Towards a dynamic approach to urban metabolism: tracing the temporal evolution of Brussels' urban metabolism from 1970 to 2010

Aristide Athanassiadis

Philippe Bouillard

Ahmed Z. Khan

Robert H. Crawford

Abstract

Urban metabolism (UM) is a concept and methodological approach for the environmental assessment of an urban system comparing it to a living organism requiring energy and other resource flows to function. Over the last 40 years, this approach has been applied in numerous case studies and is now well received from within academic and environmental realms. However, due to the data-intensive nature of an UM study, this methodology still suffers from some shortcomings. In fact, most studies only present macroscopic results on either energy, water or material flows at a particular point in time. This snapshot of particular flows does not allow the assessment of temporal dynamics of a city and whether it is heading towards a more sustainable state or not.

To understand the temporal dynamics of urban metabolisms, this paper first presents the UM for Brussels Capital Region for the year 2010, including energy, water, and material flows as well as the pollution generated. A temporal evolution of these metabolic flows starting from the seminal study of Duvigneaud (Duvigneaud and Denayer-De Smet 1977) to 2010, will then be presented. Finally, this paper will also provide the evolution of some socio-economic and built environment indicators of Brussels in order to explore their impacts on resource use and atmospheric pollution.

<Heading 1> Keywords

Urban metabolism, temporal evolution, urban characteristics, trends, resource use

<Heading 1> Introduction

In a context of evident and pressing environmental concerns, ranging from natural resource depletion (Prior et al. 2012) to the alteration and the permanent damage of natural ecosystems and the provision of ecosystemic services (Corvalan et al. 2005) the mitigation of natural resource use and their respective environmental impacts is of the highest importance. While covering only 2% of the Earth's land surface (Balk et al. 2005), cities now host more than 50% of the global population and are estimated to account for 71-76 % of CO₂ emissions from energy use and between 67–76 % of global energy use (Seto et al. 2014). In fact, cities can be seen as concentration nodes of resource consumption that mobilize material and energy flows from around the world in order to match its inhabitants and production needs. In this mobilization of matter and energy, resources are extracted, processed, transformed and after their consumption they are also discarded. All these activities have local as well as global economic, social and environmental consequences as very often all of these actions occur outside of the city boundaries (Tukker et al. 2014). The need to mitigate the environmental effects of global natural resource use is even more critical as these have increased significantly during the last century (Krausmann et al. 2009) due to the creation and expansion of urban systems.

Considering that the urban population is likely to continue to increase, especially in developing countries (UN 2014), it can be estimated that cities will continue to be created and expanded to host this additional population and therefore create ever-increasing environmental pressures. In order to assess, forecast and coherently reduce the present and

future global environmental effects of urban resource consumption, it is essential to have a better understanding of how cities or urban systems consume resources over time and what the underlying drivers are (Baynes and Bai 2012). While a comprehensive environmental assessment provides a snapshot of the environmental state of a city, tracing its temporal evolution creates a *movie* about the changes in its environmental performance. In fact, it is only with this *movie* that we can be informed about the ever-changing bivocal relationship between a dynamic urban system composed of socio-economic, political and built environment parts, on the one hand, and its resource use and environmental effect on the other hand.

However, to do so, it is first necessary to assess resource consumption using a comprehensive methodology that can take into account most physical flows entering and exiting the urban area. Currently two assessment approaches are used, namely the production or metabolism-based approach and the consumption or input-output-based approach (Baynes and Wiedmann 2012). The metabolism-based approach takes into account all consumption and emissions directly occurring inside the city territory regardless of whether this consumption is serving local inhabitants' needs or foreign needs through the manufacturing and exporting of goods and services (Minx et al. 2011). This is often based on the collection of local statistics and data from a number of administrations (Barles 2009). The consumption-based approach requires national and multi-regional input output (MRIO) tables as well as national expenditure data (Wiedmann 2009) in order to measure direct and indirect (or embodied) resource use and environmental impacts of local consumption (Lenzen et al. 2004). While this second approach is systematically complete and therefore accounts for resource use and environmental effects at all life stages of the imported products and services, it often uses data at a national scale that do not necessarily reflect

the specific urban situation. In addition, MRIO tables are quite recent and are not available prior to 1990 which makes it difficult to trace a long-term evolution of resource use (Dietzenbacher et al. 2013; Lenzen et al. 2013).

