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Urban Metabolism: From Molecular Scale to Anthropogenic Systems

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Abstract

The aim of this paper is to show how an "Urban Metabolism" approach can be used for analyzing, designing, and optimizing material and energy flows and stocks in human settlements. For this purpose, material flow analysis (MFA) and substance flow analysis (SFA) is applied in a rigid way to quantitatively model metabolic processes such as supply and disposal of goods in a city. The characteristics of relevant material flows and stocks of urban areas in space and time are examined. Results of two metabolic case studies on resources, waste management, and environmental protection are presented. By introducing the so called "Activity" concept, it is shown how the Urban Metabolism approach is instrumental for the design of sustainable anthropogenic systems. Finally, it is suggested to use the methodology for technology assessments and the optimization of entire anthropogenic systems.

Keywords: Anthroposphere, resource management, waste management, sustainability, material flow analysis (MFA), substance flow analysis (SFA)

1. Introduction

Affluent and densely populated cities have become epicenters of material and energy turnover, characterized by extensive resource consumption on one side and significant environmental pollution on the other. While isolated management strategies can provide localized relief, it is evident that a comprehensive governance framework is now essential. Addressing the pressing challenges of resource scarcity, environmental degradation, and climate change requires integrating the fundamental demand for materials and energy with the concept of 'urban metabolism.' This involves balancing inputs, stocks, and outputs in a manner analogous to biological organisms and their biochemical reactions.

The metaphor 'urban metabolism' illustrates the dynamic processes and flows of energy, materials, and resources to sustain human activities within a city. It likens the city to a living organism that consumes inputs such as food, water, and energy, processes them, and generates outputs like waste, emissions, and products. This concept provides urban planners and researchers with a framework to analyse how cities operate, their environmental impact, and strategies for sustainable management. Analysing a city's metabolism reveals inefficiencies of resource use, reduces waste and environmental loading, and enhances sustainability. Urban metabolism is a component of the broader concept of the 'metabolism of the anthroposphere,' which includes both human-induced (anthropogenic) and natural (geogenic) flows and stocks of materials and energy within defined spatial boundaries. (Bahers et al, 2022)

Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) are valuable tools for studying how materials and substances move through systems, particularly in the context of human activity (anthropogenic metabolism). MFA focuses on the flow and stocks of tradeable goods and materials, while SFA examines the movement of individual chemical elements and compounds. Both approaches help define system boundaries and analyze material flows and stocks, making them useful for sustainability assessments and resource management. (Giboulot, et al, 2024)

The synergy between MFA and SFA provides a powerful framework for exploring and

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optimizing metabolic processes. The key advantage is redundancy: grounded in the principle of mass balance, missing or inaccessible data in one domain can be inferred from flow and concentration data in another, more readily available segment of the metabolism. As economic data on goods is often significantly more abundant than data on chemical substances, the combined approach provides substantial benefits.

This paper promotes the 'Urban Metabolism' approach and its application. Two case studies highlight the power of the approach. The introduction of the activity concept links human needs to resources and pollution and gives direction for future improvements. Based on these findings, the paper provides conclusions for the future development and implementation of urban metabolism strategies. A distinct feature of the approach is the link between the molecular scale of chemical substances and the economic scale of tradeable goods. This allows to relate bulk material flows to their values as resources and/or environmental pollutant, and to identify pathways to sustainability.

The paper concentrates on materials, substances, and energy. While other factors - such as land use, socio-economic values, culture - are also critical for understanding and managing urban metabolism, they are beyond the scope of this work. Also, objectives for improvement are not considered. Addressing these additional aspects would require a broader focus and more extensive discussion. However, some of the cited literature does explore these factors in greater depth.

2. Methodology

Numerous researchers have developed and proposed methodologies for investigating urban metabolism (Wolman, 1965; Baccini, 1997; Barles, 2009; Zhang, 2023; Zhang, 2013; Brunner & Rechberger, 2017; Chavez et al., 2018; Dijst, Worrell, Böcker et al., 2018; Perrotti, 2020, among others). Despite these significant contributions, a universally accepted methodology has not yet been established. In this paper, we use the often-applied MFA/SFA approach as described by Bahers et al, 2022 and Giboulot et al, 2024. Originally developed and published around 1990, this approach has been extensively applied and cited in over 4,200 publications. Its widespread adoption is further supported by the free STAN software (Cencic & Rechberger, 2008) which provides a robust, standardized, and user-friendly platform for constructing and analysing MFA systems. It is available at https://www.stan2web.net/ and includes tools for managing uncertainties and visually presenting results, making it an invaluable resource for metabolic studies.

Given the vast scope of urban metabolism, two specific case studies have been selected to illustrate the approach. The first case study provides an overview of all flows and stocks of *goods* required to satisfy human needs ("activities") within an urban settlement. It identifies the four essential activities necessary to sustain human life and quantifies the corresponding material flows and stocks associated with these activities. The second case study focuses on cadmium, showcasing how the urban metabolism approach can also be applied at the *substance* level. This example demonstrates its utility for process design in view of product quality and emissions, particularly with a focus on environmental protection.

