Mapping diversity of urban metabolic functions – a planning approach for more resilient cities

Marc Spiller*, Claudia Agudelo
*Urban Environmental Technology and Management - Sub-department of Environmental Technology, Wageningen University Bomenweg 2, 6703 HD Wageningen Tel +31 (0) 317483344 marc.spiller@wur.nl

Key words: functional diversity, urban metabolism, ecology, resilience

Urbanisations have a metabolism that converts inputs into outputs. Nowadays this metabolism is mainly linear, where resources are used mostly once and then discharged to the environment. Transitions towards more circular urban metabolism may increase resilience of urban systems and will be crucial for achieving environmental sustainability. In ecosystems diversity of functions is crucial for circulation of nutrients, substitution of functions and cascading of energy. As a result, eco-systems are resilient to disturbance. In this paper the relationship between diversity of urban metabolic functions and resilience is explored. It is concluded that diversity of urban metabolic functions improves resilience through substitution of functions and through a higher overall efficiency. Following this conclusion a methodology is proposed to analyse the spatial distribution of urban metabolic diversity using mass flow analysis and ArcGIS software. This method offers the opportunity for planners to identify resource inputs and outputs in space; thus providing a first step to plan for matching existing outputs (e.g. heat, waste, water) and inputs in a circular urban metabolic system.

1 Introduction

Urbanizations are the centres of resource consumption and waste production. Globally urbanizations accommodate more than 50% of the world's population and are estimated to be responsible for 70% of pollution and resource depletion.

The conversion of resources into products that is taking place in urbanizations (i.e. waste, commercial products) can be viewed as a metabolism. In ecology, metabolism is defined as (Odum, 1994): *"the energy driven production (via photosynthesis) and consumption (by respiration) of organic matter"*. A similar definition can be used for urbanizations (Kennedy et al., 2007): "*Urban metabolism is the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste"*. Nowadays urban metabolism is linear, where resources are used mostly once and then discharged to the environment. This linear consumption pattern is at the heart of present resources exploitation, saturation of 'waste' sinks and consequently the imbalance of (global) ecosystems. A transition towards more circular urban metabolism, by increasing efficiencies, reusing and recycling, will avoid waste, increase resilience of urban systems and will be crucial for achieving environmental sustainability (Girardet, 1999).

In ecosystems, two types of diversity are important for social-ecological systems: (1) functional diversity, which influences system performance, and (2) response diversity, which influences resilience (Walker et al., 2006). Functional diversity is crucial to enable circular metabolism. It essential to enable the cascading of energy and the cycling of nutrients and water, because different functional elements are responsible for balancing inputs and outputs. Consequently, ecosystems that are diverse can sustain higher population densities than less diverse ecosystems, because they utilise energy and materials more efficiently (Pulliam & Johnson, 2002). Furthermore, diversity of function has been shown to increase ecosystems resilience, because organisms can substitute each other, thereby compensating for disturbance and maintaining the function of the ecosystem (Gunderson & Holling, 2002).

For urbanizations, diversity or multi-functionality has been argued to be a vital factor for the development of liveable cities that offer employment and social cohesion (Jacobs, 1961). However, little research has been done on how diversity of metabolic functions (i.e. the flows of nutrients, water and energy within cities) affects urban resilience.

The paper is divided in two parts. First the relationship between metabolic diversity and resilience will be discussed. For this purpose simplified hypothetical examples of urbanisations in the form of maps will be used. The urban elements contained in these maps and their different metabolisms (i.e. their diversity) will be explained. Then an example of today's linear metabolism will be given, and its relationship to resilience will be discussed. Thereafter, an alternative scenario is discussed that takes into account diversity of metabolic functions. Using this example it is demonstrated how planning for diversity can increase the resilience of urban systems. In the second part of the paper a research approach and methodology that aims to develop urban metabolism planning guidelines founded on the understanding of diversity of urban metabolic functions will be described.

1.1 Diversity of metabolic functions and resilience

Resilience can be defined as a measure of resistance to disturbance and speed of return to equilibrium. In the discussion below we will focus only on the aspect of resilience that describes resistance to disturbance rather than speed of return to an initial state or function. Resilience is then the magnitude of disturbance that can be absorbed before the system changes its structure. We also emphasise that for the purpose of this discussion we only investigate engineering resilience rather than ecosystem resilience. The key difference between these two view on resilience is that engineering resilience is based on the assumption that there is one single stable state - equilibrium- that needs to be maintained, while ecosystem resilience is founded on the proposition that multiple different stable states can exist (see Gunderson & Holling, 2002).

