or with new case studies, it still has a number of shortcomings (Golubiewski, 2012). The most significant limitation of the UM framework, is its “black box” approach. In other words, UM only provides a synthetic environmental profile of a city with no reference to the local specificities and the drivers that govern these resource and pollution flows.

This study proposes a comprehensive framework for expanding the urban metabolism approach. The framework adds four additional layers of analysis to the traditional UM approach, namely, the temporal evolution, spatialisation, the assessment of indirect environmental effects, and the identification of metabolic drivers. Thus, this framework will provide a context-specific and spatio-temporal analysis that will attempt to shed some light on the complex behaviour and environmental effect of an urban system. This complex analysis is not only necessary to propose coherent and comprehensive environmental policies but is also useful in order to model and forecast the future metabolic state of the studied urban system.

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This paper is structured as follows. The next section will briefly present the current UM framework as well as some strengths and weaknesses. The four aspects proposed to overcome the “black box” approach of UM will then be presented followed by the elaboration of a more complex urban environmental assessment framework. This study will conclude by discussing some limitations and future pathways for investigation.

2. Urban Metabolism: a brief definition

While the first use of UM from Marx date back to late 19th Century to describe the material relationship between humans and nature, this metaphor has been employed by a great number of disciplines ranging from social theory, to cultural and ecological anthropology and social geography, to finally urban environmental assessment (Ayres and Ayres, 2002). However, the first study that used the UM metaphor in order to assess the environmental impact of a city was the one of Wolman (1965). Since then, more than 75 UM studies have been carried out, of which 20 were relatively comprehensive (Kennedy and Hoornweg, 2012).

In contrast with other environmental accounting tools such as Life Cycle Assessment, Economy Wide-Material Flow Analysis (EW-MFA) and Input-Output Analysis (IOA), UM still lacks a common definition or methodology (Ioppolo et al., 2014). Instead, UM has been used as an accounting framework rather than a methodology per se and could be described as a “large data collection exercise” (Kennedy, 2012). These data or metabolic flows are divided into three main categories: inputs (e.g. energy, materials, water, etc.), outputs (e.g. solid, pollutants, materials, etc.) and stocks.

This being stated, UM has become a central tool to understand and address urban resource and waste flows. Indeed, the comprehensive approach of UM treats each resource, emission and waste flow individually and with its appropriate unit providing governments and administrations with more relevant data to implement relevant urban environmental policies. In addition, UM’s loose framework allows it to adapt to specific characteristics of each case study such as administrative boundaries. This flexibility of
the UM framework and the pool of case studies that make comparisons between urban systems possible (although accounting methodologies and available data differ from case to case) make UM perhaps the most relevant accounting framework at the urban scale.

However, UM still presents a number of shortcomings that hinders its acceptance amongst researchers. A number of drawbacks of UM are very similar to EW-MFA such as the “black box” approach (Golubiewski, 2012). The elaboration of an UM does not capture the complexity and interrelationship between internal mechanisms from neither social nor economic activities while it can be argued that it is impossible to separate urban metabolism from its urban characteristics due to their constant interrelationships (Pincetl et al., 2012). Finally, as UM only measures all flows entering and exiting the urban boundaries it does not take into account the environmental effects over its global hinterland embodied in trade (Baynes and Wiedmann, 2012). This can highly overestimate the “sustainability” of a city and lead to misleading environmental policies (Baynes et al., 2011).

3. Some transversal aspects to overcome the “black box” approach

Aside from the accounting framework used during the environmental assessment of cities, some transversal aspects are needed to comprehensively include the complexity of their functioning. Indeed, cities are not static, homogeneous and isolated systems. They perpetually and dynamically evolve from external and/or internal forces. The interrelationship of urban system components (such as society, economy, the built environment, politics, etc.) can influence its overall environmental effect. On the other hand, the use of natural resources and the emissions generated by a city could have a considerable influence on some of the urban components. Finally, in the present globalized economy, cities are reliant on a global hinterland in order to meet their resource use and waste disposal. This section will briefly present four perspectives to better understand the environmental state and effect of cities and how to overcome the “black box” approach of UM.

