

Chapter 7

Urban Metabolism



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Abstract Urban metabolism (UM) is fundamentally an accounting framework whose goal is to quantify the inflows, outflows, and accumulation of resources (such as materials and energy) in a city. The main goal of this chapter is to offer an introduction to UM. First, a brief history of UM is provided. Three different methods to perform an UM are then introduced: the first method takes a bottom-up approach by collecting/estimating individual flows; the second method takes a top-down approach by using nation-wide input–output data; and the third method takes a hybrid approach. Subsequently, to illustrate the process of applying UM, a practical case study is offered using the city-state of Singapore as an exemplar. Finally, current and future opportunities and challenges of UM are discussed. Overall, by the early twenty-first century, the development and application of UM have been relatively slow, but this might change as more and better data sources become available and as the world strives to become more sustainable and resilient.

7.1 Introduction

Water, electricity, gasoline, natural gas, food, concrete, and asphalt are some of the energy and resources that are imported, consumed, stored, or exported to, in, and from cities every day. Keeping track of these exchanges and processes can be extremely challenging and is at the heart of urban metabolism (UM). The term metabolism

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relates to how a human body converts nutrient intake into energy. The first attempt at quantitative (human) metabolism accounting was probably developed in the early seventeenth century where, in the first documented experiment, Sanctorius (1561–1636) spent over 30 years weighing his dietary intake and bodily excretions on a weighting chair to create a mass-balance sheet. Understanding that not everything that is consumed is directly excreted, he concluded that a significant portion of his consumption was lost through insensible perspiration via his skin (Eknoyan 1999).

Quantifying the metabolism of a city requires a similar methodological approach. The origins of the modern form of UM date back to 1965 when Abel Wolman wrote a ten-page article in *Scientific American* titled “The Metabolism of Cities” (Wolman 1965). As a sanitary engineer, Wolman’s research interests delved into pollution, recognizing that getting an account of the flows of resources inside and outside of a city was key to solving the problem at its root. The concept then grew in popularity in the early 2000s, notably aided by the rise of the global research agenda toward sustainable development and the need to identify major consumers of energy and emitters of greenhouse gases (GHG). Over the years, UM has grown in its understanding into three main schools: Marxist ecology, industrial ecology, and urban ecology (Newell and Cousins 2014). Marx defined UM as the characterization of complex nature–society relationships that produce uneven outcomes; industrial ecology looks at UM as stocks and flows of materials and energy; and urban ecology looks at it as complex socio-ecological systems. More broadly, UM fits within the realm of sociometabolism defined by Haberl et al. (2019) as “a systems approach to study society–nature interactions at different spatiotemporal scales.”

Since its origin, UM has evolved significantly from a methodological point of view, partly due to changes in data format and accessibility. Conceptually, UM remains largely an accounting framework, as illustrated in Fig. 7.1, that includes inputs (I), outputs (O), internal flows (Q), storage (S), and production (P) of water (W), energy (E), material (M), and food (F). With its initial focus on resources and materials, UM has evolved to account for energy (in addition to resources) and for the endogenous processes occurring within cities (e.g., accounting for the production of food in

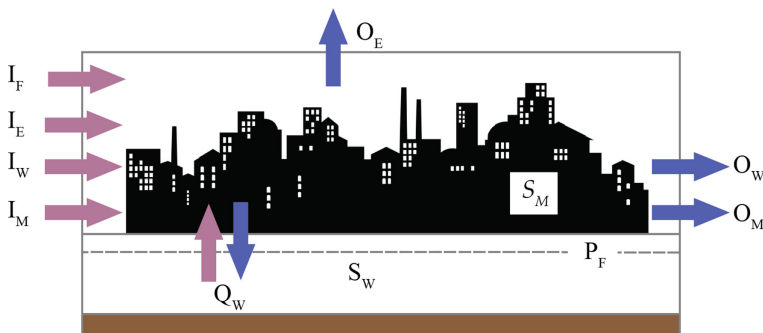


Fig. 7.1 Sketch of UM processes accounting for inputs (I), outputs (O), internal flows (Q), storage (S), and production (P) of water (W), energy (E), material (M), and food (F)

cities and for the internal reuse and recycling of materials), again in line with the global sustainability effort. A commonly adopted definition of UM comes from Kennedy et al. (2007) who defined it as: “the sum total of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste.”

From a methodological viewpoint, following the industrial ecology way of thinking, UM is largely inspired by material flow analysis (MFA), which for example quantifies the flows of a particular material across industrial sectors. An account of energy flows can then be added to the approach, thus giving material and energy flow analysis (MEFA). Broadly, there are two main methods for studying the UM of a city: the bottom-up method is based on directly collecting flow data from a city (e.g., how much water is consumed), while the top-down method is based on economic input–output data (e.g., from the United Nations International Trade Statistics Database, also known as UN COMTRADE). Both techniques are presented in this chapter. In addition, a hybrid approach combining bottom-up and top-down datasets has facilitated the development of several methods discussed in this chapter and categorized as hybrid methods.

Ultimately, the volume of data available is the main limiting factor to what can be included in an UM study. In spite of the fact that we have entered the era of big data, UM involves such a large number of flows that data availability is arguably the main reason why UM has not been applied more systematically to cities across the world. New datasets and new UM methods might help partly tackle this issue, however, as will be discussed. In fact, when it comes to urban informatics, UM holds a central presence and has the potential to directly inform policies and designs to help cities become more sustainable and resilient (Mohareb et al. 2016; Derrible 2019a).

In line with the general theme of this book, the main goal of this chapter is to give a brief introduction to urban metabolism by:

- Offering a brief review of the history of urban metabolism;
- Introducing two methods to calculate the metabolism of a city;
- Applying UM to a practical case study (Singapore); and
- Discussing the future of urban metabolism.

The structure of the book chapter follows these goals sequentially. To learn more about UM, the reader is referred to several important works (that inspired this chapter), including *Sustainable Urban Metabolism* by Ferrão and Fernández (2013), *Understanding Urban Metabolism: A Tool for Urban Planning* by Chrysoulakis et al. (2014), *Urban Engineering for Sustainability* by Derrible (2019b), and the book chapter “A Mathematical Description of Urban Metabolism” by Kennedy (2012). For quicker references and data on cities, the reader is strongly recommended to look at the Metabolism of Cities online platform accessible at <https://metabolismofcities.org/>.

7.2 History of Urban Metabolism

As an accounting framework, UM is used to gain an understanding of the flows between a city and its surrounding environment. As cities grew in size and as pollution levels increased significantly because of the Industrial Revolution—that notably spurred the initial push for suburbanization (Hall 2002)—it was only a matter of time before a technique like UM was developed. A first essay titled “Essay on the Metabolism of Berlin” was written by Theodor Weyl in 1894 and quantified the flows of nutrients in and out of Berlin (Lederer and Kral 2015). We can then see some traces of UM in Patrick Geddes’s book “Cities in Evolution” (Geddes 1915). It was only when more data started to be collected and become available, however, that UM took its more modern form, and the rise of UM from sanitary engineering and in the twentieth century is, therefore, not surprising. Issues related to data availability have always been central to UM. In fact, even in his original article, Wolman could not calculate the UM of an actual city, and instead estimated the UM of a hypothetical American city of one million inhabitants, focusing on three inputs (water, food, and fuel) and three outputs (sewage, solid waste, and air pollutants). Figure 7.2 shows the original figure used by Wolman, which illustrates the large imports of water and exports of sewage from a typical city.

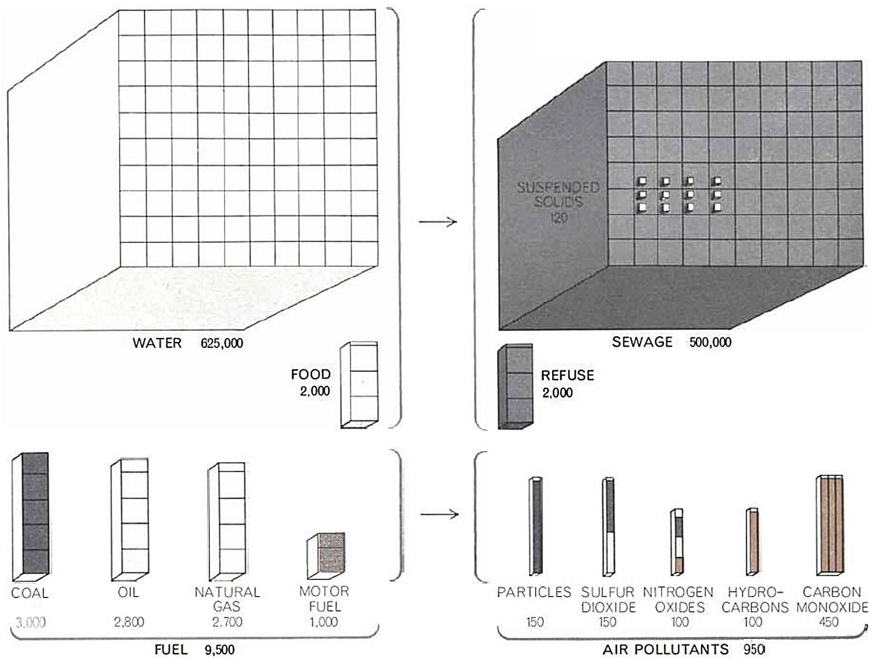


Fig. 7.2 Wolman’s 1965 urban metabolism of a hypothetical American city of one million people, focusing on water, food, and fuel as inputs and on sewage, solid waste, and air pollutants as outputs