This paper therefore proposes applying a production or urban metabolism-based approach to comprehensively assess the resource use and environmental effects of Brussels Capital Region (BCR) over 40 years. The relevance of this study is fourfold. Firstly, to update the findings of the seminal study of Duvigneaud on Brussels' ecosystem (Duvigneaud and Denayer-De Smet 1977) which are still used in some cases for comparing with other case studies due to the lack of more recent data (Kennedy et al. 2008). This paper will also provide more detail about the study itself and the limitations of some of the data. The second point, for which this paper is relevant for the urban metabolism field is the temporal evolution of a comprehensive urban environmental assessment. In fact temporal studies are still limited in the UM field (Krausmann 2013; Kim and Barles 2012; Barles 2007; Baynes and Bai 2012; Billen et al. 2012; Sörme et al. 2001; Tello and Ostos 2012; Newcombe 1976). However, temporal studies comparing more than a single flow are even less present in the literature (Warren-Rhodes and Koenig 2001; Conke and Ferreira 2015). To achieve a comprehensive temporal evolution of Brussels' UM this paper traces the evolution of energy, materials, water, waste and air pollution flows. The third reason, why this paper is pertinent is that by providing data for the urban metabolism of BCR and for some selected urban characteristics for 7 years, it is possible to determinate whether or not the evolution of some urban characteristics effect resource use and pollution and vice-versa. The final point of significance for this paper, is that it becomes easier to compare Brussels' metabolism with another city. Indeed, the considerable amount of data provided here, including different metabolic flows and urban characteristics for 7 data points across time,

enables comparisons to be made between urban metabolisms for a specific flow, year, or urban characteristic.

This paper is structured as follows. The next section will briefly present the methodology used together with some basic information about the case study of BCR. Results are then outlined, including first the urban metabolism of BCR for 2010 and then its temporal evolution from 1970 to 2010. The results are followed by a discussion about the findings as well as the limitations of the study. Finally, future pathways for investigation will conclude this paper.

<Heading 1> Method and Case study

This section briefly discusses the methodology used for the collection and analysis of data to establish the urban metabolism of Brussels. In addition, some details about Brussels and the system boundaries selected for this analysis, are provided.

<Heading 2> Methodology

As presented in the introduction, a production or metabolism-based approach was used to assess the resource use and the environmental impact of Brussels. As such, only the resources consumed on the territory and the associated pollution were into account. Perhaps the most frequently used production-based methodology that accounts for material inputs and outputs, including fossil fuels, water and air is the Eurostat, Economy-wide Material Flow Analysis (Eurostat 2001). Based on the conservation of matter principle, this accounting methodology states that for any given system, ranging from a company to regions or nations, the following identity is valid: **total inputs = total outputs + net accumulation.**

This methodology distinguishes input flows coming from domestic extraction (used and unused materials) and from imports (as well as their associated material flows). Similarly, this methodology distinguishes output flows into emissions (air pollution, solid waste and waste water)

coming from local consumption and exports (as well as their associated material flows). However, it can be argued here that while Economy-Wide MFA (EW-MFA) is the most coherent and comparative methodology, it is not very appropriate for urban areas.

In fact EW-MFA, generally only provides aggregated results in mass units directly comparing energy, water and material use figures. In this study it is argued that this aggregation over the same unit is not appropriate for an urban area as it does not effectively illustrate the diversity of the challenges that its inhabitants face. In this study, the metabolic results of water, energy, matter and air pollution will therefore be presented in the most common units for each flow, namely m³, kWh or J and tonnes. In addition, most of urban areas have no or little extractive and manufacturing activities. Therefore, urban consumption is often limited to imports and there are almost no unused flows associated with exports.

Figure 1 summarises the accounting methodology used for this study derived from the EW-MFA framework with some adjustments for the case of BCR. Indeed, this is a territorial-based approach where only local consumption and their emissions will be considered. From a simplistic point of view, this approach is like placing meters at the periphery of the city boundaries and taking into account all flows that enter and exit this system. In practice, some exceptions were made to this rule and were detailed below. Finally, the evolution of the net accumulation or net addition to stocks (NAS) for materials were not considered in this paper, due to the lack of data.

Figure 1: Overview of the flows taken into account in the Urban Metabolism of Brussels

The energy flows were accounted for in kWh and divided in to different energy sources (natural gas, electricity and petroleum products) and sectors of consumption (industry, tertiary, residential and transport). A distinction was made between locally produced and imported energy for the year 2010. The greenhouse gas emissions (GHG) associated with this energy use were expressed in kt-CO₂eq. Some other atmospheric pollution indicators found in the DuVigneaud study were also added in order to allow a temporal evolution. For the input flows of water, only consumption of water was taken into account, disregarding all natural water flows entering the territory such as streams, a chanel or precipitations. Input water flows, were also divided by sector use (industry, tertiary and residential) and again a distinction between local extraction and imports will be made. Similarly, output flows of water only included water figures from the waste water treatment plants, excluding all natural water flows exiting the territory. Material imports and exports are perhaps the flows that are the most difficult to estimate, as no data for these is available for Brussels. The only available data that provides information about the material use of Brussels, are imports and exports by different modes of transportation. However, it is unknown whether all the material flows that are entering Brussels boundaries are consumed locally, are used for manufacturing or if they are only transiting though the territory becoming outflow materials. In addition, it is important to note that Brussels does not have any extractive activities. Finally, while only municipal waste data was

available for a temporal evolution, a full description of the solid waste flow were only expressed for the UM of 2010. By subtracting this full account of solid waste as well as the materials exports from the material imports, it could in fact be possible to measure the material net addition to stock of Brussels for the year 2010.