3.1. Temporal evolution

The first element necessary to better understand current and near future resource consumption and their environmental effects, is a time series evolution of resource use. In fact, by constructing the resource use trajectory, it is possible to understand several aspects of urban consumption. Firstly, a temporal evolution enables the positioning of an environmental assessment on a timeline. Instead of analysing a snapshot of a city’s consumption, it is possible to situate a punctual assessment on a trajectory that will reveal if this urban system is heading towards a more sustainable state. Another valuable aspect that a time-series assessment offers, is the identification of structural changes and eventually the drivers of these changes (Krausmann et al., 2009). The structural change in consumption pinpoints not only technological innovations but also an evolution of urban infrastructure and consumption behaviours. A further element that temporal evolution of urban environmental assessments enables, is to confirm whether implemented policies had the desired effect or not. Finally, constructing the temporal evolution of the environmental state of a city and identifying its main trends can ultimately help to forecast future consumption and environmental effects. However, in practice, time-series assessments are seldom available for UM studies due to their data intensive nature.
3.2. Spatialisation

Another fundamental aspect that needs to be incorporated in UM studies, in order to avoid seeing cities as static and homogeneous entities, is spatialisation. By mapping metabolic flows it is possible to discern how consumption is distributed across an urban system. The emergence of different consumption patterns pinpoints different land uses; territorial organisations; infrastructures; economic activities; but also different consumption patterns (Howard et al., 2012). Thus, mapping urban consumption can lead to a preliminary identification of drivers and measure the efficiency of territorial organisations. An additional issue that can be addressed with the spatialisation of results, is that not all territorial units face the same consumption and environmental issues and therefore do not assign the same importance and priority for these challenges. To overcome this issue, spatial analysis should therefore be supplemented by a multi-scale analysis (Munksgaard et al., 2005). Multi-scale analysis, can in fact illustrate more comprehensively the full environmental effects of cities and give a better understanding of which are the most important drivers at which scales. Nonetheless, similarly to temporal evolution, the major issue of mapping urban consumption is the availability of data at different and especially small territorial scales.

3.3. Measuring indirect environmental effects of cities

The third aspect that it essential to include, in order to take into account that cities are not isolated systems, is the assessment of indirect environmental effects of cities. Accounting for the resource use and environmental effects embodied in trade is not only important to provide a full environmental profile, but also to map the complex environmental effects of urban consumption across the global economy and its supply chains (Kanemoto and Murray, 2013). In reality, calculating the indirect environmental effects of cities can be proven to be extremely difficult. To perform this calculation it is necessary to use household expenditure data at a city level and combine it with an Input-Output Table (IOT) at a city level to measure the local direct and indirect effects of local consumption. The local IOT should then be linked with a Global Multiregional IOT in order to measure the direct and indirect effects of local consumption at a global scale. To our knowledge, except for the work developed by the Australian IELab (Lenzen et al., 2014), IOT at such level are not available at an urban scale. This implies that so far, it is only possible to obtain such results based on regional or national averages of production and consumption figures (Baynes et al., 2011).

3.4. Identification of drivers

The last aspect that is necessary to add to the current UM framework, in order to make it more relevant for urban systems and for more informed decision-making when it comes to environmental pressure, is the identification of drivers. In reality, the identification of drivers is a major step towards a better understanding of urban resource use and the intertwined relationships that exist between components of a city mobilizing matter and energy; but also between the city itself and its wider environment. The relationship between resource use and local factors helps to contextualize environmental assessments and determine why such figures are exclusively valid for one city (Pincetl et al., 2012). This is especially relevant for the urban scale which is an amalgam of economic, social, cultural, political and many other forces that constantly evolve, thus making each urban system unique and incomparable to any other.

In addition, identification of drivers is a necessary step towards context-specific solutions and policies for mitigating our environmental impact. In fact, different case studies identify different local
factors as predictors of resource use and pollution emission ranging from territorial organization, climate, income, age, number of persons per household, lifestyle, etc. (Heinonen et al., 2013; Wiedenhofer et al., 2013). However, it is important to keep in mind that the results of this identification of drivers are very different at a macroscale (city scale) compared to a microscale (smaller spatial scales such as municipalities). For instance, Kennedy et al. (2015) find that while urbanized area per capita is strongly correlated with energy use at a macroscale, this correlation is less significant at a microscale.