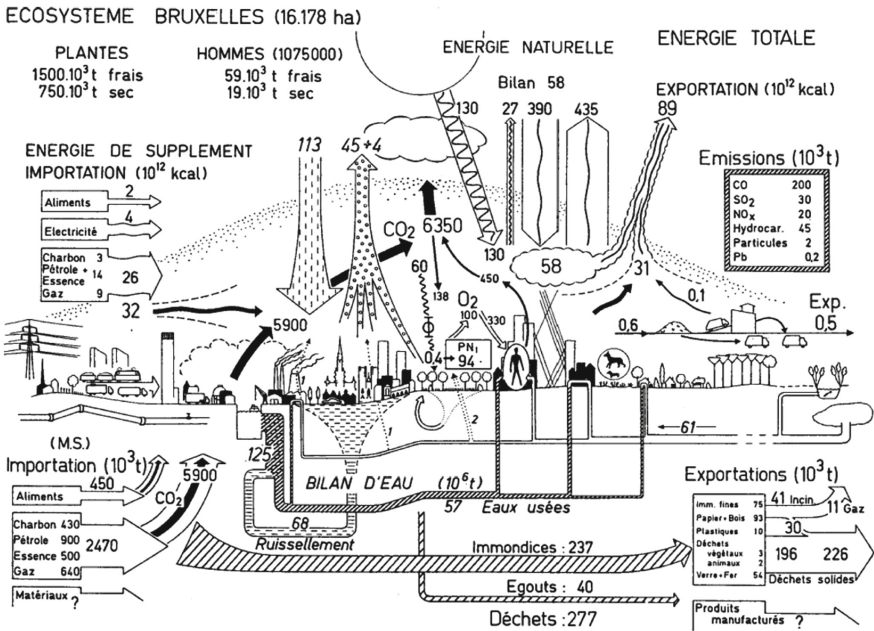


Fig. 7.3 UM of Brussels in the 1970s, Belgium. Adapted from Duvigneaud and Denaeyer-De Smet (1977)

Perhaps the most famous of all early UM studies is the surprisingly exhaustive case study of Brussels in the 1970s by Duvigneaud and Denaeyer-De Smet (1977). The main figure from the study is shown in Fig. 7.3. One year after the Brussels study, in 1978, Newcome et al. (1978) calculated the inflows and outflows of construction materials and finished goods in Hong Kong for 1971, foreseeing the amazing growth in demand for materials and resources for an increasingly wealthy and urban world. In their article, Kennedy et al. (2007) report the UM of nine cities:

- US typical (Wolman’s study) in 1965
- Brussels (Belgium) in the 1970s
- Tokyo in 1970
- Hong Kong (China) in 1971 and 1997
- Sydney (Australia) in 1970 and 1990
- Toronto (Canada) in 1987 and 1999
- Vienna (Austria) in the 1990s
- London (United Kingdom) in 2000
- Cape Town (South Africa) in 2000.

Since the early 2000s, many more UM studies have been carried out, from Paris (Barles 2009) to Ho Chi Minh City (ADB 2014), including one particularly large study by Kennedy et al. (2015) that investigated the UM of 27 megacities. Significant data requirements remain a limiting factor to calculate the UM of more cities. In the

next section, we will review two standard methods to estimate the metabolism of a city.

7.3 Methods of Urban Metabolism

Estimating the flows in Fig. 7.1 can be done in many different ways. In fact, there is no right technique as long the flows can be identified. Broadly, we can categorize techniques in three groups: bottom-up, top-down, and hybrid methods. From the bottom up, flows are investigated individually, for example, by contacting local water, gas, and electricity utility companies. From the top down, economic input–output (IO) data can be collected, often at the country scale, and then disaggregated to the city scale.

The bottom-up approach is generally preferred because it tends to provide more insights about a city; for example, to investigate differences between residential and commercial consumption patterns. The bottom-up approach tends to be arguably more accurate as well since disaggregating data from the national scale to the urban scale can be challenging. Nevertheless, methodologically, the top-down approach may be easier to apply and thus might be preferred in some instances. Other approaches including using emergy, ecological, or environmental network analysis and other methodological advancements have found lesser momentum but can be powerful tools for UM study. The three groups of approaches are introduced in this section.

7.3.1 Bottom-Up Methods

Identifying the flows in Fig. 7.1 from the bottom up can be done by asking the proper authorities for data or by using some means to estimate them. Flows related to the consumption of water, electricity, gas, and other resources can be collected from local utility companies, for example. Flows related to the amount of water received from precipitation can be collected from local weather stations. Nevertheless, collecting these data can be challenging—local utility companies may not want to share data or they may not have access to data in the first place. This section introduces some of the ways these flows can be estimated.

Primarily, we will use the divide and conquer technique by breaking down a problem into multiple parts; the general approach (not related to UM) is well discussed by Mahajan (2014). This approach is greatly influenced by the IPAT equation, initially developed by Ehrlich and Holdren (1971) and defined as

$$I = P \cdot A \cdot T \tag{7.1}$$

where I , P , A , and T stand for impact, population, affluence, and technology, respectively. Essentially, the end goal is to estimate total energy use or emissions (e.g., in watt-hours or Wh) and the problem is divided cleverly to play with units. For example, if we are looking for the total energy use linked with water consumption in liters [L], we can use the IPAT equation by estimating the average water consumption per person and the average energy use per liter of water; in terms of units, we get: $[\text{Wh}] = [\text{pers}] \times [\text{L/pers}] \times [\text{Wh/L}]$. In this section, we will cover four sectors: materials, energy, water, and food. The chapter is greatly inspired by Kennedy (2012) and more details can be found in Derrible's (2019b) book.

7.3.1.1 Materials

Cities are physically composed of countless materials. While it is impossible to quantify the flows of every material imported to or exported from a city, certain materials are worth investigating. In particular, for many cities, the two giants are concrete for buildings and asphalt for roads—in terms of weight, concrete production actually tends to be the most produced material in the world, over oil and gas production (Ashby 2013). In this section, we will see two ways to estimate these two materials, but the methods can easily be extended to account for other materials such as steel and other metals.

For buildings, we can try to divide the problem into estimating the floor space available per person, A , in a city in $[\text{m}^2/\text{pers}]$, and the material intensity M of a building in tons per square meter (i.e., $[\text{t}/\text{m}^2]$). Specifically, for building type i , the stock S of material m (e.g., concrete) can be estimated from

$$S_{i,m} = P \cdot A_{i,m} \cdot M_{i,m} \quad (7.2)$$

The units of the three variables on the right-hand side are $[\text{pers}] \times [\text{m}^2/\text{pers}] \times [\text{t}/\text{m}^2]$, thus giving us an answer in $[\text{t}]$ (i.e., a weight). For roads, we can follow the same procedure or instead try to estimate the proportion of roads space taken by unit area in $[\text{km}/\text{km}^2]$ for A , using the following equation:

$$S_{i,m} = D \cdot A_{i,m} \cdot M_{i,m} \quad (7.3)$$

where $S_{i,m}$ is the stock of road type i for material m in $[\text{t}]$, D is the area of a city in $[\text{km}^2]$, A is the affluence of roads in $[\text{km}/\text{km}^2]$, and M is the material intensity in $[\text{t}/\text{km}]$.

Results in units of weight can then be multiplied by an energy or carbon conversion factor, for example, in $[\text{MWh}/\text{t}]$ and $[\text{t CO}_2/\text{t}]$, respectively. These conversion factors can be found in the literature. For example, the Circular Ecology group offers a fairly extensive and free database accessible at <https://www.circularecology.com/>. In this database, the energy and carbon conversion factors of concrete are 1.53 MWh/t and

0.95 t CO₂/t, and the same factors for asphalt are 696.95 kWh/m² and 99 kg/m²—note the difference of units between concrete and asphalt.

7.3.1.2 Energy

The UM of energy can include a number of sources since virtually every process requires some kind of energy. Here, we divide total energy use into six sources: buildings, transport, industry, construction, water pumping, and waste, such that:

$$I_E = I_{E,\text{buildings}} + I_{E,\text{transport}} + I_{E,\text{industry}} + I_{E,\text{construction}} + I_{E,\text{water pumping}} + I_{E,\text{waste}} \quad (7.4)$$

where I and E stand for impact and energy, respectively. Quantifying these six sources of energy can be challenging, and other sources might exist depending on the scope of the study. Ideally, data can be collected from local utilities. If not, individual sources can be broken down into quantities that are simpler to estimate.

Energy use in buildings can be broken down into energy use for heating, cooling, water heating, and light and appliances—about 50% of the energy used in buildings is consumed for space conditioning (heating and cooling) and about 20% for water heating, although values vary greatly, especially with climate. In the USA, data for these four subcategories are available from the Department of Energy. Other strategies are available in Derrible’s (2019b) book. For transport, we either need to know how much fossil fuel was consumed and convert it into energy/emissions, or we need to estimate the average distance traveled per vehicle type (e.g., car and bus) and multiply it by an energy conversion factor. Local surveys are generally needed to estimate distances traveled per vehicle type, although national surveys can help. In the USA, the National Household Travel Survey offers US-wide travel pattern data, and the Environmental Protection Agency (EPA) offers typical conversion factors for distance traveled to carbon emissions.