Figure 1 shows a simple hypothetical urbanisation with five elements:

- Housing building
- Industry
- Green houses
- Office and shop buildings
- Power plant / water treatment works and waste water treatment works (items are combined here for simplicity)

Figure 1: A simplified urbanization with five structural elements

Each of these elements of the urban tissue has a specific metabolic function. Table 1 characterises these metabolic functions only considering water and natural gas. The table further describes the time pattern of metabolism. It can be seen that the metabolism of each of these elements differs in terms of character (i.e. how inputs are converted into outputs) and diurnal consumption cycles (i.e. metabolism peaks at different times during the day). In other words the five metabolic elements of the urbanisations show diversity in terms of their metabolism. In the following, we will discuss three diversity-resilience scenarios for this hypothetical urbanisation; one which does not accounts for metabolic diversity of metabolic functions and one which does for diversity. In addition, a third scenario is discussed that demonstrates how technological progress alters the metabolism and therefore the diversity that can be exploited.

Table 1: Metabolic functions for the elements of the hypothetical urbanization

Scale	Resource	Conversion	Time pattern
House	Water	Converts drinking water into waste water which is enriched with N, P and has a temperature of about 37°C	**Diurnal variations** Morning and evening peaks **Seasonal variation** garden watering in summer
	Natural Gas	Uses natural gas for heating the house to ambient temperature, heating water and for cooking	**Diurnal variations** Consumption peaks for 12h during the day (6am-12pm) **Seasonal variations** Higher heating requirements in winter
Industry	Water	Uses drinking water to cool process thereby heating it up water	**Constant demand** possibly 24/7
	Natural Gas	Burns natural gas to e.g. process paper, metal, produce food etc., thereby producing heat	**Constant demand** possibly 24/7
Offices and shops	Water	Converts drinking water into waste water which is enriched with N, P and has a temperature of about 37C	**Diurnal variations** For about 8 to 10h a day (10 am – 20pm) – with variation
	Natural Gas	Uses natural gas for heating the house to ambient temperature, heating water and for cooking	Diurnal variations For about 8 to 10h a day (10 am – 20pm)
Green house	Water	Uses drinking water for irrigation and enriches it with nutrients to fertilise plants	**Once or twice a day** subject to season variation
	Natural Gas	Uses natural gas for heating the green house	**Seasonal variations** depending on strength of winter (note: modern green houses can store excess heat from the summer into the winter)

1.2 Today's approach – disregard of metabolic diversity

Today's centralized supply systems deliver water and energy to all urban elements without accounting for the diversity of their metabolic functions (Figure 2). One way in which this 'disregard' of diversity can be expressed is in terms of the quality of energy and water. In the present approach all urban elements are served with the same high quality of energy and water despite lower quality requirements of some activities.

For instance, natural gas has a high energy density and burns at 1500 °C. It is commonly used to heat homes to about 20 °C. However, the work that could be extracted from a flame burning at 1500°C can be much larger (because of the large difference temperature difference - i.e. 1480°C (Dobbelsteen et al., 2008). It could for instance be used in bakeries or even to melt metals. Thus using natural gas for low temperature applications is inefficient. Dobbelsteen et al. (2008) thus proposed that heat should be cascaded from high temperature applications to low temperature applications. He further suggests that Exergy maps can help planers to identify sources of heat and sites or heat demand. Exergy is defined as the amount of work that can be extracted from a temperature difference ΔT (Dobbelsteen et al, 2008).

A concept similar to exergy can be applied to water. Comparing water use versus water consumption at domestic level, it is evident that there is a ’’quality surplus” supplied. Only 6% of the high quality potable water supplied to households is consumed by humans (i.e. drinking and cooking), while the remaining 94% are used for other purposes (personal hygiene and cleaning) that do not required this quality. During these processes water is not lost from the household, but its quality is deteriorating. As an output, water enriched with Nitrate and Phosphorous is produced and discharged into the wastewater treatment plant (WWTP) (Agudelo et al., 2009).

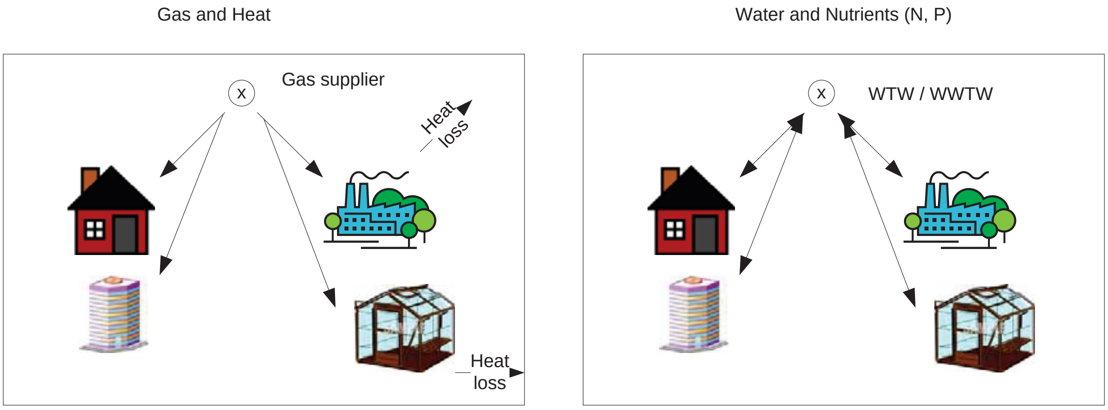

Figure 2: Today’s predominant approach to water and energy service provision.