Finally, a regression analysis between resource use, pollution emission and local factors, greatly depend on the indicators used. In fact, correlation of direct or indirect resource use with local factors can give completely different results (Wiedenhofer et al., 2013). Hence, when identifying drivers, it is necessary to consider a variety of indicators and metrics to best reflect the environmental state of a city (Ramaswami and Chavez, 2013).

4. Establishment of a comprehensive urban metabolism framework

After briefly presenting the UM framework along with its main strengths and weaknesses, the previous section identified four layers that should complement UM in order to achieve a more comprehensive and insightful understanding of the environmental state of cities. This section will in turn attempt to integrate the current UM approach with these four layers in order to establish a more comprehensive UM framework. This comprehensive UM framework illustrated in Figure 1, indicates a number of steps that can help to better comprehend the complex behaviour of cities in terms of resource use and environmental effect.

![Figure 1: An overview of a comprehensive urban metabolism framework. Note: UM: Urban Metabolism, IOA: Input-Output Analysis, TEMP: Temporal evolution, SPAT: Spatial analysis, DRIV: Identification of drivers. Dark grey boxes represent the UM approach, while light grey represent the IOA approach. Numbers in dotted circles represent the combination of UM and IOA approaches while numbers in solid line circles indicate that approaches where considered separately.](image)

4.1. Including temporal and spatial dimensions for a better understanding of UM drivers

The first and most important step (I) as the base of a complex urban environmental assessment is to carry out a comprehensive UM with as many flows as possible and when possible disaggregated by
sectoral use. Based on this UM study it is possible to trace the temporal evolution (II) of each flow enabling the identification of any significant trend. Comparing the temporal evolution of different metabolic flows enables an understanding of whether the needs of an urban system change over time, if there has been any structural change (e.g. due to a technological innovation), if there has been an economic shift towards primary, secondary or tertiary activities or finally the effect of mitigation or efficiency policies on metabolic flows. Similarly, spatialisation (III) of a comprehensive UM would also help to investigate whether the urban system is a homogeneous entity or if each spatial scale has different patterns for each of the resource use and pollution emissions flows considered.

While establishing temporal evolution and a spatial evolution of the current UM framework adds two new dimensions of understanding, these additions do not enable the identification of underlying drivers of the metabolic flows. Indeed, steps (I), (II) and (III) are more descriptive than analytical. However, it is important to note that without the temporal and spatial elements, it would be impossible to search for local drivers. In order to find any relationship between a metabolic flow and a socio-economic or territorial organisation factor there needs to be at least two values for each metabolic indicator. Depending on the statistical test, the number of values needed to establish a relationship between metabolic indicators and local factors can vary and reach up to several hundreds.

Temporal evolution of local factors data is usually available through census and surveys data or from reports elaborated from the appropriate administration. However, surveys and census are very time consuming and therefore their periodicity can vary from yearly up to intervals of 10 years. In addition, in some cases, the questions asked or indicators measured within surveys and census may change over time. Finally, a more delicate issue is that the spatial classification within which data is collected or the urban boundaries may vary over time, creating thus a discontinuity within a longitudinal analysis. In practice, long-term annual time-series are only available if the urban boundaries correspond with administrative boundaries and both have been unchanged for this period of time.

In any case, identifying the effect of local drivers on the temporal evolution of an UM (IV) can provide insightful information about the relationship between the urban development of a city and the associated metabolic flows needed at each stage of this development. The results could also be helpful to estimate the resource use and pollution emission of other cities that will undergo similar stages of urban, demographic, economic and social development.

Establishing a statistical relationship from a spatial perspective on the other hand, implies that data values should be available for a large sample of spatial entities. In this study, two options for spatialising an UM are explored. The first option of a spatialised UM could be achieved by disaggregating UM into smaller spatial entities. For the statistical relationship to be meaningful, the division of the urban system into smaller spatial entities should be carried out in a way that all units should have a comparable number of inhabitants but also homogeneous social and territorial characteristics, i.e. a similar land-use, building typologies, socio-economic and socio-demographic profiles. Similarly to the temporal case, disaggregated and meaningful local data can be easy to obtain through national, regional or urban census and surveys. However, metabolic data at smaller urban scales are very difficult to obtain due to the sensitivity of these data. In order to obtain accurate data for energy and water (this is not possible for other materials), it is necessary to access data from energy and water suppliers or grid operators. In a number of cities, the energy and water market is owned by one or a number of public and/or private companies. Therefore, mapping the metabolism of an entire city could reveal to be the difficult task of putting together a patchwork of confidential data. However, the results from a correlation at a spatial scale would be of great importance as it could identify patterns of consumption or pollution of different
local socio-economic and socio-demographic profiles as well as building typologies, land use, population or built-up density.