For industry and construction, the flows can even be harder to estimate; this is where the top-down approach might offer an alternative. For water pumping, energy uses vary greatly based on several factors, including the topology of a city (i.e., hilly vs. flat terrain). Chini and Stillwell (2018) have gathered and made available a large database for the USA. Other values are available in the literature. We have to be a little bit careful since some values in the literature might take into account the full life cycle of a water distribution system (i.e., including the construction, operation, and disposal of the water treatment plant and water distribution system), while many others will not.

For waste, the quantity of waste generated as a weight must first be estimated (e.g., in [kg/y]). Urban-scale data are rarely available, but many countries offer national per capita estimates that can be sufficient—the World Bank has also compiled a significant database (Kaza et al. 2019). What may be more difficult is to get a breakdown of how much of the waste is recycled versus incinerated versus landfilled. Once

achieved, however, the WASTE Reduction Model (WARM) of the EPA offers carbon-emission intensity values for different disposal strategies. Finally, some studies also include natural energy inputs, such as the amount of energy received from the sun (that was included in Fig. 7.3). Kennedy (2012) offered an equation which can be referred to if needed. Ultimately, energy uses included in an UM study depend on the scope of the study.

7.3.1.3 Water

As Wolman had already illustrated in his study, water is one of the largest resources imported in a city, and water use is often included in UM studies. Moreover, although energy use and carbon emissions linked to water use tend to be relatively small, water is essential to generate electricity (i.e., Energy–Water Nexus) and for agriculture irrigation (i.e., to produce food), and monitoring water flows within an UM framework is typically desirable.

In general, the overall water balance of a city can be captured by seven variables, following the equation:

$$I_{W,precip} + I_{W,pipe} + I_{W,surface} + I_{W,ground} = O_{W,evap} + O_{W,out} + \Delta S_W \quad (7.5)$$

where $I_{W,precip}$ denotes natural inflow from precipitation, $I_{W,pipe}$ denotes pipe inflow, $I_{W,surface}$ denotes net surface-water inflow (e.g., streams), $I_{W,ground}$ denotes net groundwater inflow, $O_{W,evap}$ denotes water loss through evapotranspiration, $O_{W,out}$ denotes pipe outflow, and ΔS_W denotes annual change in water stored within the city—typically close to 0 unless groundwater levels are changing, for example, because of over pumping.

In Eq. (7.5), four variables are hydrological (precipitation, surface-water inflow, groundwater inflow, and evaporation) and should be available from local weather stations in most places. Pipe inflow relates directly to water use. Pipe outflow relates both to water use and stormwater management. Pipe inflow tends to match water use and accounts for both consumption and losses (e.g., through leaks). Estimating water use can be challenging without adequate data, however. Leakage rates can vary greatly from about 6% in some US cities to 50% in places like Rio de Janeiro (Derrible 2019a). For water consumption, Kennedy (2012) proposed a method that accounts for a base demand and a seasonal demand that was reproduced by Derrible (2019b). Ideally, metered data from water-treatment plants can be collected since it accounts for both consumption and leakage.

Pipe outflow can be broken down into three types: sanitary, stormwater, and infiltrated wastewater (from groundwater aquifers that penetrate the sewer system). Sanitary wastewater comes directly from water use, although the two quantities are not equal since some of the water used is lost through leakage, some evaporates, and some simply does not enter the sanitary sewer system (e.g., lawn watering); Kennedy (2012) found that 20–25% of the water consumed in Toronto did not enter

the wastewater system. Here, again, data may be available from local wastewater utilities. Stormwater and wastewater comprise mostly surface runoff that enters the sewer system during heavy precipitation. Local wastewater utilities may have some data here as well, depending on whether the sewer system is combined or separated. Estimates of stormwater flows can also be generated through modeling, for example, by using the Natural Resources Conservation Service curve number model. Infiltrated wastewater flows are harder to estimate and may be negligible.

7.3.1.4 Food

Historically, food, as a specific sector, has rarely been included in UM studies. Nonetheless, UM studies that focus on energy and water often include the amount of energy and water used to prepare and dispose of food. Moreover, it may be more difficult to collect data on food, but we can still think about ways to estimate the UM related to food. First, the term food here includes both solid food and liquid food. Packaged drinks, for example, can be accounted for here. Water use related to food, such as water used in the kitchen, $I_{W,Kit}$, can be included here, but we should be careful not to double-count it if it was already included in the UM section related to water.

Furthermore, food can be both imported into a city, I_F , as well as produced within a city, P_F . In terms of exports, food waste, $O_{F,FW}$, can either be disposed of in landfills or it can be recycled (e.g., through composting). We can also account for the carbon and water lost by transpiration and evaporation, $O_{F,MET}$ (where met stands for metabolism), and for the water disposed of in the sanitary sewer, $O_{F,S}$ (unless it is accounted for in the UM section related to wastewater). Altogether, we get the following equation for the UM of food:

$$I_F + P_F + I_{W,Kit} = O_{F,FW} + O_{F,Met} + O_{F,S} \quad (7.6)$$

All or only some of the variables in Eq. (7.6) may be available depending on the scope of a study. In particular, food imports and exports may be available from freight data sources. It might be more challenging to estimate the other variables. In terms of units, food is generally expressed both as a weight in tons, although it could be expressed as an energy in Wh or Joules with the proper conversion factors. This is all we will cover in this section, but many more methods and techniques can be imagined and applied to study UM from the bottom up. Now, we will switch to a different conceptual approach to UM by estimating flows from the top down.

7.3.2 Top-Down Methods

Bottom-up approaches for UM accounting often tend to be time consuming and data intensive. As an alternative, most countries maintain data for economy-wide import,

export, and production of resources, which can be tapped for an UM assessment. A top-down approach primarily benefits from the availability of relevant data in aggregate form. Often generating economy-wide insights on UM can be a powerful tool to influence sustainability efforts at the national or regional scale. In addition, the top-down approach tends to be easier to carry out and relies on international datasets, which helps in making time-series assessments to track progress over time. This section first provides a historical evolution of top-down economy-wide material flow accounting. It also discusses resources categories, data sources, and the accounting methods that can be chosen based on the scope and boundaries of an UM study.

7.3.2.1 General Approach

The MFA in an economy-wide (ew) exercise signifies the socioeconomic metabolism of a territory. Even though this section provides a methodology for an ew-MFA, often only partial accounts are performed, both in terms of materials and commodities as well as inflows and trade, or outflows in some combinations. As illustrated in Fig. 7.4, ew-MFA aims to assess the overall material inputs into a national economy, material stock changes within the economic system, and the material outputs to the external environment and economies (Krausmann et al. 2018). Such an exercise aims to describe the total scale of socio-economic activities in physical quantities. While initial efforts for ew-MFA were initiated in the 1990s in Austria, Japan, and Germany, credit for leading the global comparative ew-MFA methodology has often been assigned to a seminal study by Matthews et al. (2000). They assessed five countries, namely Austria, Netherlands, Germany, Japan and the USA, for their comprehensively mass-balanced material flows from 1975 to 1996, and they developed material flow indicators.

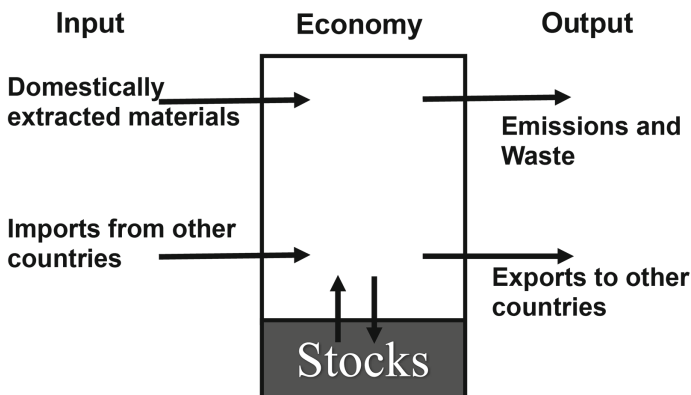


Fig. 7.4 General framework of economy-wide MFA. Adopted and modified from Eurostat (2001) and Krausmann et al. (2018)

In the same fashion, and to harmonize methodological details and indicators, Eurostat published its 2001 report “Economy-wide material flow accounts and derived indicators: A methodological guide” (Eurostat 2001), which has evolved over the years (Eurostat 2018) and which remains widely adopted for ew-MFA. For a step-by-step procedure to perform ew-MFA, the reader can refer to the comprehensive guide developed by Krausmann et al. (2018).

The basic concept of ew-MFA follows the mass-balance principle with a unit of metric tons per year (i.e., [t/y]) where:

$$\begin{aligned} \text{Input} &= \text{Output} + \text{Additions to Stock} - \text{Removals from Stock} \\ &= \text{Output} + \text{Net Stock Changes} \end{aligned} \tag{7.7}$$

Covering over 70 material groups, a typical MFA approach aggregates four material categories, namely biomass, metal ores, non-metallic minerals, and fossil energy carriers. In terms of biophysical bases for society, these four major material categories fulfill all the material and energy requirements for socio-economic metabolism such as food, feed, energy, housing, and infrastructure, including all man-made artifacts. Water and air are typically not accounted along with these four major groups of materials, excluding the mass balancing items such as moisture.