In summary, these existing service delivery systems are highly inefficient, because they do not match the quality of supplies to demand. Ecosystems on the other hand often achieve this match, by accounting for metabolic diversity, thus making them more efficient. Additionally, this approach to service delivery resulted in large delivery networks, with high and ever increasing maintenance costs.

For resilience the system configuration described above implies that disturbance at one point in the system might have large impacts on the function of the whole system. Rising fuel prices are one example for this. They represent a disturbance to the system that could be better buffered by a system that is more efficient and diverse, than by a system that relies on a large quantity of inputs per unit of output and has a single source. Centralisation of the networks further implies that damage of the network or contamination at the water treatment works can leave whole districts or urbanizations without water or energy. Examples for such black outs, water shortages or water contamination are frequent.

Lastly, these centralised systems are rigid, meaning that when demand is growing bottlenecks in the distribution networks can occur, because existing networks cannot deliver the flows required (a symptom of this is for instance pressure loss in water pipes). Thus these systems can be considered to compromise their own resilience when demand is growing. Such growth in demand can be caused by population growth or other demographic changes and new socio-economic patterns that result in higher consumption. Another reason for the occurrence of bottlenecks can be peak demands during the day, which exhaust the capacity of existing networks.

1.3 Recognition of functional diversity

In this scenario the diversity of different heat requirements are taken into consideration and exergy networks are designed accordingly, while still maintaining the ‘old’ more central system (Figure 3). Cascading of exergy takes places thereby using existing energy more efficiently. Such linkages can for instance be developed between industry and housing estates. It is not uncommon that industries simply pump their cooling water to near by housing estates. Likewise, there are green houses that can store excess heat from the summer into the winter. A part of this heat can then be exported to heat local houses. These decentralised solutions make the system less vulnerable to changes in market prices of natural gas, because higher efficiencies can be achieved.

Likewise, disturbance, in the form of damage to the gas supply networks, will have a smaller impact on the overall system function, since the heating of houses can be substituted by other linked functions (for instance between industry and housing). Indeed, a similar rational has prompted the EU to diversify it gas and energy supply source (Costantini *et al.*, 2007). Furthermore, these systems are less vulnerable to growth in demand and resulting bottleneck, because the system does not rely solely on centralised supply functions, but it could be imagined that these systems co-evolve and grow together.