Unfortunately yearly data for each of these flows were not available, therefore in order to deal with this it was decided to use data for 7 different years between 1970 and 2010. Table 1 indicates the years considered as well as the source of each data point.

<Heading 2> Case study

This section, describes the Brussels case study as well as the selection of the system boundary. Boundary selection is critical as it will determine the extent of flows within a city as well as the extent of environmental effects (Barles 2009). For instance, an UM at smaller scales could stress relationships between socio-economic factors and resource use, whereas a metabolic balance at larger scales could inform us about more structural changes in the urban structure such as suburbanisation and land use transformation but also in the consumption patterns and the impact on the concerned hinterland (Bai 2007). However, in practice UM balances are performed at spatial and administrative scales where enough data are available.

In the case of Brussels, it is important to mention that what is generally referred to as the city of Brussels, is also one of the administrative regions of Belgium that have their own government and parliament giving them autonomy in a number of competencies. Indeed, Belgium is divided into three regions, Flemish Region in the North, Walloon Region in the South and BCR which is enclosed within Flanders (see Figure 2).

The metabolic analysis of this case study is focused on BCR. The specificity of Brussels being a city-region offers a considerable advantage for data availability. However, it is important to underline that the boundaries of Brussels used here do not coincide with the metropolitan area of Brussels. In fact, in 2010 BCR covered only 161.4 km² with 1,090,000 inhabitants, whereas the metropolitan area

covered around 4,300 km² with 3,250,000 inhabitants (Bruxelles Mobilité 2012). In addition, it should be noted that a great majority of the middle and upper-middle class left Brussels in the seventies in order to become owners of detached or semi-detached houses in the suburbia of Brussels (this is represented in Table 1). This triggered a significant increase in daily commuting to Brussels to work and represents almost half of the workforce of BCR (Bruxelles Mobilité 2012). This last aspect distorts the urban metabolism of Brussels as the total amount of energy, water and materials consumed in Brussels is not consumed only by its inhabitants. In addition, by not taking into account the larger metropolitan area, a large quantity of resource consumption related to residential and mobility activities of Brussels is not included, making it difficult to realistically assess Brussels' (un)sustainability.

Figure 2: Brussels Capital Region and its metropolitan area in 2010. Data from (IBSA 2014e; IBSA 2014c; Bruxelles Mobilité 2012)

<Heading 2> Data Collection

Data on energy, water and materials consumption as well as waste and pollution generation were collected through a number of official reports originating mostly from regional and national environmental, economic and mobility administrations. Some more precise data on energy and water use were also collected through grid operators reports. Socio-economic factors were collected mainly through Brussels' regional statistical office (Institut Bruxellois de Statistique et d'Analyse) and Belgium's national statistical office (Direction Générale Statistique et Information Economique).

Finally, territorial organisation information was collected through the urbanism administration of Brussels and the cadastral plan managed by the Belgian Ministry of Economy.

For the temporal evolution shown in Table 1, the seminal study of Duvigneaud was used as a benchmark (Duvigneaud and Denayer-De Smet 1977). The system boundaries used for their study were also BCR, therefore the results of the evolution are comparable. However, a specific year of the results could not be determined in the core text of the study. Results are most likely to depict the situation of the early 1970s. However, the population figures and water supply figure indicated in Figure 3, could correspond to Brussels' situation in a number of different years. In addition, it is important to mention here that except these two figures, most of the rest are rough estimates based on some selected indicators. For instance, the energy use of Brussels was estimated as 13% of the total energy imported into Belgium, as it corresponded to, amongst others, electricity use and the proportion of the vehicle fleet. The atmospheric pollution figures were directly calculated by assuming a total combustion of imported fossil fuels and their respective pollutant content. However, when trying to compare the results of energy use of this study with other sources of data, most of the figures seem overestimated, including electricity use which was used to calibrate the rest of the energy use (Perez Mibelli 1978). In addition, in contrast with the Duvigneaud and Denayer-De Smet study, the present study did not include figures from natural phenomena such as precipitations, evapotranspiration, solar radiation or biomass primary productivity. Therefore, the current study did not study Brussels as an "urban ecosystem" as such. Instead, this study is a coherent collection of environmental and urban data that enables the establishment of the evolution of BCR's resource use and environmental performance or most commonly its urban metabolism. While the seminal study of Duvigneaud and Denayer-De Smet remains of great importance for benchmarking purposes, the data found in this study should be used with great caution.

Figure 3: The urban ecosystem of Brussels in the early 1970s (Duvigneaud and Denayer-De Smet 1977)

For the time-series evolution of the urban metabolism of Brussels, a 40 year timespan was chosen. While some data are available for all 40 years, most of the data are fully available after 1990 when the environmental administration of Brussels started to produce frequent reports on the environmental state of Brussels. This also coincides with the proclamation of Brussels as a separate federal region in 1989. For illustrating the temporal evolution of the UM, seven snapshots in time were chosen, one every 10 years starting from 1970 and thanks to better data availability after 1990 two additional points, one in 1995 and one in 2005. Before 1970, no “metabolic” data of Brussels were found, except for the consumption of water. The sources and the year of each figure can be found in the far right column of Table 1.