Table 7.1 defines the main MFA parameters for input and output into the economy, as well as for societal stocks. Most commonly, ew-MFA considers direct flows, which are defined as flows crossing the system (national) boundary. Major direct material flow categories include domestic extraction (DE) and imports on the input side, with

Table 7.1 MFA parameters and definition

Parameter	Definition
Domestic extraction (DE)	Used extraction of materials including solid, liquid, and gaseous raw materials from the natural environment (excluding water and air)
Imports, exports	All imported or exported commodities as weights (e.g., metric tons). Traded commodities comprise of goods at all stages of processing from basic commodities to highly processed products
Stocks	Physical structures of society: humans, livestock, and manufactured capital
Manufactured capital	All in-use artifacts (buildings, infrastructures, and durable goods)
NAS	Net additions to stock; year to year change of stocks
DPO	Domestic processed output of wastes and emissions including deliberately applied materials (e.g., fertilizers)
DPO*	DPO excluding balancing flows of oxygen and water (i.e., the fraction of DPO contained in DE)
Balancing flows	Oxygen taken up during combustion and respiration and water uptake by humans and livestock
Metabolic rate	Material consumption per capita of population
Material intensity	Material consumption per unit of GDP

exports and domestic processed outputs (DPO) of waste and emissions on the output side. DPO includes all waste and emissions from processing, manufacturing, use, and final disposal of materials. Unused or indirect flows that do not become an input for production or consumption are ignored. Because of the direct flows into and out of an economy, there are net changes in the stocks, which are taken into consideration to assess the physical growth. All accumulated materials in the form of manufactured capital and discarded or demolished artefacts lead to a net addition to stock (NAS) that can be positive or negative based on the overall balance. Negative NAS is rare in growing cities and national economies.

Considering the mass balance nature of ew-MFA, it is important to account for the water and air flows required in the processing and transformation of materials. Such flows are categorized as balancing items on the input and output sides. These may include water vapors for respiration, oxygen required for combustion of fossil fuels, and atmospheric gases captured or transformed into commodities such as fertilizers. These balancing items can be calculated using stoichiometric equations. Based on these material flow categories, a national material balance for a given year can be given by:

$$\begin{aligned} \text{DE} + \text{Imports} + \text{Input Balancing Items} &= \text{Exports} + \text{DPO} \\ &+ \text{Output Balancing Items} + \text{NAS} \quad (7.8) \end{aligned}$$

In socioeconomic metabolism, material flows represent the pressure on the environment from an economy. These pressures can be measured through aggregated material flow indicators, which capture the socioeconomic sustainability of the system being studied. Direct material input (DMI) measures the direct input of all materials with an economic value and used in production and consumption activities. Domestic material consumption (DMC) provides all material inputs into an economy that are destined to be consumed and eventually released into the environment as waste, representing domestic waste potential. Physical trade balance (PTB) represents the balance of imports minus exports. These indicators are mathematically defined by:

$$\text{DMI} = \text{DE} + \text{Imports} \quad (7.9)$$

$$\text{DMC} = \text{DE} + \text{Imports} - \text{Exports} \quad (7.10)$$

$$\text{PTB} = \text{Imports} - \text{Exports} \quad (7.11)$$

For cross-country comparisons, material flow indicators require appropriate measures to account for differences in size. Overall, material efficiency is assessed by relating DMC to GDP. The ratio of DMC to GDP is defined as material intensity while the ratio of GDP to DMC is defined as material productivity. The ratio of material flows to total land area measures the scale of the physical economy to its

natural environment. The DE to DMC ratio measures the dependence of the physical economy on domestic raw material supply. The proportion of import or export with DMI measures the trade intensity for import or export for a physical economy.

7.3.2.2 Data Sources

Several data sources exist to meet the data requirements needed to carry out an ew-MFA; for example, to collect inflow, outflow, or domestic extraction. National statistics and databases serve as the primary and most reliable data sources due to their direct collection mechanisms. Multiple international databases with harmonized values across countries and commodities also exist. In particular, the United Nations International Trade Statistics Database (UN COMTRADE) remains one of the most comprehensive datasets for international trade that provides monetary as well as quantity data for import and export commodities. This dataset can be aligned with the MFA computation tables based on the focus of the UM exercise for biomass, metals, fossils or non-metallic minerals. In addition, the Food and Agriculture Organization (FAO) maintains the FAOSTAT database for all biomass production and trade, which is more detailed and reliable.

Table 7.2 provides major data sources for various material categories. It is important to highlight that both the time scale (1917–2018) and the geographical coverage

Table 7.2 Major data sources for material flows in world economies

Material	Flows	Main source
Biomass (food, paper, wood, timber, and products, etc.)	Production, import, export, consumption	FAOSTAT, UN COMTRADE
Metals (steel, aluminum, copper, etc.)	Production, import, export, consumption	World Steel Association, The Aluminum Association, British Geological Survey, US Geological Survey, UN COMTRADE, UN Industrial Commodity Statistics Yearbook
Non-metallic minerals (sand, gravel, etc.)	Production, import, export	UN COMTRADE, UN Industrial Commodity Statistics Yearbook, United States Geological Survey
Cement	Production, import, export, consumption	CEMBUREAU, UN COMTRADE, UN Industrial Commodity Statistics Yearbook
Asphalt	Production, import, export, consumption	International Energy Agency (IEA)
Fossil materials and petroleum products (coal, crude and refined oil, gas, etc.)	Import, export, consumption	IEA, UN COMTRADE

(from a few countries to worldwide) of these data sources vary significantly. Additional sources of data include scientific studies, reports, and surveys, which can be very useful in certain cases.

For countries with limited datasets, several academic studies over the years have led to a comprehensive understanding of socio-economic metabolism, leading to significant datasets. Ongoing efforts in UM and industrial ecology communities have resulted in data repositories such as the industrial ecology database at the University of Freiburg Germany (<https://www.database.industrialecology.uni-freiburg.de/>), the UNEP MFA database (<https://www.resourcepanel.org/global-material-flows-database>, <https://www.materialflows.net/>), and the Eurostat MFA database (<https://ec.europa.eu/eurostat/web/environment/data/database>).

In case of poor data quality for certain commodities or countries, various datasets can be combined. When combining datasets for UM assessment, proper validation processes should be followed. For instance, data for domestic extraction of primary resources such as mining activities and food and vegetable production should ideally be validated with national statistics. Data for consumption of non-metallic minerals can be validated with consumption data for cement and asphalt. Likewise, gross metal ore production can be estimated from metal production and ore grades data in mining. Such exercises help in ensuring the mass balance of material flow. We now move on to hybrid methods to perform a UM study.

7.3.3 *Hybrid Methods*

Based on the scope and boundary of an MFA study, raw material equivalents (all materials used in the production of a commodity) for traded commodities can be calculated based on life-cycle assessment (LCA), environmentally extended input–output models, or by combining both. This is particularly useful for estimating consumption-based indicators such as the material footprint of an economy. Multiregional input–output (MRIO) models have been most widely used for sectoral resolution of physical flows based on monetary inputs and outputs. Allocating physical amounts of material extraction to products of final consumption can be carried out based on monetary information about the economics and structure of a sector while considering global processing chains and trade; however, challenges also exist (Krausmann et al. 2017a).

To estimate material and substance stocks, several extensions have been developed with varied temporal, sectoral, and spatial resolutions. Methodologically, it includes top-down and bottom-up static or dynamic stock assessment models. The basic concept of stock assessment depends on the service life of built-up stock and stock renewal rates, which are estimated for stock building artifacts such as infrastructure, buildings, road networks, and vehicles (Fishman et al. 2014; Krausmann et al. 2017b). Techniques such as geographical information systems and satellite-based imaging have allowed for various advances in the measurement of stocks and resource flows. In addition, hybrid approaches combine both the bottom-up and top-down approaches for assessing the UM of a city. From an ecological system's point

of view, the use of emergy and ecological network analysis (ENA) has found greater interest.

The use of emergy originated in the 1950s through the pioneering work of the Odum brothers on the energetic basis of ecology on Earth. Hau and Bakshi (2004) suggest that emergy analysis “provides an ecocentric view of ecological and human activities, which can be used for evaluating and improving industrial activities.” This approach is fundamentally based on the principle that the sun is the primary source of energy for all ecological and economic activities on earth. It considers tidal energy and deep earth heat as additional non-solar sources of energy on Earth and converts them into an objective matrix of energy quality that can be added altogether. As a result, all direct or indirect energy required to manufacture or deliver any or all products and services can be characterized in terms of solar energy equivalents. Emergy, hence, is estimated based on energy required to perform a function or service, with solar energy as the only source of energy (Odum 1996). As a scientific unit, emergy is represented in terms of solar embodied joules, abbreviated as [sej]. To account for energy transformations from high to low quality or into heat, the concept of solar transformity has been developed. Solar transformity, as a measure of energy quality or transformations, is defined as the solar emergy required to make one J of a service or product (measured in [sej/J]). Mathematically,

$$M = \tau \cdot B \quad (7.12)$$

where M is emergy, τ is transformity, and B is available energy.