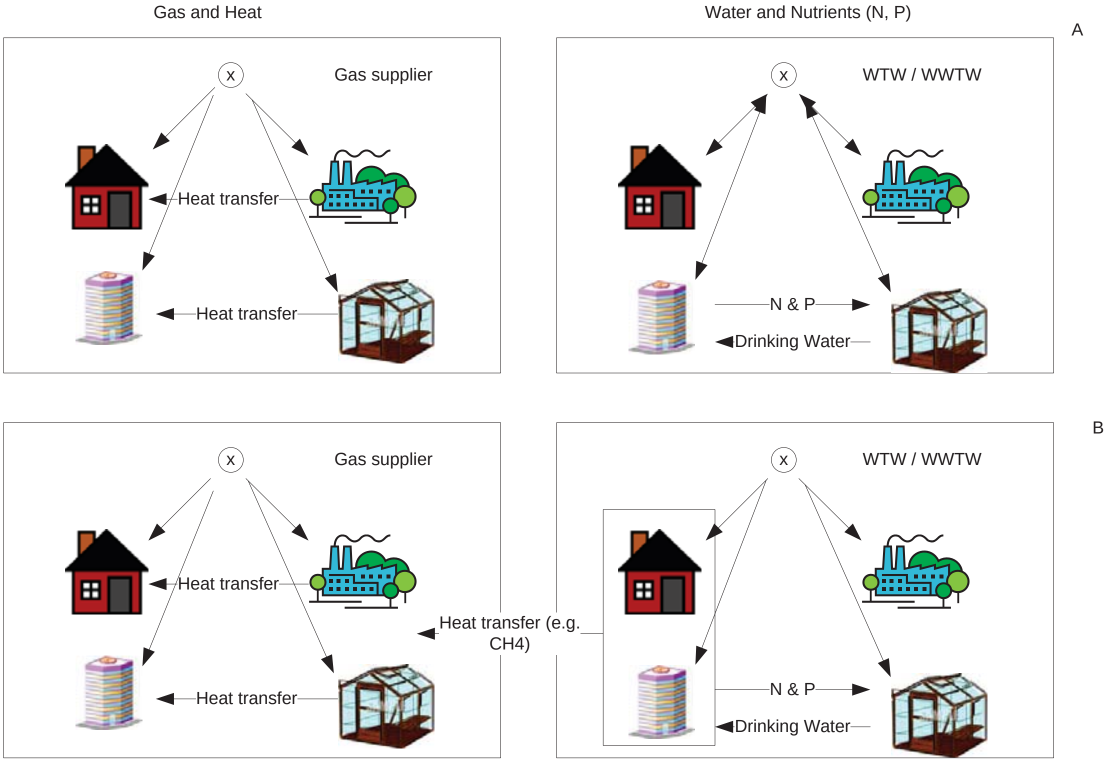

Figure 3: Appreciation of diversity and emerging linkage of functions

For water, a number of examples show how progress in decentralised water treatment methods can alter the metabolism - expressed as change to the conversion of inflows into outflows - of individual urban elements; consequently increasing the diversity of functions that exist in urban system. Examples for such new decentralised approaches are the installation of green roofs and grey water reuse, decentralised water treatment and rain water collection. And overview of these infrastructures for sustainable communities is given by (Makropoulos & Butler, 2010).

About 125l of drinking water are delivered each day to customers in the Netherlands. Through a number of activities pathogens, pharmaceutical and N and P are added to the water. N and P are valuable nutrients in fertilisers. They can be made available to agriculture through process such as struvite precipitation or direct application of urine (Graaf de, 2010). Mapping the demand for fertiliser it can then o recognise how these nutrients can best be used in green houses or to fertilise urban green space. Viewed as a more dynamic system the existence of the resource ‘nutrients’ could also trigger the planning and implementation of a greenhouse or green space nearby, this leading to diversification of functions.

Further technological progress of water treatment has opened the opportunity to use wastewater as a source of heat and electricity in the form of Methane (Graaf de, 2010). This can then result in further connecting linkages, thus reducing the dependence on heat provision in centralised systems. Hence, these linkages increase resilience, by increasing efficiency and reducing reliance on centralised heat services.

1.4 Conclusion

In summary, resilience of these systems can be increase through a higher diversity of linked urban metabolic functions that increase efficiency and enable substitution. These conclusion highlights that metabolic diversity per se is not enabling urban resilience, but rather that linkages between metabolic functions are essential utilise metabolic diversity. Furthermore, the discussion above showed that technologies affect the metabolism of urban elements. The present development towards small scale water and energy generation technologies is therefore likely to increase the diversity of urban functions and hence resilience. Lastly, the theoretical discussion above also emphasis that focus on urban metabolic functions, rather than for instance only on urban structure or form, reveals important information to plan for more resilient future cities.

Building on these conclusions the next section will develop a method that can help planners to identify metabolic diversity and potential links between metabolic elements.

2 Method

2.1 Background and rational for the research approach

Existing studies on urban metabolism used Mass Flow Analysis (MFA) on the scale of the city or regions (Kennedy *et al.*, 2007; Ngo & Pataki, 2008). MFA is a method to quantify and characterise the input-output balance of energy, materials and water. The underlying principle of this method is the law of the conservation of mass – matter or mass in a closed system cannot be destroyed – suggesting that:

$$\sum system\ inputs = \sum outputs + \sum mass\ stored$$

MFA is commonly applied in manufacturing to determine efficiency in single processes or process lines. For complex processes that require more than one input it can written:

$\Sigma m_R = \Sigma m_P + \Sigma\ m_W + \Sigma m_S$
(where Σ (sigma) denotes the sum of all terms)
$\Sigma m_R = \Sigma m_{R1} + \Sigma\ m_{R2} + \Sigma m_{R3}$ = Total Raw Materials
$\Sigma m_P = \Sigma m_{P1} + \Sigma\ m_{P2} + \Sigma m_{P3}$ = Total Products
$\Sigma m_W = \Sigma m_{W1} + \Sigma\ m_{W2} + \Sigma m_{W3}$ = Total Waste Products or losses
$\Sigma m_S = \Sigma m_{S1} + \Sigma\ m_{S2} + \Sigma m_{S3}$ = Total Stored Products

MFA can also be applied (with some limitations) to energy. Energy balances are often complicated because forms of energy can be inter-converted, for example mechanical energy to heat energy, but overall the quantities must balance. Figure 4 shows a simplified mass flow diagram for an urban metabolic element.