<Heading 1> Results

This section presents the results of the UM analysis of Brussels in 2010 as well as the temporal evolution of this metabolism starting from the Duvigneaud study in the 1970s to 2010. This section also presents the effect of some urban characteristics on resource use and environmental performance.

<Heading 2> The Urban Metabolism of Brussels Capital Region in 2010

The results of Brussels' UM in 2010 based on the territorial approach presented in the previous section are summarised in Figure 4 and their respective data sources provided in Table 1. To facilitate the comparison of these figures with other cities, all figures are expressed both in absolute values and per inhabitant. The indicator per inhabitant is preferred to per capita, as due to the high amount of work commuters, it is difficult to estimate the number of people consuming a specific resource. This means that the indicator per inhabitant includes resource use and environmental impacts from sectors other than households and therefore overestimates the consumption of Brussels inhabitants.

Figure 4: The Urban Metabolism of Brussels Capital Region in 2010

Figure 4 shows that, in 2010, BCR consumed 24,306 GWh or 21 MWh/inh of energy out of which 42% is natural gas (10,243 GWh), 24% is electricity (5,798 GWh), 33% is petroleum products (8,049 GWh) and 1% is others which is not included in the incoming flow. The final energy use by sector was divided as such: residential 42% (10,127 GWh), tertiary 33% (8,087 GWh), transport 22% (5,263 GWh), industry 3% (618 GWh), and 1% by others (211 GWh). Almost all of the energy used is imported with only about 5% locally produced, mainly by waste incineration (IBGE 2013).

In 2010, BCR used approximately 58 million m³ (or Mm³) of water. Again, the great majority was consumed by households (67%), followed by tertiary activities (29%), industry (1%) and an

insignificant amount by the agricultural sector. Information about water supply were also provided in Table 1. The difference between the supply and the consumption is approximately 10 Mm³, part of which is generally used by municipality and firefighting services and the other is losses due to network leakage (approximately 3.5 Mm³) (HYDROBRU 2010). Similarly to energy, 97% of the water supply is imported and comes from the Walloon Region and only 3% is locally extracted in Brussels.

The amount of waste water is here defined as the total amount treated by the two water treatment plants situated in the territory of Brussels region. Once treated this waste water is then returned to the stream crossing Brussels, the Senne. The amount of waste water treated is approximately double the water supply. This is due to the fact that the water treatment plants treat not only the supplied water but also two other flows. The first flow is estimated at about 32 Mm³ and is supplied water that is consumed in Flanders but is treated by the local water treatment plants (IBGE 2011). The second flow taken into account comes from precipitations. In fact, Brussels has a unitary sewage network mixing waste water and precipitation waters which contribute to an additional 40 Mm³ of treated water. This figures are only available for 2010 as the first water treatment plant was constructed in 2000 and the second in 2007.

The assessment of material flows was the most difficult task as data are less precise and available than for energy and water. Furthermore, it is important to note that the 2010 data of road transport only includes the imported and exported materials by Belgian trucks with a load capacity greater than 1 tonne. Also there is no knowledge if the imported materials are locally consumed, if they are used for some manufacturing activities (very limited in Brussels), or just transit through the BCR territory waiting to be exported again. In any case, approximately 8,000 kt (7 t/inh) of materials were imported in 2010 and 4,500 kt (4 t/inh) were exported. Road and water transport represent around 45% each for the imported quantities of materials and road transport represents almost 85% of the exported materials. However, there was insufficient data to split the input and output material quantities per type of goods in an accurate manner.

Another material flow coming out of Brussels, in 2010, is solid waste and it was estimated to account for slightly over 2,150 kt or 2 t/inh. For 2010, the waste flow was subdivided into four main categories, namely: municipal waste (457 kt), industrial activities (500 kt), construction and demolition waste (600 kt) and other types of waste (596 kt) including office waste (100 kt), incineration residues (137 kt), dredgings (123 kt), commercial waste (80 kt), transport waste (40 kt), health activities waste (40 kt), restaurant and hotels waste (35 kt), educational activities waste (35 kt), and cleaning wastes (6 kt) (Bruxelles-Propreté 2010; IBGE 2011). While the municipal waste figure is for 2010, the rest of the data were only available for 2005.

Finally, the last flow included in this UM of Brussels is the atmospheric pollution flow. Figure 4 presents the total amount of GHG emissions of 4,250 kt of CO₂-equivalents, out of which 4,055 kt were CO₂ (IBGE 2014). While in this figure only GHG and CO₂ emissions were represented, Table 1 gives some additional information about other atmospheric pollutants emitted in BCR.