This equation provides a convenient way of estimating the emergy of commodities, resources, and services. Odum pioneered the estimation of transformity for most inputs and, at the time of this writing, research still relies on Odum’s matrix to estimate emergy. Total emergy input to the Earth can be derived from the sum of emergy of solar exposure, tidal energy, and deep Earth heat. To estimate ecological and metabolic pressures, emergy estimations can be carried out from the planetary level to the product or city level. To integrate economic and ecosystems activities, it is possible to estimate emergy of economic inputs based on the total emergy of a country and its gross national economic product, thus allowing for an objective comparison. The thermodynamic rigor behind this approach, the inclusion of ecological contributions in economic activities, and the ease of objective comparison based on a single measurement unit are some of its major advantages. The reader should refer to Odum (1996) for a detailed methodology.

As a different approach, modeling the complexity of nature–societal interactions has been carried out in some studies through ecological network analysis and its variations. This approach develops urban metabolic networks between different actors and assigns possible transformative processes to the flows (Fath et al. 2007). In comparison to linear relationships, network analysis captures more realistic interactions between various stakeholders and flows. However, complexity and assumptions involved in network simulations are primarily data limited. The methodology has evolved to capture the complete dynamics of urban metabolic activities. The scope

and boundary of an urban metabolic network varies according to carbon emissions, pollutants, energy, materials, nutrients, and other substances. Finally, several studies have combined network analysis with emergy and MFA to provide robust comparable results for cities such as Beijing and Vienna (Chen and Chen 2012; Zhang et al. 2009). As a practical case study, we will now turn to the UM of Singapore.

7.4 A Case Study: The Metabolism of Singapore

Singapore has unique characteristics that makes it a good case study for showcasing the methodologies of UM. In 2016, the small and dense city-state in Southeast Asia housed 5.6 million people on a total land area of 720 km² and imported most of its material, food, and energy requirements. Unlike many other cities, the city-state has clear national and urban boundaries that coincide with each other (Abou-Abdo et al. 2011). Thus, all flows in and out of the city are classified as international trade and are well documented at Singapore's highly regulated ports of entry. Moreover, water flows in Singapore are highly managed by the Public Utilities Board (PUB), making for relatively easy accounting. Stormwater and used water are collected in "separate storm and sanitary sewer systems" (Irvine et al. 2014), which channel stormwater and surface runoff to rivers and reservoirs, and used water to water treatment plants (Tortajada et al. 2013). The water distribution network is robust, with "[no] illegal connections, and all water connections are metered" (Tortajada and Buurman 2017).

The study of Singapore's UM from the perspective of material flows began with Schulz (2007), who used physical trade flows and other data sources to conduct an ew-MFA, as described in the previous section. The flows of biomass, construction materials, industrial minerals, fossil fuels, and semi- and final products were analyzed over a 41-year period from 1962 to 2003. The study found that DMC "remained closely coupled to economic activity," rising in tandem with Singapore's massive economic growth since independence. Chertow et al. (2011) continued this work into the years 2000, 2004, and 2008, and have expanded the scope of flows to include emissions, waste, and recycling. The authors found large variations in DMC of between 14 and 55 metric tons per capita, which is mainly explained by variations in the import of construction minerals. Other UM studies in Singapore include an analysis of phosphorus flows (Pearce and Chertow 2017), and stocks and flows of concrete and steel in residential buildings (Arora et al. 2019). Beyond the analysis of material flows, system dynamics have been used to study urban resource flows (Abou-Abdo et al. 2011) and water (Welling 2011), while Tan et al. (2019) use exergy and ecological network analysis to study Singapore's resource effectiveness.

As an illustration of UM methods, this section adopts the simpler top-down approach to estimate the UM of Singapore in 2016, owing to the fact that as a city-state, national data do not need to be disaggregated to the urban scale. A wide range of data sources was used, such as international trade statistics from UN COMTRADE, data from the Food and Agriculture Organization (FAO), the International Energy Agency (IEA), and Singapore's Department of Statistics. The physical flows reported

by these data sources are combined and adjusted to achieve mass balance. From these balanced flows, the key metabolism indicators, such as DMI and DMC (Eurostat 2001), are calculated and compared with the same indicators during Singapore’s independence in 1965 (Schulz 2007).

Figure 7.5 shows the material flows of Singapore’s economy in 2016. In total, 270.3 million metric tons of material were imported, with a large majority being fossil fuels (187.2 Mt, 69%) followed by non-metallic minerals (65 Mt, 24%), which are mainly used for constructing buildings and infrastructure, such as the 9,308 lane-kilometer long road network (Government of Singapore 2019). As a major oil trading and refining hub, most of the fossil fuels it imports are in the form of crude oil, which is traded or refined into other petroleum products for export (160.8 Mt). As a small island with no natural resources and limited options for renewable energy (NCCS 2019), 95% of Singapore’s electricity is generated from the combustion of imported natural gas. A small proportion of energy is also produced from solar power and waste-to-energy facilities that produce energy from incinerating waste (MEWR 2019). Of the 48.6 TWh of electricity consumed in 2016, the largest share was by the manufacturing industry (38%), followed by businesses in the commerce and services sector (36%), and households (16%) (Singstat 2019). Altogether, oil refining, electricity generation and the 956,430 motor vehicles (Land Transport Authority, 2018)—most of which run on fossil fuels—contributed 51.5 Mt of greenhouse gases (CO₂ equivalent) emitted into the air in 2016 (MEWR 2019).

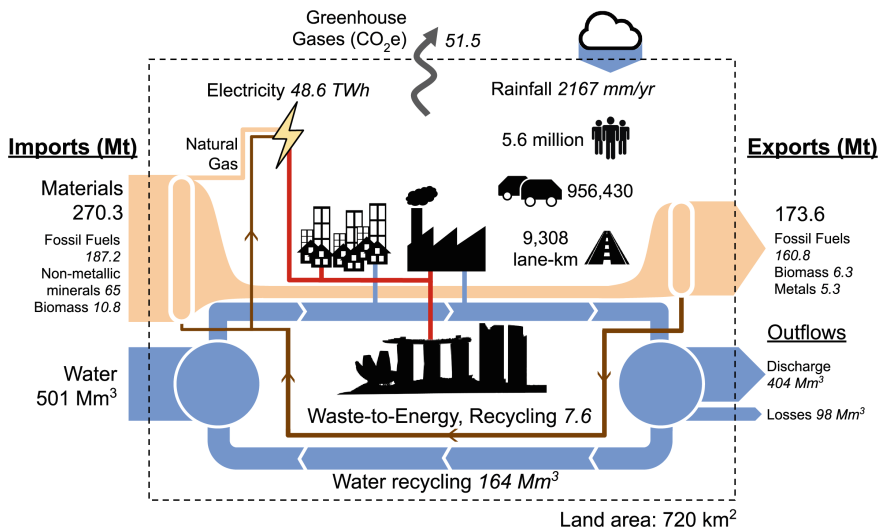


Fig. 7.5 Metabolism of Singapore in 2016. Major flows of materials (in million metric tons, Mt), water, and energy are displayed, along with several key statistics. Data on water flows, recycling, and greenhouse gas emissions obtained from MEWR (2019). Singapore skyline by Kiraan on VectorStock

With a total renewable water resource (TRWR) per capita of 105.1 m³/year, Singapore is considered to be facing absolute water scarcity (Food and Agriculture Organization 2014, 2019). Even though Singapore is located just one degree north of the equator and receives more than two meters of rainfall per year (weather.gov.sg 2019), its small size gives little room for water catchment sufficient to meet its water demand. Historically reliant on its closest neighbor for water imports, Singapore has invested heavily in water recycling (locally branded as NEWater) and desalination to “close the water loop” (PUB 2016) and achieve self-sufficiency in water resources. Investments in water recycling have resulted in the significant secondary flow of water that makes up more than 25% of all the water sent to the end-users.

Table 7.3 shows how Singapore’s UM has grown since independence from 1965 to 2016. Except for DE, which has virtually disappeared relative to the other indicators, all other indicators in 2016 have increased by 5–7 times their values in 1965, with imports growing the most from 6.8 to 48.2 metric tons per capita. Fossil fuels have always made up the bulk of Singapore’s imports and exports, although the share of fossil fuels in total exports has increased while the opposite is true for imports. These metabolic indicators show the phenomenal growth of the material flows of Singapore, which occurred in tandem with Singapore’s rise from a predominantly agricultural economy to a global one with manufacturing, oil refining, and service industries.