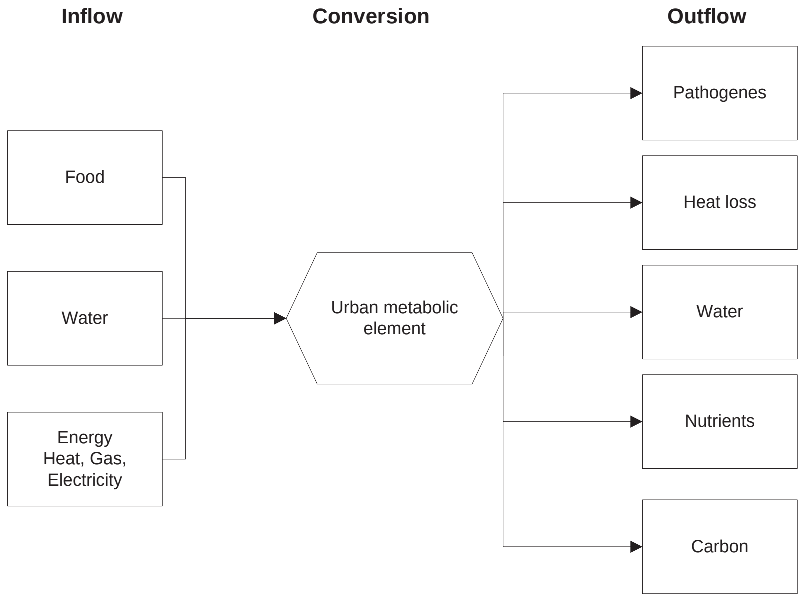

Figure 4: Simplified mass flow diagram for an urban metabolic element

In urban metabolism studies, MFA has mostly been applied at the city or regional level, by aggregating the data to determine an overall balance. Furthermore, as pointed out by Kennedy et al. (2010) urban metabolism have not widely been applied in planning and design. One reason for this lack of applicability could be that metabolic studies aggregated data to the city or even region scale. As a result they do not show the wide diversity of functions that exist within urbanisations, which are essential to work towards more circular metabolism.

Furthermore, aggregation of metabolism to city scale does not match the level at which practical urban planning and design operates; namely the building, block, neighbourhood or district scale. In this paper a 'bottom up approach' to urban metabolism is advocated, which is capable to build up a city metabolism from the smallest functional unit (e.g. building), by up scaling to the entire urbanisation or even region. Yet, another reason urban metabolism has not been applied by planners is that existing studies lack a spatial dimension. Hence, planners have no tools that assist them in understanding spatial organisation of metabolic functions through which they can optimise urban metabolism. One exception is Dobbelsteen (2008) who suggest Exergy potential maps to improve the efficiency of energy use.

Given these shortcoming of present methods, this study proposes an approach where different MFA patterns are identified, characterised and classified at the smallest scale; resulting in maps that show the diversity of urban metabolic functions.

2.2 Data

The 'bottom up' approach proposed here requires data on a smaller scale than whole city metabolism studies. This makes this study somewhat more challenging than aggregated studies, which do suffer from a lack of available data. However, it is suggested that data availability has improved dramatically in recent years (Kennedy *et al.*, 2010).

Data are gathered for individual urban elements and land use types (e.g. detached housing, high rise buildings, parks, offices, mixed use houses, commercial, urban agriculture) to determine their metabolism. As this may not be feasible or too time consuming, MFA data can be estimated for groups or classes of urban elements that share common metabolic characteristics, so called patches. Such resources input-output data is available in national statistics or from municipalities. However, data collected on site through interviews and site visits will be crucial, too. For instance, data for industry will be gathered through expert interviews or estimated based on best available practice guidelines of the sector. Another key data source are land cover information, aerial photographs in combination with site visits, since they will reveal detailed information about metabolic functions. All data are collected along with spatial references to enable analysis in ArcGIS.

2.3 Analysis

Collated data is analysed in ArcGIS. This software enables effective management of large amounts of spatial data by representing multiple variables as individual data layers (Figure 5). It also facilitates query for relationships within and across these layers. In this research four initial data layers are required urban fabric, inputs, outputs and time pattern for each of the flows to be analysed (Figure 5). The urban fabric layer is a structural description of the urbanisation in terms of the urban elements: buildings, green space, roads etc. Different metabolic patches (discreet area of relatively homogeneous conversion of flows into similar types and quantities of outputs – see section 2.3.4) and urban elements are presented as vector data. As compared to raster data vectors have the advantage that elements or metabolism are not calculated per cell, but in the actual shape of the urban element. Thus results are not subject to the resolution of raster grids, which can influence the outcome of the analysis (Batty *et al.*, 2004). The analysis can be sub-divided in five steps:

1. Calculate the mass flow
2. Classification of mass flow results
3. Adding the temporal dimension
4. Analysis of diversity
5. Calculation of inter patch distance

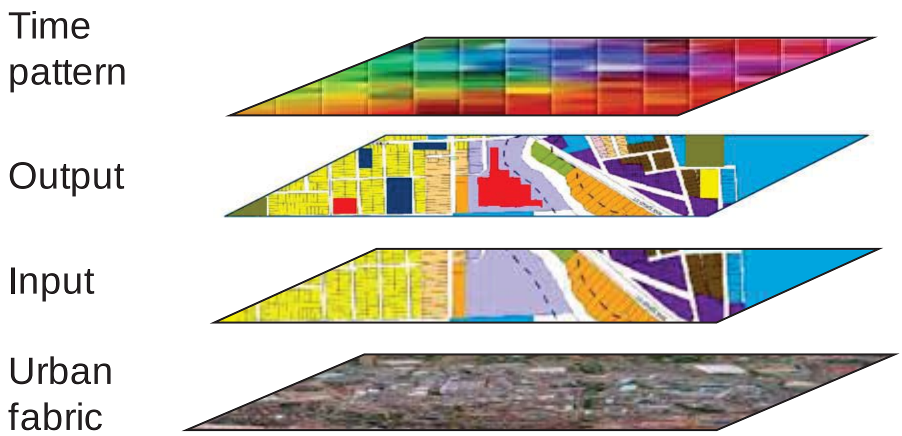

Figure 5: Input data layers used in this study with re-classification of input and output layers (example).