Another way to take into account the spatial element of UM is by doing a multi-scale analysis where different administrative scales are considered ranging for instance from household or neighbourhood, to urban and metropolitan scale or even national scale. This would complement the traditional metabolic approach with a micro- and macro-scale analysis. However, obtaining data at different spatial scales from the same data source, for the same year or with the same periodicity can prove to be quite difficult. In addition, in many cities, the metropolitan scale is a geographical delimitation convention more than an administrative entity that collects data. Ideally, to obtain an accurate multi-scale analysis regardless of whether the spatial boundaries considered coincide with administrative data, it would be necessary to have precise data at the smallest spatial scale possible and then aggregate this data for all the larger spatial scales. The issues of obtaining data at smaller spatial scales were presented, however, in practice, to achieve a multi-scale approach it is often necessary to combine top-down and bottom-up data. Nevertheless, identifying multi-scale metabolic drivers helps to manifest the complex interrelationship between all the nested spatial entities that compose an urban system as well as the importance of the global hinterland for the provision of natural resources and the disposal of waste. This helps to stress that cities are not isolated systems and that while spatial entities can be nested they face different sustainability challenges and priorities at each spatial scale.

To sum-up, identifying metabolic drivers from a spatial perspective (V) highlights that there is no one-size-fits-all policy for every territorial scale. Indeed, each spatial entity has a different metabolic profile that can be influenced by a different set of local factors. In addition, a statistical relationship for a given territorial scale is not necessarily true for another one. Thus, applying a similar policy for the entire city or metropolitan area may lead to conflicting, counter-productive or even non-desired results.

4.2. Combining temporal and spatial dimensions

The previous section considered the benefits of adding temporal and spatial perspectives for the identification of metabolic drivers and therefore for a more comprehensive understanding of the UM of cities. The present section will discuss the relevance of combining these two layers to obtain a more context-specific analysis (steps (VI) and (VII)). Similarly to the two options available for the spatialisation of UM, there are two options for combining a temporal and spatial approach. In addition, the data limitations presented for each of the options are also relevant here.

The first approach to combine spatial and temporal perspectives is to perform a temporal evolution of a disaggregated UM into smaller spatial entities. This approach would essentially need the same data as the first spatialisation option but for several points in time. Indeed, if metabolic data at smaller spatial scales are previously accessed through energy and water suppliers or grid operators, obtaining them for a series of years (or even months) should be an easy task. However, as these data are only available through digital databases of suppliers or grid operators, the available data over time could be limited. In addition, as energy and water companies may supply and operate different areas over time, the temporal evolution of spatially disaggregated metabolic flows can prove to be challenging. On top of that, it is important to consider that geographical classification of surveys and census data also evolve over time which makes it very difficult to carry out a longitudinal study over the same small spatial units. All in all, the identification of drivers using this option of combining temporal and spatial dimensions can enable for instance a deeper understanding of the environmental effects of certain building typologies across their lifecycles. The identification can also help to determine, if the same statistical relationships
between metabolic flows and local factors remains valid for each year of analysis or if they have altered over time. Thus, assessing if local factors have a similar effect on UM over time ensures that the correlation for a given year is not an exception or due to a particular conjuncture.

The second approach is to perform a temporal evolution of different spatial scales UM’s. This approach is confronted with similar limitations from step I to V and with the first approach. The interest of identifying the drivers of an UM temporal evolution at different spatial scales, is to trace changes at micro- and macro-scales and their effect on metabolic flows. These changes can be socio-economic changes such as financial crisis and unemployment; the shift of economic activities from secondary to tertiary; urban sprawl; the introduction of transportation infrastructure projects; etc.