Nonetheless, Singapore is not alone in its trajectory. Other cities have also experienced great increases in material consumption per capita in the past century (Kennedy et al. 2007). For example, the total material consumption per capita in Hong Kong increased by 141% from 2.9 metric tons in 1971 to 7.0 metric tons in 1997 (Warren-Rhodes and Koenig 2001). While cities around the world are growing and reaching new economic heights, will the trend of increasing material consumption and intensity continue without bounds? If the theory of the Environmental Kuznets

Table 7.3 Comparison of Singapore’s UM indicators from 1965 to 2016

Indicators (metric tons per capita)	1965 ^a (Schulz 2007)	2016 ^b	%-change
Imports	6.8	48.2	612
Fossil fuels (% of total)	4.9 (72%)	33.4 (69%)	582
Domestic extraction (DE)	1.4	0.07	–95
Direct material input (DMI)	8.2	48.3	489
Exports	5.0	31.0	522
Fossil fuels (% of total)	4.3 (87%)	28.7 (93%)	561
Domestic material consumption (DMC)	3.2	17.3	441
Population (million)	1.89	5.6	196
GDP per capita (S\$, 2015)	5804	77,754	1240

^aValues estimated from figures published by Schulz (2007)

^bThis study

Curve (EKC) holds, environmental impacts would decline as societies become more affluent. Empirical support for the theory is mixed. DMI, DMC, and DPO were found to correlate poorly with GDP per capita for affluent industrial economies (Fischer-Kowalski and Amann 2001), with similarly poor correlations for water use and solid waste production in megacities from 2001 to 2011 (Kennedy et al. 2015). On the other hand, the latter found that energy use is growing at half the rate of economic growth, with London even reducing its electricity consumption per capita while its GDP grew. Returning to the case of Singapore, DMC grew at less than half the rate of GDP growth from 1965 to 2016 (Table 7.3). Furthermore, Abou-Abdo et al. (2011) presented evidence of per capita water consumption for Singapore following the EKC, reaching a peak in the early 1990s with water consumption at 115 m³ per capita and a gross urban income of about S\$34,000.

The material footprints of cities are direct consequences of their metabolism; to recall the definition of Kennedy et al. (2007): “the sum total of the technical and socio-economic processes.” Analyzing the flows of material and energy into, within, and out of cities provides us with a glimpse under the hood of the engine that keeps our cities running. These flows also serve as fingerprints of our cities, reflecting the unique circumstances—past and present—that drive their continuing growth and adaptation.

7.5 Urban Metabolism Applications, Challenges, and Opportunities

The study of UM has been considered for the purposes of urban planning and urban infrastructure planning. The study of resource stocks and flow exchanges in cities offers a perspective for urban systems analysis, and a potential to understand self-sufficiency, efficiency, and resilience. The merit of UM lies in examining resource requirements, availability, rates of change, and accumulation. It offers an understanding of sources (inflows) required to sustain growth, or the abilities of the city to regulate flows, assimilate or treat waste, and capture emissions. As a communications tool, UM can also be used to convey the consumption of resources within cities and allude to limits to growth. Many cities are in fact resource sinks, often accumulating material stocks, and requiring continuous inflows. While UM studies help profile the past and current status of urban systems, many UM studies have not led to actionable recommendations beyond the initial assessment. One main criticism of UM is that since it fundamentally offers a retrospective view of resource stocks and flows, it has to be coupled with other approaches in order to consider opportunities for achieving resource efficiency. UM studies therefore provide diagnosis but are missing a prescription to follow. John et al. (2019) found that two-thirds of 221 UM studies followed a problem-oriented approach to characterize the metabolism of the system and understand risks, as opposed to seeking ways to solve the challenges uncovered.

This limitation of UM is partly due to its systems perspective, which masks many complex interactions that take place within cities and cannot yet be adequately captured. It, therefore, lacks visibility about which actors are driving the flows, where the flows occur, and the underlying usage and consumption patterns. Without a view on the causes and drivers for resource flows, this makes it difficult to extract details on specific infrastructure systems, levers of control, and to consider how to manage, let alone optimize. Many UM scholars have, therefore, highlighted the need to advance the field of practice beyond accounting, assessment, and reporting, to guidance for designing, optimizing, and decision making.

A number of studies have suggested options to couple UM with notions of sustainable design, in order to translate the assessment into practical urban design and planning. Examples include:

- The European BRIDGE research project (2011) developed a GIS-based decision-support UM assessment tool that evaluates urban planning alternatives. The research team emphasized a need for UM to focus on the local scale.
- González et al. (2013) used UM to assess the sustainability impact of urban planning alternatives, such as building types or the location of transportation and infrastructural developments.
- Thomson and Newman (2018) explored the influence of different urban forms on resource inflows, and waste and emissions outflows, for the city of Perth, Australia.
- In a comparative study of UM of different megacities, Han et al. (2018) considered the industrial structures of cities and suggested that the pursuit of service industries instead of manufacturing can allow cities to achieve green growth.

As the field advances, we see four challenges in the further application of UM:

1. As mentioned, unless the internal flows within cities are adequately portrayed in UM, it will be difficult to translate the findings into intervention options. Pincetl et al. (2012) suggested to connect metabolism studies with the actors driving their dynamics. They also highlighted a need to consider the internal political, economic, and social processes within cities, to better understand the complexities of possible change. The aim is to better understand “socioeconomic and policy drivers that govern the flows and patterns.”
2. The quantities or qualities of energy and material flowing through cities may not always be the right metric of concern, nor are they all that matter. The forces driving resource consumption are the demands for services derived from these resources, or the utility obtained. There is a need to capture the value of the services derived, and not just the amounts of resources. Carreón and Worrell (2018) argue for the consideration of energy services, and drivers of them, in UM research.
3. The study of UM remains highly constrained by the availability of quality data. Most existing UM studies cover a limited set of resources—materials (particularly metals), energy, water, and nutrients. Analyses are also usually limited to a single time period (e.g., a single year). Moreover, Currie and Musango (2017)

highlighted that UM studies have generally been limited to the cities in the Global North, given the lack of data elsewhere.

4. While there have been attempts to carry out comparative UM studies across cities (including those by Currie and Musango 2017; Han et al. 2018), it is generally difficult to compare UM studies without a standard approach. Beloin-Saint-Pierre et al. (2017) reported on the lack of consistency on assessment methods. Zhang et al. (2015) recommended the establishment of “a multilevel, unified, and standardized system of categories to support the creation of consistent inventory databases,” which can guide comparative analysis. Even so, the harmonization of efforts will likely remain highly challenging given disparate and often missing datasets.

Despite these challenges, we see related opportunities to advance the field in several ways. Most essentially, new data sources are becoming more available to better examine urban systems. This allows for disaggregated UM that (i) operates at finer temporal resolutions, (ii) is spatially explicit, and (iii) integrates relevant sources of information. Enabled by pervasive sensing and improved communications technologies, time-series data on the building-, district- and even city-level are increasingly available, such as real-time electricity use, individual mobility patterns, water use, and management tools. With the shortening of the timescale of analysis, it is possible to monitor and track resource consumption more carefully. This also allows for understanding rates of change, to better understand the timescale of impacts and potential interventions. In this direction, Shahrokni et al. (2015) proposed what they termed smart urban metabolism, which is capable of integrating UM concepts with information and communication technologies (ICT) and smart-city technologies, thus enabling user-generated automated data collection, real-time analytics, and feedback for city planners.

The mapping of resource flows for a more spatially explicit UM analysis is another potential area of development. By moving beyond scalar quantities, this allows for an understanding of the direction and distribution of internal flows within the city. Impact arises from the distributed nature of activities that drive the demand for resources, resulting in flows. Planners can then consider the resource efficiency implications of land use or infrastructure location decisions. Voskamp et al. (2018) also recommended finer spatio-temporal resolution for monitoring energy and water flows, arguing that this is required in order to develop interventions to optimize resource flows. There is also the opportunity to integrate different types of information at the disaggregated level to evaluate UM. Related sources of information and tools include supply chain data (e.g., transaction data from enterprise resource planning systems) or building information modeling (BIM) data. Researchers have even used satellite and night-light imagery (Xie and Weng 2016), GIS tools (Li and Kwan 2018), and freight transportation surveys (Yeow and Cheah 2019) to better examine UM.

Furthermore, data concerning different resources can be fused or integrated to allow analysts a better understanding of the interdependencies and relationships between different resource flows, as opposed to examining individual resources separately. Exploring the interactions between water consumption and energy use

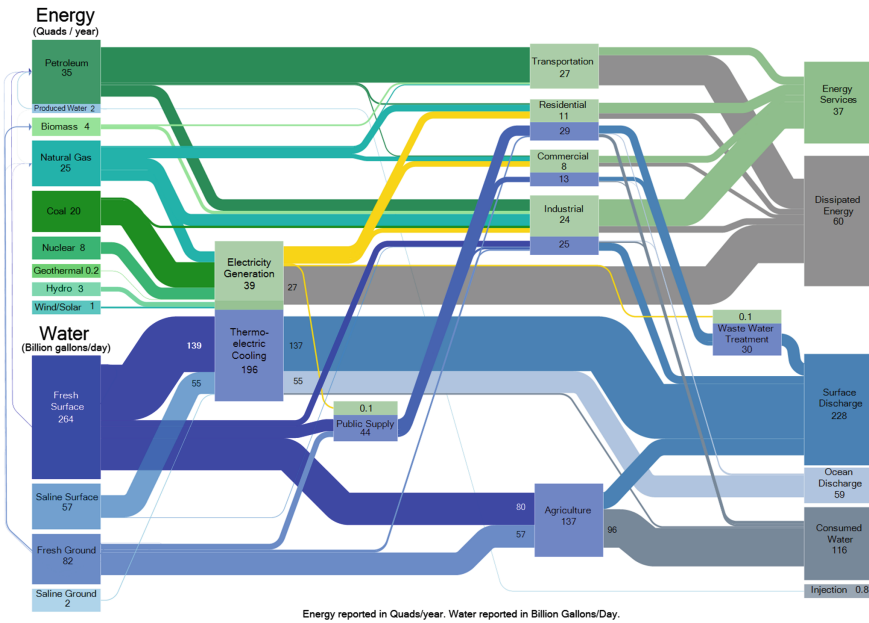


Fig. 7.6 Hybrid Sankey diagram of 2011 U.S. water and energy flows. *Source* U.S. Department of Energy

(water–energy nexus), or linking resource demand with urban activities can aid with holistic policy decision-making and integrated resource management. Hamiche et al. (2016) conducted a review of the water–energy nexus to reveal the complex links between water and electricity generation. Movahedi and Derrible (2020) studied the interrelationships between water, electricity, and gas consumption in large-scale buildings in New York City. Figure 7.6 shows a hybrid Sankey diagram depicting interconnected water and energy flows in the United States in 2011, developed by the US Department of Energy (Bauer et al. 2014).