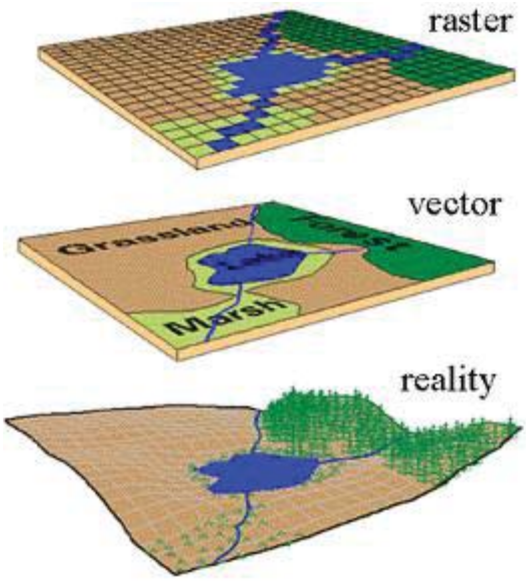

Figure 6: Example of vector data vs. raster data (source: http://2.bp.blogspot.com)

2.3.1 Step 1 – estimate mass flows for unknown flows

A first analytical is to calculate mass balances and to estimate unknown outflows. As mentioned above, it not necessary to collect data on all urban elements separately. In some situations, such as for housing, the mass balance can be estimated. This only requires knowledge of the number of inhabitant and the building type in terms of technical appliances (e.g. water saving devices, insulation, on site treatment). Knowledge of the number inhabitants enables estimation of demand, combined with knowledge of the appliances and technologies in use it can then be estimated how inputs are converted into outputs or how much is stored in the system.

$$\sum outputs\ (incl.\ losses) + storage = \sum inputs * conversion\ factors$$

The conversion factors are statements about the quantities of energy or water that are converted into other forms of energy or water often with a lower "quality". Their value is between 0-1. Sankey diagrams are a graphical representation of this conversion processes (Figure 7). The conversion processes are dynamic over time. Specifically, within a diurnal cycle the intensity of the conversion processes might change. This is for example the case for energy use or water consumption that peaks in the mornings or afternoon and are low during the night when people sleep (section 1.1). Likewise, these conversion processes are dynamic throughout a year due to different season that require different heating, water consumption or come with different precipitation. A last aspect of the dynamic of these conversions is that they are dependent of the technologies used. Technologies can change the intensity of resource consumption as well as the character of the conversion. Specifically, different technologies that mediate human consumption may produce different outputs from the same inputs. Therefore, knowledge about technological performance in terms of how inputs are converted into outputs and products is important. Technological modelling is a useful to better understand this conversion and more research is necessary on this.

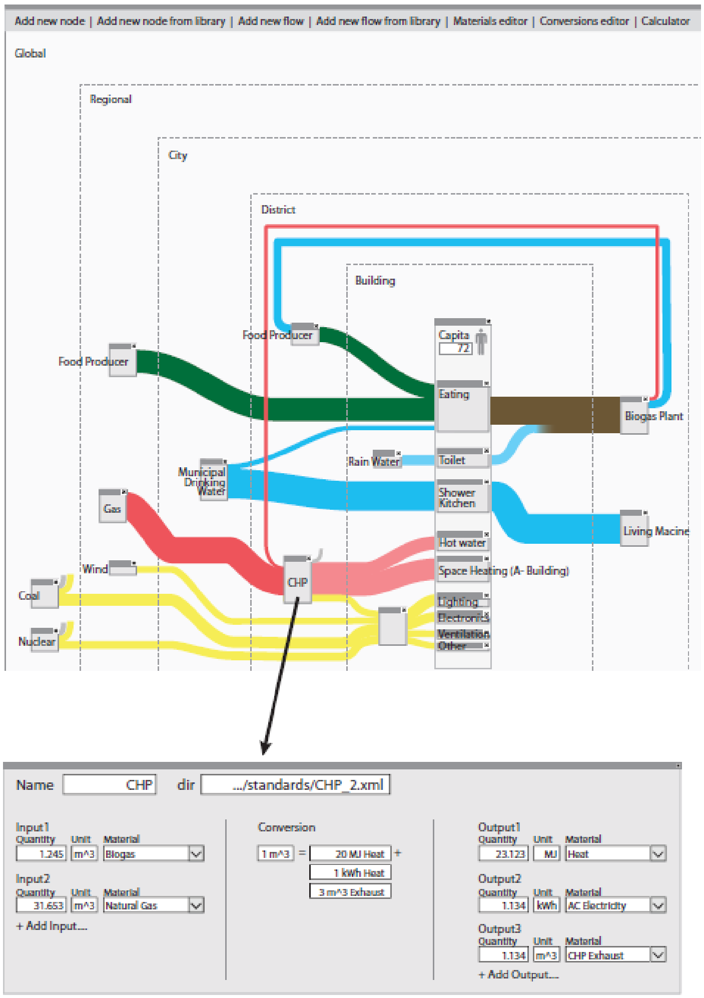

Figure 7: A Sankey diagram of mass and energy flows (source: www.nelsonelson.com).