4.3. Combining UM and IOA-based approaches for a better understanding of metabolic drivers

The previous sections (steps I to VII) covered how to add spatio-temporal context to current UM studies and what type of information their corresponding drivers could provide. While such analysis can become very data intensive it should be kept in mind, that so far all metabolic data were direct use of natural resources and emission of pollution. Measuring indirect metabolic flows (VIII) enables the assessment of the overall environmental effect of cities over their global hinterland. This is important especially for a number of cities based on tertiary activities economy that do not import metabolic flows for manufacturing but only import flows necessary to operate the built environment and end products to satisfy the consumption needs of its inhabitants. Similarly, as there are no or few industrial activities present in these urban systems, they do not export (semi-)manufactured goods or particular pollution flows. As primary and secondary activities tend to leave the urban or national boundaries of developed countries, resource use and pollution emission is not typically accounted for within their territory. Combining local and global multi-regional IOTs for measuring indirect metabolic flows will also enable tracing of the origin and destination of input and output flows. This enables a measurement of the span of each flow’s hinterland, showing the dependence and vulnerability of a city. However, as IOA results can have considerable uncertainties, comparing them with UM results (XV) would also help to validate them. In addition, their combination would also enrich UM results by providing information that is not bounded to the urban territorial boundary.

In addition, measuring the temporal evolution of indirect metabolic flows (IX), can illustrate how the evolution of trade can affect the overall environmental profile and hinterland of a city. Identifying the drivers of this temporal evolution (XI) could inform which demographic, socio-economic and urban development indicators have the highest influence on the trade global supply chains. It would also be possible to identify which economic activities and which consumption products add the most pressure to the environment as well as which products are coming from local activities and which from international trade. Comparing the temporal evolution of UM- and IOA-based metabolic flows (XVI) as well as their respective drivers (XVIII) helps to take into account the local and global parameters that influence metabolic flows entering and exiting a city. This also enables the creation of a hinge between global and local conjunctures, helping to understand this complex connection.

Spatialising the indirect metabolic flows (X), would essentially provide information about the environmental effect of household consumption and production patterns at smaller spatial scales. The drivers of this spatialisation could help to inform which socio-demographic and territorial organisation indicators influence household expenditure and thus its environmental effect (XII). Comparing the spatialised UM- and IOA-based metabolic flows (XVII) as well as their respective drivers (XIX) enables a
comparison of the flows used by the built environment and production activities (UM) vs. the flows used by the consumption and production activities (IOA). This can be of great interest as material consumption at small scales is practically impossible to assess for the UM approach. In addition, comparing UM and IOA results at smaller spatial scales would help to further validate the IOA results by expanding the sample of comparisons.

Finally, the four last steps that this comprehensive urban metabolism framework takes into account are the assessment of the temporal evolution of spatially explicit indirect metabolic flows (XIII), the identification of their drivers (XIV), as well as the comparison of the two previous steps with UM results (XX and XXI). The first of these steps can help to explain changes in household consumption patterns and their environmental effects along their global supply chains. Exploring the evolution of these particular drivers may help to understand how urban development and lifestyles are connected with global environmental and socio-economic challenges.

5. Discussion and Conclusion

The extended UM framework presented here, provides a number of steps to overcome the “black box” approach that current urban environmental assessment studies suffer from. This comprehensive framework can provide a vast matrix of information encompassing the complexity that revolves around the UM of cities. However, there are limitations inherent to data and accounting approaches and therefore to all of the steps presented here. In addition, in the use of this wealth of context-specific data and indicators, it is recommended that extreme caution be used as they provide a multitude of slightly different angles to view the metabolism of a city that only when assembled can be used to describe the complex, dynamic, heterogeneous, interconnected and ever-changing character of a city. It should also be noted that more elaborate identification of drivers is possible through more complex statistical analyses such as multivariate analysis and principal component analysis.

To conclude, this comprehensive UM framework creates a solid basis for better understanding cities and their metabolism. Comparing the temporal evolution of spatialised UM and IOA metabolic flows, helps to construct a complex understanding of cities as the articulation of local and global environmental, social and economic challenges. Upon this solid basis it is ultimately possible to create a theoretical model that describes urban systems and urban dynamics within a set of non-linear equations. In turn, this complex UM model could serve to forecast different scenarios of environmental effects based on different policies, socio-economic and territorial organisation inputs. It also serves as an important tool for the sustainable design and management of new and existing cities.

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References


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Author/s:
Athanassiadis, A; Crawford, RH; Bouillard, P

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