Finally, UM analysis may progress from a descriptive approach toward a more prescriptive one, when it is considered in simulations of resource flows through cities, allowing the analyst an opportunity to test potential interventions. Figure 7.7 shows the potential evolution of the field, advancing toward more disaggregated analysis with finer temporal and spatial resolution, and eventually using real-time data to offer predictions on the state of the system. With live data streams, one can monitor demand and regulate resource flows in or near real time. This would be analogous to real-time system monitoring, even with the possibility of feedback and control. Such advances are already becoming available at the scale of individual buildings and even neighborhoods, with the possibility of scaling up to virtual city representations in the form of the city’s digital twin, albeit with greater complexity. For instance, in the *Virtual Singapore* project, a digital twin of the city has been developed with the intention for urban planners to simulate alternative policies (Wall 2019). When

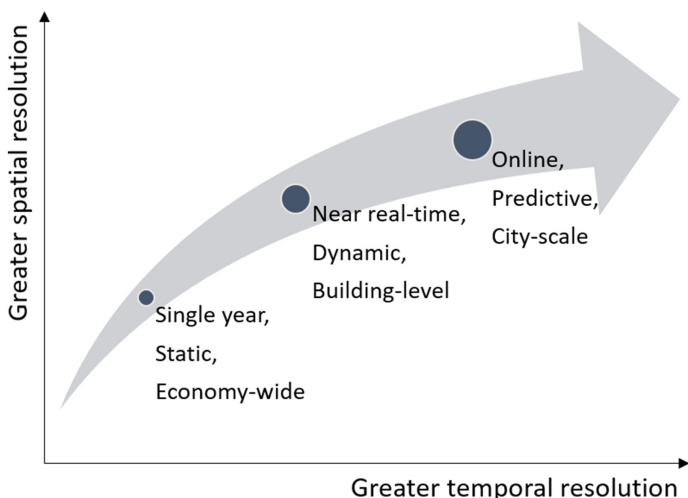


Fig. 7.7 Envisioned developments in the field of urban metabolism

available, such virtual representations of a city's metabolism allow for an opportunity to better monitor, manage, and optimize resource use. In the future, the metabolism of cities can even be predicted and self-regulated.

Ultimately, the coupling of urban metabolism portrayal with sustainable urban planning and design can provide both a comprehensive diagnosis, as well as the capabilities to consider solutions. This allows stakeholders to explore impact mitigation pathways, and consider strategies to achieve sustainable urban renewal and growth. Cities and their metabolism are an outcome of the agglomeration of the complex behaviors of their residents. The study of UM monitors the pulse of the city, allowing insights and actions toward greater urban sustainability.

7.6 Conclusions

From its humble beginnings in quantifying flows of nutrients in and out of Berlin and in sanitary engineering, UM has evolved to become an established field whose main goal is to quantify the inflows, outflows, and production of energy and resources to, from, and in cities. In this chapter, a short history of UM was first offered, notably recalling Wolman's findings from his 1965 study. Because of the significant number of flows that need to be estimated, carrying out a UM is not necessarily straightforward. Methodologically, the goal is primarily to perform a Material and Energy Flow Analysis (MEFA) of a city. In this chapter, two main families of UM approaches were described. The first family attempts to calculate UM from the bottom up by either collecting or estimating individual flows, such as quantifying the amount of water consumed. The second family takes a top-down approach by leveraging and

disaggregating nation-wide economic input-output data sources. Finally, some hybrid methods exist to pursue UM studies, including one that utilizes concepts of energy and another that utilizes concepts of ecological network analysis.

As a practical case study, the UM of Singapore was then studied. As a city-state, Singapore is particularly interesting since both bottom-up and top-down approaches can be adopted. The exercise led to the development of Fig. 7.5 that offers an interesting and insightful snapshot of the material and energy flows that entered or exited Singapore in 2016. Subsequently, the applications, opportunities, and challenges of UM were reviewed. In particular, one main challenge of UM resides in the fact that it is purely an accounting method and it does not directly lead to the development of appropriate designs and policies to tackle specific problems. In contrast, as more numerous and larger data sources are becoming available, it is becoming increasingly possible to perform UM in much finer spatiotemporal resolutions.

Overall, the development and use of UM have evolved relatively slowly in the past century, but significant advances are likely to emerge in the future. On the one hand, more and better data sources are becoming available; on the other hand, cities around the world are striving to become more sustainable and resilient. UM, therefore, offers significant opportunities to help understand how energy and resources are being consumed and, therefore, can contribute to inform better designs and policies to radically change how people live in cities in the twenty-first century.

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References

- Abou-Abdo T, Davis NR, Krones JS, Welling KN, Fernández JE (2011) Dynamic modeling of Singapore's urban resource flows: historical trends and sustainable scenario development. Paper presented at the 2011 IEEE International symposium on sustainable systems and technology
- ADB (2014) Urban metabolism of six Asian cities. Asian Development Bank, Metro Manila, Philippines
- Arora M, Raspall F, Cheah L, Silva A (2019) Residential building material stocks and component-level circularity: the case of Singapore. *J Cleaner Prod* 216:239–248
- Ashby MF (2013) Chapter 2—Resource consumption and its drivers. In: *Materials and the environment*, 2nd edn. Butterworth-Heinemann, Boston, MA, pp 15–48
- Barles S (2009) Urban metabolism of Paris and its region. *J Ind Ecol* 13:898–913
- Bauer D, Philbrick M, Vallario B (2014) The water–energy nexus: challenges and opportunities. US Department of Energy, Washington DC
- Beloin-Saint-Pierre D, Rugani B, Lasvaux S, Mailhac A, Popovici E, Sibiude G, Benetto E, Schiopu N (2017) A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation. *J Cleaner Prod* 163:S223–S240
- BRIDGE (2011) About BRIDGE project. Retrieved from <https://www.bridge-fp7.eu/>. Accessed 3 Oct 2019

- Carreón JR, Worrell E (2018) Urban energy systems within the transition to sustainable development. A research agenda for urban metabolism. *Resour Conserv Recycl* 132:258–266
- Chen S, Chen B (2012) Network environ perspective for urban metabolism and carbon emissions: a case study of Vienna, Austria. *Environ Sci Technol* 46(8):4498–4506
- Chertow M, Choi E, Lee K (2011) The material consumption of Singapore's economy: an industrial ecology approach. In: *Environment and climate change in Asia: ecological footprints and green prospects*. Prentice Hall, Englewood Cliffs, NJ
- Chini CM, Stillwell AS (2018) The state of US urban water: data and the energy–water nexus. *Water Resour Res* 54(3):1796–1811
- Chrysoulakis N, de Castro EA, Moors EJ (2014) *Understanding urban metabolism: a tool for urban planning*. Routledge, London, UK
- Currie PK, Musango JK (2017) African urbanization: assimilating urban metabolism into sustainability discourse and practice. *J Ind Ecol* 21:1262–1276
- Derrible S (2019a) An approach to designing sustainable urban infrastructure. *MRS Energy Sustain* 5:E15
- Derrible S (2019b) *Urban engineering for sustainability*. MIT Press, Cambridge, MA
- Duvigneaud P, Denaeyer-De Smet S (1977) L'écosystème urbain Bruxellois. In: Duvigneaud P, Kestemont P (eds) *Productivité biologique en Belgique*. Duculot, Paris, pp 608–613
- Ehrlich PR, Holdren JP (1971) Impact of population growth. *Science* 171(3977):1212–1217
- Eknonyan G (1999) Santorio Sanctorius (1561–1636)—founding father of metabolic balance studies. *Am J Nephrol* 19(2):226–233
- Eurostat (2001) *Economy-wide material flow accounts and balances with derived resource use indicators: a methodological guide*. Office for Official Publications of the European Communities, Luxembourg
- Eurostat (2018) *Economy-wide material flow accounts and balances with derived resource use indicators: a methodological guide*. Office for Official Publications of the European Communities, Luxembourg
- Food and Agriculture Organization (2019) *Country fact sheet—Singapore*. Retrieved from https://www.fao.org/nr/water/aquastat/countries_regions/index.stm. Accessed 6 Oct 2019
- Food and Agriculture Organization (2014) *Water stress*. Retrieved from https://www.fao.org/nr/water/aquastat/infographics/Stress_eng.pdf. Accessed 6 Oct 2019
- Fath BD, Scharler UM, Ulanowicz RE, Hannon B (2007) Ecological network analysis: network construction. *Ecol Model* 208(1):49–55
- Ferrão P, Fernández JE (2013) *Sustainable urban metabolism*. MIT Press, Cambridge, MA
- Fischer-Kowalski M, Amann C (2001) Beyond IPAT and Kuznets curves: globalization as a vital factor in analyzing the environmental impact of socio-economic metabolism. *Popul Environ* 23(1):7–47
- Fishman T, Schandl H, Tanikawa H, Walker P, Krausmann F (2014) Accounting for the material stock of nations. *J Ind Ecol* 18(3):407–420
- González A, Donnelly A, Jones M, Chrysoulakis N, Lopes M (2013) A decision-support system for sustainable urban metabolism in Europe. *Environ Impact Assess Rev* 38:109–119
- Government of Singapore (2019) *Length of roads maintained by LTA*. Retrieved from <https://data.gov.sg/dataset/length-of-road-maintained-by-lta>. Accessed 11 Sept 2019
- Geddes P (1915) *Cities in evolution: an introduction to the town planning movement and to the study of civics*. Williams and Norgate, London, UK
- Haberl H, Wiedenhofer D, Pauliuk S, Krausmann F, Müller DB, Fischer-Kowalski M (2019) Contributions of sociometabolic research to sustainability science. *Nat Sustain* 2(3):173–184
- Hall P (2002) *Cities of tomorrow*, 3rd edn. Blackwell Publishers, Oxford, UK and Malden, MA
- Hamiche AM, Stambouli AB, Flazi S (2016) A review of the water-energy nexus. *Renew Sustain Energy Rev* 65:319–331
- Han W, Geng Y, Lu Y, Wilson J, Sun L, Satoshi O, Geldron A, Qian Y (2018) Urban metabolism of megacities: a comparative analysis of Shanghai, Tokyo, London and Paris to inform low carbon and sustainable development pathways. *Energy* 155:887–898