2.3.2 Step 2 - Classification of mass flow results

Once all inflows and outflows are know they can be classified and the spatial diversity of metabolism can be shown (i.e. the different colours of input and output layers in the Figure 6). In this research only the following flows will be investigated: natural gas, district heating, nitrates, phosphates, water. Classification of outflows should be adapted to the characteristic of individual flows. Water can be classified in grades of quality such as grey water and backwater with different N and P contents. Natural gas and heating maybe best classified in terms of their remaining exergy. The classification will depend on the specific objectives and research question asked. Several approaches to classification exist such as natural Log, equal classes (i.e. each class represents the same amount), percentiles, arbitrary number of classes. Multiple approaches to classification / aggregation should be tested since they can generate different insights (Alberti, 2008). By taking this approach, we hope that this the research will arrive scientifically grounded taxonomies of urban metabolic functions for each flow.

2.3.3 Step 3- Adding the temporal dimension

In a third step the temporal dimension is added to assess the dynamic of different metabolic patterns in time (Figure 5). Temporal consumption patterns describe the diurnal and seasonal cycles of resource use (i.e. metabolism). The day is divided into three eight hour time intervals – 08:00 – 16:00; 16:00 – 00:00; 00:00 – 08:00 (Kajtazi, 2007). This division follows urban time patterns that dominate in the western world, where people spend approximately 8 hours at work, 8 hours for leisure activities and 8 hours asleep. However, this choice is arbitrary and may not follow the real pattern of various flows in the urban system. An analysis of the temporal distribution of flows would therefore be of importance, but is beyond the scope of this study.

All flows are calculated for each of the time intervals. This reveals insights into times of production of outflows and consumption of inflows; which is likely to underline the importance of storage of inflows / outflows. Surpluses of useful outflows in one time interval can then be made available as inflows in following time intervals if necessary. Additionally, knowledge of times of production and demand of flows will also underline the importance of demand management or diversification of demand patterns.

2.3.4 Step 4 – Analysis of diversity

The first item to be identified in the analysis is the metabolic patch, which is defined as a discreet area of relatively homogeneous conversion of flows into similar types and quantities of outputs; in other words an area where two or more buildings or land use functions convert inputs into outputs of a similar compositions and quantity. The concept of patch is adopted from ecology where it serves to identify homogenous environmental conditions relevant to a specific species or ecological phenomena (e.g. forests, agriculture)(Alberti, 2008).

Having identified patches of metabolism it is then possible to identify the metabolic diversity of an area such as an urban tissue, district or a whole city. This can be achieved simply assessing the richness and the evenness of the urban metabolic functions (Kajtazi, 2007). Richness represents the total number of different functional classes within an area. In other words areas with a higher count of different classes of metabolism will have a higher richness. Evenness on the other hand expresses the relative contribution of each class to overall diversity and area will be considered less diverse if it is dominated by one class (Figure 8). These characteristics of richness and evenness result in a situation where each measure has its limitation. Richness ignores the density of functions in an area, while both richness and evenness do not considering the overall availability of diversity of functions that may exist.

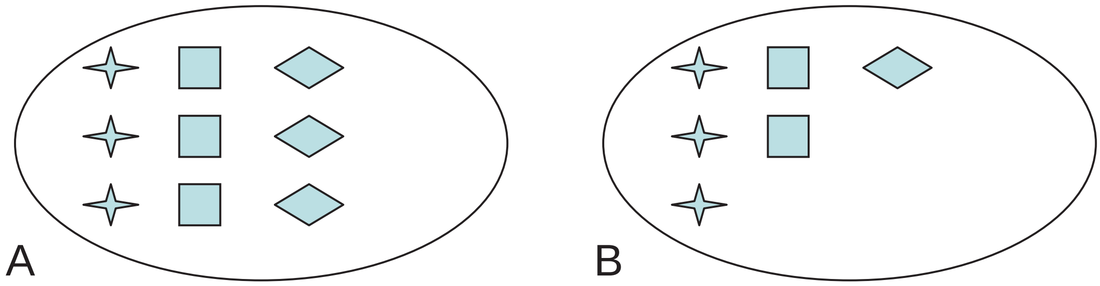

Figure 8: The difference between evenness and richness. Examples A and B have the same richness but the evenness is higher in A (Kajtazi, 2007).