As mentioned previously, this metabolic analysis of BCR is only a snapshot of its environmental flows during 2010. While this result could be interesting for comparisons with other spatial scales or cities during the same year, in itself it does not enable an analysis of whether or not Brussels is heading towards a more sustainable state. This UM analysis is mainly carried out as a point of reference for the temporal evolution. As such, while Figure 4 presents an updated version of Duvigneaud and Denayer-De Smet's study, it is not meant to be as comprehensive as possible. In fact, only results were presented here, leaving aside some characteristics of the building stock, the vehicle fleet, the energy and water grid, the amount of renewable and non fossil-fuel energy produced on-site, and the origin and destination of material flows, etc..

<Heading 2> A temporal evolution of the Urban Metabolism of Brussels

This section presents the results of a 40 year evolution of the UM of BCR. This temporal analysis aims to question how the major metabolic flows have evolved during the last 40 years and if some trends in resource consumption and atmospheric pollution are evident.

The results of the 40 year evolution of the UM of Brussels are presented in Table 1, which includes: general information about the region of Brussels, energy use (per source and per activity), water use (per activity, including wastewater production), material use (imported and exported materials and waste generation) and atmospheric pollution emissions. Data from the Duvigneaud study were also added for comparison whenever they were available. In addition, while important to provide exact data for each of the seven snapshots of the urban metabolism for future comparison with other case studies, a number of sparklines have been included to also allow a better picture of data trends.

Before presenting the evolution of metabolic flows, it is important to describe some of the changes within the region of Brussels over the past 40 years that may have an effect on its resource consumption and generation of pollution. In fact, it is interesting to notice that from 1970 to 2000 population decreased by 116,000 inhabitants and increased again from 2000 to 2014 by 204,000 inhabitants – a trend that is predicted to continue in the coming years (IBSA 2014c). However, most of the other indicators have only been increasing throughout the last 40 years, such as the number of buildings; income and expenditure of households which have both more than doubled; and office floor area that has increased 4-fold.

In terms of energy use, electricity and natural gas data were available for all time periods studied. For the rest of energy sources as well as the division per sector use data were only available after 1990. This implies that this study only presented the evolution of the total amount of energy use from 1990. In the case of electricity and natural gas use, it is clear that they have greatly increased over the last 40 years. However, while the increase of electricity use is mainly due to the increase of tertiary activities, the increase of natural gas use is due to an increase in demand for domestic (and tertiary) heating as well as the shifting of domestic heating from petroleum products to natural gas. In fact, due to the relatively little amount of industrial activities in Brussels almost no natural gas is used for production purposes. The shift from petroleum products to natural gas for

heating could also explain a slow decrease in petroleum product use. In addition, it is important to highlight that the energy use figures proposed in Duvigneaud's study are overestimated as Brussels lacks the extent of industry found in other parts in Belgium.

Data about input water flows are available starting from 1970 for supply, 1980 for consumption and from 1995 for consumption per activity sector. Table 1 shows that water supply has been steadily increasing for the last 40 years. However, since the 1990s water consumption seems to be stabilising at 58 to 60 million m³. The fluctuation of non-registered consumed water is due to network losses, firefighting services, as well as the road cleaning services of each municipality (HYDROBRU 2010). The evolution of water use per activity sector shows us that over the last 15 years, residential consumption has been slightly decreasing (7%), tertiary consumption has increased by 27% and industrial consumption has decreased by almost half.

Due to the novelty of the water treatment plants (installed in 2000 and 2007, respectively), only one data point exists for water treatment. In order to maintain a level of accuracy in the data there has been no estimation made for previous years. However it is interesting to note that the value for 2011 is very similar to the approximation of Duvigneaud's study which had estimated that 95% of imported water was rejected in the sewage system and almost 60% of the precipitations were also joining the sewage system from run-off and drainage.

Material flows imported and exported from Brussels show a decreasing trend from 1990 to 2010. Within these figures, water transport is still increasing both for imports and exports, rail transport is barely represented and materials imported and exported by road transport have almost halved in the last 20 years. However, it is important to highlight again, that these data do not reflect the exact picture of the evolution of material consumption in Brussels, as they only include a portion of the materials transported by road and there is a level of uncertainty about how these quantities are measured and what they include. Therefore, it is possible that decreasing exportations could be

due to decreasing manufacturing and industrial activity and that decreasing importations could be due to a reduction in the use of construction materials.

Concerning the waste generation evolution, only municipal waste data were available for all the years examined. Table 1 informs us that the generation of municipal waste increased about 100 kt from 1975 to 2000 and then slowly decreased by 36 kt until 2010. This data correspond to the collection of waste by the regional agency and therefore this slow reduction could have been achieved through a better regulation of waste sorting before collection.