- Hau JL, Bakshi BR (2004) Promise and problems of energy analysis. *Ecol Model* 178(1):215–225
- Irvine K, Chua L, Eikass HS (2014) The four national taps of Singapore: a holistic approach to water resources management from drainage to drinking water. *J Water Manag Model* 22:1–11
- John B, Luederitz C, Lang DJ, von Wehrden H (2019) Toward sustainable urban metabolisms. From system understanding to system transformation. *Ecol Econ* 157:402–414
- Kaza S, Yao L, Bhada-Tata P, Van Woerden F (2019) What a waste 2.0: a global snapshot of solid waste management to 2050. World Bank, Washington, DC
- Kennedy C (2012) A mathematical description of urban metabolism. In: Weinstein MP, Turner RE (eds) *Sustainability science*. Springer, New York, NY, pp 275–291
- Kennedy C, Cuddihy J, Engel-Yan J (2007) The changing metabolism of cities. *J Ind Ecol* 11(2):43–59
- Kennedy C, Stewart I, Facchini A, Cersosimo I, Mele R, Chen B, Uda M (2015) Energy and material flows of megacities. *Proc Natl Acad Sci* 112(19):5985–5990
- Krausmann F, Schandl H, Eisenmenger N, Giljum S, Jackson T (2017) Material flow accounting: measuring global material use for sustainable development. *Annu Rev Environ Resour* 42(1):647–675
- Krausmann F, Wiedenhofer D, Lauk C, Haas W, Tanikawa H, Fishman T, Miatto A, Schandl H, Haberl H (2017) Global socioeconomic material stocks rise 23-fold over the 20th century and require half of annual resource use. *Proc Natl Acad Sci* 114(8):1880–1885
- Krausmann F, Weisz H, Eisenmenger N, Schütz H, Haas W, Schaffartzik A (2018) Economy-wide material flow accounting: introduction and guide. *Social Ecology Working Paper 151v1.2*. Institute of Social Ecology, Vienna
- Lederer J, Kral U (2015) Theodor Weyl: a pioneer of urban metabolism studies. *J Ind Ecol* 19:695–702
- Li H, Kwan M-P (2018) Advancing analytical methods for urban metabolism studies. *Resour Conserv Recycl* 132:239–245
- Land Transport Authority (2018) Annual vehicle statistics 2018: motor vehicle population by vehicle type. Land Transport Authority, Singapore
- Mahajan S (2014) *The art of insight in science and engineering: mastering complexity*. MIT Press, Cambridge, MA
- Matthews E, Amann C, Bringezu S, Fischer-Kowalski M, Huettler W, Kleijn R, Moriguchi Y (2000) The weight of nations: material outflows from industrial economies. World Resources Institute, Washington DC
- MEWR (2019) Key environmental statistics 2019. Retrieved from <https://www.mewr.gov.sg/docs/default-source/default-document-library/grab-our-research/kes-2019.pdf>. Accessed 7 Oct 2019
- Mohareb E, Derrible S, Peiravian F (2016) Intersections of Jane Jacobs' conditions for diversity and low-carbon urban systems: a look at four global cities. *J Urban Plann Dev* 142(2):05015004
- Movahedi A, Derrible S (2020) Interrelated patterns of electricity, gas, and water consumption in large-scale buildings. *enr Xiv*. <https://doi.org/10.31224/osf.io/ahn3e>.
- NCCS (2019) Singapore's approach to alternative energy. Retrieved from <https://www.nccs.gov.sg/climate-change-and-singapore/national-circumstances/singapore's-approach-to-alternative-energy>. Accessed 7 Oct 2019
- Newcombe K, Kalina JD, Aston AR (1978) The metabolism of a city: the case of Hong Kong. *Ambio* 7:3–15
- Newell JP, Cousins JJ (2014) The boundaries of urban metabolism: towards a political–industrial ecology. *Prog Hum Geogr* 39(6):702–728
- Odum HT (1996) *Environmental accounting: EMERGY and environmental decision making*. Wiley, New York, NY
- Pearce BJ, Chertow M (2017) Scenarios for achieving absolute reductions in phosphorus consumption in Singapore. *J Cleaner Prod* 140:1587–1601
- Pincetl S, Bunje P, Holmes T (2012) An expanded urban metabolism method: toward a systems approach for assessing urban energy processes and causes. *Landscape Urban Plann* 107(3):193–202

- PUB (2016) Our water, our future. Retrieved from <https://www.pub.gov.sg/Documents/PUBOurWaterOurFuture.pdf>. Accessed 6 Oct 2019
- Schulz NB (2007) The direct material inputs into Singapore's development. *J Ind Ecol* 11(2):117–131
- Shahrokni H, Lazarevic D, Brandt N (2015) Smart urban metabolism: towards a real-time understanding of the energy and material flows of a city and its citizens. *J Urban Technol* 22(1):65–86
- Singstat (2019) M890841—Electricity generation and consumption, Annual. Retrieved from <https://www.tablebuilder.singstat.gov.sg/publicfacing/createDataTable.action?refId=14602>, accessed 7 October 2019
- Tan LM, Arbabi H, Brockway PE, Densley Tingley D, Mayfield M (2019) An ecological-thermodynamic approach to urban metabolism: measuring resource utilization with open system network effectiveness analysis. *Appl Energy* 254:113618
- Thomson G, Newman P (2018) Urban fabrics and urban metabolism—from sustainable to regenerative cities. *Resour Conserv Recycl* 132:218–229
- Tortajada C, Joshi Y, Biswas A (2013) *The Singapore water story*. Routledge, London, UK
- Tortajada C, Buurman J (2017) [Singapore Handbook of Public Policy] Water policy in Singapore. Retrieved from <https://lkyspp.nus.edu.sg/gia/article/water-policy-in-singapore>. Accessed 7 Oct 2019
- Voskamp IM, Spiller M, Stremke S, Bregt AK, Vreugdenhil C, Rijnaarts HHM (2018) Space-time information analysis for resource-conscious urban planning and design: a stakeholder based identification of urban metabolism data gaps. *Resour Conserv Recycl* 128:516–525
- Wall M (2019) Virtual cities: designing the metropolises of the future. BBC.com, 18 January 2019. Retrieved from <https://www.bbc.com/news/business-46880468>. Accessed 12 Oct 2019
- Warren-Rhodes K, Koenig A (2001) Escalating trends in the urban metabolism of Hong Kong: 1971–1997. *AMBIO J Hum Environ* 30(7):429–438
- weather.gov.sg (2019) Climate of Singapore. Retrieved from <https://www.weather.gov.sg/climate-climate-of-singapore>. Accessed 4 Oct 2019
- Welling KN (2011) Modeling the water consumption of Singapore using system dynamics. Master of Science, Massachusetts Institute of Technology, Cambridge, MA
- Wolman A (1965) The metabolism of cities. *Sci Am* 213:179–190
- Xie Y, Weng Q (2016) Detecting urban-scale dynamics of electricity consumption at Chinese cities using time-series DMSP-OLS (Defense Meteorological Satellite Program-Operational Linescan System) nighttime light imageries. *Energy* 100:177–189
- Yeow L, Cheah L (2019) Using spatially explicit commodity flow and truck activity data to map urban material flows. *J Ind Ecol* 2019:1–12
- Zhang Y, Yang Z, Yu X (2009) Ecological network and emergy analysis of urban metabolic systems: model development, and a case study of four Chinese cities. *Ecol Model* 220(11):1431–1442
- Zhang Y, Yang Z, Yu X (2015) Urban metabolism: a review of current knowledge and directions for future study. *Environ Sci Technol* 49(19):11247–11263



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