A methods that compensates for this limitations has been used by Batty et al. (2004). This density-diversity index first calculates the metabolism within an area, which is then expressed as a proportion of the maximum number of metabolic functions. They use the following equation, which expresses the amount of urban function as the proportion of its maximum:

$$d(i) = \sum_k (a(i,k) / \max_i a(i,k))$$

In the equation *i* represents the area for which the calculation is carried out, *k* denominates the number of metabolic elements. Therefore *a(i, k)* expresses the number of metabolic elements in a defined area. The value of *d(i)* varies between *0*-*k*. If *d(i)=k* then the number of metabolic diversity has reached its maximum.

2.3.5 Step 5 – Calculation of inter patch distance

In section 1.4 it was argued that links between metabolic functions are crucial to achieve more resilient urban systems. To assist planners in identify linkages it is proposed to calculate the distance between complementary metabolic patches (i.e. patches where the outflow matches the inflow demands) for each flow. This can be done by using the Euclidian distance (ECSRI, 2010). In its basic form, the Euclidean distance calculates the shortest distance (a straight line) between two patches.

It is appreciated that the result of this calculation will be a strong simplification of realty, since actual linkages will depend on infrastructures that are unlikely to be just straight lines. Thus, more realistic results could be obtained by adding layers that contain infrastructural networks. This is however, beyond the scope of this research.

2.4 Summary of methodology

In summary, the methodology proposed here will help to visualise the urban environment in the form of maps that show the diversity urban metabolism. It offers the opportunity to planners to identify resource inputs and outputs in space; thus providing a first step to plan for matching existing outputs (e.g. heat, waste, water of a certain quality) and inputs in a circular urban metabolic system.

3 Limitations of the method and future research

The research approach proposed in this paper should be further developed and specified. Some of the key challenges encountered while developing this method were:

- The methods to show and develop appropriate spatial linkages between metabolic functions need to be improved. As the discussion has shown diversity of metabolic functions can only increase resilience of urban systems if functions can be linked. Presently there is little research carried out on the identification and development of such links between urban metabolic functions.
- The impact of urban forms on metabolic function needs to be studied in more detail. It is likely that urban form can have significant impact on the possibilities for technical change, and thereby also on impact on the urban metabolism. A better understanding of this relationship would greatly assist in modelling efforts such as the one presented in this paper. In the same vein improved technological modelling to better quantify the conversion of inflows into outflows would be of great assistance.
- The methods proposed here needs to be empirically tested, to demonstrate whether it can produce valuable outcomes for urban planners and designers.

4 References

Agudelo, C., Mels, A., and Rovers, R., (2009). Urban Water Tissue: Analysing the Urban Water Harvest Potential. . In: Dobbelsteen, A., Dorst, M. and Timmeren, A, ed. *Smart building in a Changing Climate.* Amsterdam: Techne Press.

Alberti, M. (2008). *Advances in urban ecology: integrating humans and ecological processes in urban ecosystems*: Springer Verlag.

Batty, M., Besussi, E., Maat, K., & Harts, J. (2004). Representing multifunctional cities: density and diversity in space and time. *Built Environment*, 30(4), 324-337.

Costantini, V., Gracceva, F., Markandya, A., & Vicini, G. (2007). Security of energy supply: Comparing scenarios from a European perspective. *Energy Policy*, 35(1), 210-226.

Dobbelsteen, A. v. d. J., Taeke M. de (2008). Exergy potential maps. *Concept The 2nd WSEAS/IASME International Conference on energy planning, energy saving, environmental education*. Corfu, Greece.

ECSRI (2010). Understanding Euclidean distance analysis.

Girardet, H. (1999). *Creating sustainable cities*: Chelsea Green Publishing.

Graaf de, M. A. (2010). Resource recovery from black water. *Environmental Technology*: Wageningen UR.

Gunderson, L., & Holling, C. (2002). *Panarchy: Understanding Transformations In Human And Natural Systems*: Island Press.

Kajtazi, B. (2007). Measuring Multifunctionality of Urban Area.

Kennedy, C., Cuddihy, J., & Engel Yan, J. (2007). The changing metabolism of cities. *Journal of Industrial Ecology*, 11(2), 43-59.
Kennedy, C., Pincetl, S., & Bunje, P. (2010). The study of urban metabolism and its applications to urban planning and design. *Environmental Pollution*.
Makropoulos, C., & Butler, D. (2010). Distributed Water Infrastructure for Sustainable Communities. *Water Resources Management*, 1-22.
Ngo, N., & Pataki, D. (2008). The energy and mass balance of Los Angeles County. *Urban Ecosystems*, 11(2), 121-139.
Odum, H. (1994). *Ecological and general systems: an introduction to systems ecology*: University Press of Colorado CO.
Pulliam, H., & Johnson, B. (2002). Ecology's New Paradigm: What Does it Offer Designer and Planners. *Ecology and design: Frameworks for learning*, 51–84.
Walker, B., Gunderson, L., Kinzig, A., Folke, C., Carpenter, S., & Schultz, L. (2006). A handful of heuristics and some propositions for understanding resilience in social-ecological systems. *Ecology and Society*, 11(1), 13.