Finally, when it comes to atmospheric pollution, only the pollutants present in the Duvigneaud and Denayer-De Smet's study were presented to enable a better comparison. These figures show a clear decrease over the last 40 years of most of the pollutant emissions. This may be due to a decrease in industrial activity and a reduction in atmospheric pollution due to technological advancements and environmental regulations. For instance, the decrease of Pb emissions are mostly due to the implementation of the catalytic converter in the vehicle fleet of Brussels. However, CO₂ emissions which are very closely linked with energy use have remained relatively stable over the last 20 years. Finally, once again the data used in Duvigneaud and Denayer-De Smet's study seem to have overestimated the atmospheric pollution figures of Brussels ecosystem in the early 1970s as they were based on full combustion of natural gas and petroleum products.

Table 1: A 40 year evolution of the urban metabolism of Brussels

	Unit	Duvigneaud 70s	1970	1980	1990	1995	2000	2005	2010	Sparkline	Sources
URBAN CHARACTERISTICS											
Precipitation	[mm]	-	727	916	760	763	852	751	914		(IRM 2014) for 70, 80, 90, 95, 00, 05, 10
Degree days 15/15		-	2,103	2,192	1,736	1,934	1,726	1,840	2,320		idem
Inhabitants	'000	1,075	1,075	1,008	964	952	959	1,007	1,089		(INS 1970) for 70, (IBSA 2014c) for 80, 90, 95, 00, 05, 10
Vehicles	'000	-	333	418	482	504	586	585	629		(AB 1976) for 71, (AB 1986) for 81, (IBSA 2014f) for 90, 95, 00, 05, 10
Number of houses	'000	-	448	454	491	498	510	527	546		(AB 1976) for 70, (AB 1986) for 80 (IBSA 2013) for 90, 95, 00, 05 and (IBSA 2014a) for 10
Number of buildings	'000	-	182	194	196	197	192	193	194		idem
Income per inhabitant	[€/inh]	-	-	-	8,468	8,848	9,934	11,482	12,593		(IBSA 2014b) for 93, 95, 00, 05, 10
Income per household	[€/hh]	-	-	14,972	18,830	28,841	32,672	36,208	37,539		(DGSIE 2014b) for 78/79, 87/88, 95, 00, 05, 10
Expenditure per household	[€/hh]	-	-	12,493	18,056	23,500	27,916	28,132	31,751		idem
Built-up area	[km ²]	-	-	64.00	67.60	69.80	71.40	72.80	73.90		(DGSIE 2014a) for 82, 90, 95, 00, 05 and 10
Office floor area	[10 ⁶ m ²]	-	3.00	5.00	7.00	-	11.80	12.60	12.98		(IBGE 2013) for 70, 80, 90, 00, 05, 10
Residential floor area	[10 ⁶ m ²]	-	48.00	-	-	-	-	-	55.35		(AB 1976) for 68, (Service Public Fédéral des Finances 2014) for 12
ENERGY											
Per Source											
Electricity	[GWh]	4,652	2,229	3,156	4,091	4,643	5,350	5,765	5,798		(FPE 1972, 1979, 1990, 2000) for 72, 79, 90, 95, 00 and (IBGE 2013) for 05, 10
Natural gas (LHV)	[GWh]	10,467	3,400	5,855	7,670	8,986	9,077	9,567	10,243		(Perez Mibelli 1978) for 1972, (FIGAZ 1980) for 1980, (IBGE 2013) for 90, 95, 00, 05, 10
Petroleum products (LHV)	[GWh]	16,282	-	-	9,250	9,836	9,796	9,468	8,049		(IBGE 2013) for 90, 95, 00, 05, 10
Coal, wood, heat/steam	[GWh]	3,489	-	-	295	344	125	134	217		idem
Per Sector											
Industry	[GWh]	-	-	-	955	933	1,025	872	618		idem
Tertiary	[GWh]	-	-	-	6,424	7,190	7,253	7,807	8,087		idem
Residential	[GWh]	-	-	-	8,554	10,069	9,893	10,272	10,127		idem
Transportation	[GWh]	-	-	-	5,336	5,617	6,046	5,766	5,263		idem
Total consumption	[GWh]	34,890	-	-	21,269	24,029	24,217	24,934	24,306		idem

WATER											
Water IN											
Residential consumption	[10 ³ m ³]	-	-	-	-	43,002	43,819	39,822	39,926		(VIVAQUA 2014) for 95, 00, 05, 10
Tertiary consumption	[10 ³ m ³]	-	-	-	-	12,291	12,104	17,093	16,801		idem
Industry consumption	[10 ³ m ³]	-	-	-	-	2,404	1,772	1,665	1,362		idem
Total consumption	[10³ m³]	-	-	53,351	58,545	59,165	58,162	60,312	58,019		(IBDE 1989, 1990, 2000) for 80, 90, 95 and 00 (HYDROBRU 2010) for 05, 10
Supply	[10 ³ m ³]	61,000	59,269	62,224	66,541	67,089	67,112	68,331	68,945		(CIBE 1970; 1980; 1990) for 70, 80, 90; (IBDE 2000) for 95, 00, 05; (VIVAQUA 2010) for 10
Water OUT											
Treated water	[10 ³ m ³]	125,000	-	-	-	-	-	-	130,521		(SBGE 2011) for 2011
MATERIALS											
Materials IN											
Water transport IN	[kt]	-	-	-	3,216	3,149	3,207	3,432	3,745		(Port de Bruxelles 2014) for 90, 95, 00, 05, 10
Rail transport IN	[kt]	-	-	-	1,594	974	509	561	443		(IBSA 2014d) for 90, 95, 00, 05, 08
Road transport IN	[kt]	-	-	-	7,359	7,129	6,004	4,477	3,819		(IBSA 2013) for 91, 95, 00, 05 and (STATBEL 2014) for 10
Total transport IN	[kt]	-	-	-	12,169	11,252	9,720	8,470	8,007		Same as Water + Rail + Road
Materials OUT											
Water transport OUT	[kt]	-	-	-	359	360	429	759	636		(Port de Bruxelles 2014) for 90, 95, 00, 05, 10
Rail transport OUT	[kt]	-	-	-	1,015	307	413	294	85		(IBSA 2014d) for 90, 95, 00, 05, 08
Road transport OUT	[kt]	-	-	-	6,185	5,778	5,292	4,284	3,752		(IBSA 2013) for 91, 95, 00, 05 and (STATBEL 2014) for 10
Total transport OUT	[kt]	-	-	-	7,559	6,445	6,134	5,337	4,473		Same as Water + Rail + Road
Waste											
Municipal waste	[kt]	277	384	400	437	450	493	477	457		(IBGE 1990) for 75 and 1980 (Bruxelles-Propreté 1990, 2000, 2010) for 90, 95, 00, 05, 10
ATMOSPHERIC POLLUTION											
CO ₂	[kt]	5,900	-	-	3,874	4,240	4,087	4,142	4,055		(IBGE 2014) for 90, 95, 00, 05, 10
CO	[kt]	200	-	-	61.61	33.45	17.51	12.21	7.61		idem
NMVOC	[kt]	45	-	-	15.60	11.23	7.57	5.98	3.68		idem
Pb	[t]	200	-	-	1.26	-	0.97	0.93	0.88		idem
SO _x	[kt]	30	20.34	14.83	4.43	2.76	1.61	1.41	0.58		(Kummer 1980) for 72 and 77 and (IBGE 2014) for 90, 95, 00, 05 and 10
NO _x	[kt]	20	20.71	22.14	11.10	10.34	7.86	7.62	5.49		idem
Particles (PM _{2,5} + PM ₁₀)	[kt]	2	3.33	2.60	1.90	-	0.91	0.78	0.63		idem

Table 1 (continued): A 40 year evolution of the urban metabolism of Brussels

<Heading 2> An exploration of the effect of some urban characteristics on the Urban Metabolism of Brussels

The findings of the UM analysis of Brussels show that most of the local parameters considered have shown a steadily increased over the last 40 years, except for population. Indeed, the increase of purchasing power, floor area of residential and office space and number of vehicles show that BCR has been through a number of socio-economic and built environment changes. Therefore, the last point that this study explores is how and whether these changes to the urban system have effected the urban metabolism of BCR.

It is interesting to note that the growth in these indicators is not necessarily reflected in the evolution of metabolic flows. In fact, while energy and water use have increased in absolute terms over the last 20 years, they have now stabilised. However, this trend is not the same for all sources or sectors. For instance, the increase of office floor area is reflected in the tertiary consumption of energy and water. In addition, it can be noticed that the growth in office floor area is similar to the growth of electricity use. While this is not obvious in Table 1, it is important to note that climate and especially degree days have a considerable impact on energy use and particularly on natural gas use which is the main energy source for heating in BCR.

Another evolution of an urban characteristic that is noteworthy is the effect of the number of vehicles on metabolic flows. While the former is steadily increasing from the 1970s, energy use of transportation as well as the consumption of petroleum products have been decreasing over the last 20 years. In addition, most of atmospheric pollution related to vehicles, such as Pb, has also been decreasing over the last 40 years.

The most surprising fact though is that most metabolic flows do not seem directly influenced by the population evolution. This implies a number of deductions for the case of BCR. Firstly, as population density evolved in the exact same way as population, this implies that in the last 40 years population density did not directly influence metabolic flows and environmental effects. Secondly, the U shape evolution of population in parallel to the increase of the energy and water flows implies

that the consumption of energy and water per inhabitant peaked when the population was reaching its lowest value. Therefore, this implies that the evolution of absolute energy and water consumption do not coincide with the evolution of consumption per inhabitant and neither of them with the evolution of the population. Finally, considering that the population of BCR is expected to increase and that so far there is no clear correlation between its evolution and most metabolic flows, it seems difficult to forecast the future state of consumption.

It seems almost impossible to single out only one urban characteristics to explain the evolution of a particular resource use or atmospheric pollution flow. Indeed, urban characteristics not only have complex interrelationships between one another but they also have a multi-variate and bilateral influence on resource use and environmental impact. Therefore, in order to better understand the evolution and the drivers of Brussels metabolism it would be necessary not only to add more data on urban characteristics (for instance, more details about the vehicle fleet, the building stock typologies, about the demographic profile of its inhabitants and Brussels' households, etc.) but also to better define resource use and atmospheric pollution flows (provide the sectoral use of all energy sources, material and waste flows, establish the material stock, etc.). Lastly, it is important to keep in mind that these are still macroscopic results and do not express the complexity and heterogeneity of an urban system. A spatially disaggregated urban metabolism and a correlation with urban characteristics at small spatial scales would be necessary to achieve this.

<Heading 1> Discussion and Conclusions

This study provided the results of an analysis of the evolution of Brussels Urban Metabolism over 40 years. This study provides an update to the original study of Brussels' ecosystem by Duvigneaud and Denayer-De Smet (1977) but is also used to determine if Brussels is heading towards a more sustainable state. Finally, an exploratory analysis of how the evolution of some selected urban characteristics have influenced resource use and environmental performance of BCR has been attempted.

To ensure a comprehensive analysis of Brussels metabolism and of its temporal evolution this study aimed to examine simultaneously the flows of energy, water, materials and atmospheric pollution. In addition, to make these flows comparable with other cases studies, essential climatic data and urban characteristics for BCR were also included. Due to the broad range of data used in the study, 7 different snapshots of BCR's Urban Metabolism were included. As a number of data are missing, especially for the years between 1970 and 1990, it is difficult to ascertain if the evolution of a specific flow is similar to the period from 1990 to 2010. Another limitation of this study is that the evolution did not go further back than the 1970s and therefore does not provide an indication of the evolution of resource use and environmental effects during the urban development of Brussels. Therefore, it would be difficult to transpose the findings of this study and especially the evolution and the identification of drivers to a developing city.

However, while these snapshot balances do not offer a time-series evolution of all flows and only show a general trend that could in fact conceal some peculiarities due to single climatic, political or socio-economic events, they offer a more dynamic view of the urban system itself and of its metabolism. In addition, if we consider that UM studies are a good proxy for assessing the sustainable development of an urban system (Conke and Ferreira 2015; Barles 2010), then a temporal evolution of an UM study provides the necessary data to add another dimension in understanding and embracing the complexity of the functioning of urban systems. For instance, the dynamic character of UM allows us to see the constant change, motion and evolution of an urban system. The temporal evolution lens also enables the acknowledgement of metabolic flows as forces that can shape an urban system but also how the evolution of socio-economic, demographic, political, cultural and territorial factors of an urban system can influence its environmental performance.

Therefore, the main conclusion of this study is that it only manages to consider the "tip of the iceberg". In fact, it showed that there is no simple and clear answer to the questions of whether

Brussels is performing more sustainably, what the drivers are for its urban metabolism and what the most suitable policies might be to reduce its resource use and improve its environmental performance. Furthermore, this analysis brings forth a number of limitations that should be acknowledged in any attempt to additionally to comprehensively understand the metabolism of an urban system (Pincetl et al. 2012). Firstly, this study only considers the direct consumption on BCR and does not include the direct consumption of the Brussels metropolitan area nor the resource use and environmental effects embodied in this consumption (Barles 2009; Lenzen and Peters 2010). This implies that a more comprehensive accounting methodology is necessary to take into account all associated impacts of urban consumption (Chester et al. 2012; Goldstein et al. 2013; Baynes and Wiedmann 2012). Secondly, as pointed out earlier, a spatial disaggregation of Brussels' metabolism is also necessary to correlate metabolic flows with socio-economic and territorial organisation indicators (VandeWeghe and Kennedy 2007; Howard et al. 2012; Wiedenhofer et al. 2013; Wilson et al. 2013; Zhang et al. 2014). Finally, in order to better understand the urban metabolism of cities, it is first necessary to better understand the complexity that is inherent in the functioning of cities from a socio-economical, territorial, political, cultural, trade and even identity perspective.

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<Heading 1> About the authors

Aristide Athanassiadis is a joint-PhD student at the Building Architecture and Town Planning of Université Libre de Bruxelles and at the Faculty of Architecture, Building and Planning of the University of Melbourne. Aristide is also a research fellow at the Belgian National Fund for Scientific Research. Philippe Bouillard is a professor at Université Libre de Bruxelles and Vice Dean at Nazarbayev University School of Engineering. Ahmed Z. Khan is an associate professor at Université Libre de Bruxelles and Robert H. Crawford is a senior lecturer at the University of Melbourne.

<Heading 1> Address Correspondence to:

Aristide Athanassiadis

Department BATir - Building, Architecture & Town planning, Université Libre de Bruxelles (ULB)

Avenue F.D. Roosevelt 50, CP 194/2 B-1050 Brussels

<http://batir.ulb.ac.be/index.php/people/249>

Phone: +32 (0)2 650 66 04

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Author/s:

Athanassiadis, A;Bouillard, P;Crawford, RH;Khan, AZ

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