A metabolic system's boundaries in space and time are crucial for defining its scope and behavior (Erlandsson et al, 2023). The limits in space are usually given by the perimeter of the urban area. It may be necessary to include stocks, flows, and processes of the so-called *Hinterland* if they are relevant for answering a specific research question. Hinterland stands here for geographical areas outside the city boundaries that are instrumental for the functioning of the urban metabolism. Examples are coal mining areas for energy supply or sanitary landfills for disposal of wastes. Boundaries in time are chosen according to the research question and the availability of data. Often, annual data on import and consumption are readily available, but seasonal or even daily data is much scarcer and more difficult to get. Thus, for large systems such as cities, materials and substance balances on a yearly base are often the method of choice.

In addition to boundaries, a metabolic system consists of flows, stocks, and processes of materials, energy, and information. Materials can be classified into goods, which are economic entities with either a positive value (e.g., water) or a negative value (e.g., sewage), and substances, which refer to chemical elements (atoms) or compounds (molecules). Goods, in turn, are composed of substances. Materials and substances can be transported, transformed, or stored within processes. A metabolic system is defined by its boundaries, processes, and balanced flows and stocks. However, due to system redundancy, detailed measurement of all elements is often unnecessary. Material Flow Analysis (MFA) is designed to reduce uncertainty in understanding material and energy flows by utilizing the most efficient amount of data possible. Rather than relying on extensive datasets, MFA focuses on strategic data selection and methodological consistency to provide accurate and reliable insights into the movement, transformation, and accumulation of materials within a defined system. This approach allows for effective decision-making and resource management even in data-limited contexts (Deshpande et al, 2020).

Data on the flow and stock of goods is usually easy to find through economic databases, company records, market studies, and consumer reports. In contrast, information about substances is often limited and requires expert chemical knowledge. Also, product compositions are sometimes protected by patents, making it hard to identify specific chemical elements or compounds. In such cases, applying the law of conservation of mass to track substances in different processes can help. Overall, analyzing urban metabolism based on goods is easier than doing so at the substance level. For substances, using the overlap between different processes in the system can be helpful. When it comes to energy, a lot of data has been collected over the years—mainly to understand climate change and CO_2 emission sources. Carbon balances, in particular, are useful for studying urban metabolism.

In an MFA system, the flow of information is crucial and must be seamlessly integrated with the flows of materials and energy. This information can encompass monetary and other value-oriented data, making it particularly significant for interpreting and optimizing inefficient metabolic systems. Such systems often contribute to excessive environmental burdens or depend heavily on scarce, non-renewable resources. Examples of sources for monetary and value-oriented information include economic databases, company reports, life cycle analysis data, and market research accounts. Chapter 3 provides a summary of the case study results, while Chapter 4 presents the conclusions derived from these studies.

3. Results and Discussion

On a global scale, nearly 60% of the population now resides in cities - a striking contrast to the 19th century when rural populations accounted for up to 75% of all people. Alongside the rapid growth of urban populations, per capita material turnover has increased even more, driven by economic growth. Today, urban metabolism represents the most significant material turnover on a global scale, except for certain resource-extractive mining regions.

The rapid growth in materials consumption in cities is unprecedented, leading to two significant consequences. On one hand, it poses challenges for material supply due to the limitations of global resources. On the other hand, the substantial flows of solid, liquid, and gaseous waste materials place a heavy burden on the environment, which must ultimately absorb and accommodate these materials after their use and consumption.

In the following discussion, the implications of modern urban metabolism for resource management and environmental protection are explored through illustrative examples. To provide a clear framework, the activity concept is utilized. Four fundamental human needs are defined as activities, and for each, the flows and stocks of materials and selected substances are examined.

‘To nourish’ addresses the biologically driven human need for food, drinks, and air necessary for breathing. Depending on the scope of the analysis, it may encompass household activities, such as shopping, cooking, and eating, or extend to the entire chain of food production, from farming, industrial processing, distribution, and both in-house and out-of-house food consumption.

‘To clean’ refers to the separation of desired and undesired goods in households and beyond, driven by physiological, hygienic, health, and aesthetic considerations. The toilet serves as the central process, with water and sewage as the primary material flows.

‘To reside and work’ encompasses all material flows and stocks associated with building materials and textiles used for living and working. Examples include concrete, wood, glass, plastics, and fuel. And ‘To transport and communicate’ stands for the transportation of people, materials, energy, and information. It includes all infrastructure (roads, cables, cars, phones, fuel etc.) required to perform these tasks.

The concept of 'activities' underscores the diverse ways in which basic human needs have been met throughout history. Over the past 100,000 years, human diets and food production methods have undergone profound transformations, significantly affecting land use and impacting the health of humans, animals, and the environment. Justus von Liebig's discovery that plants absorb essential nutrients in the form of minerals at the molecular level, coupled with the subsequent discovery and application of artificial fertilizers, revolutionized the practice of nourishment. This breakthrough led to an abundance of food, ensuring greater sustenance for growing populations, but also contributed to nutrient pollution in water systems, presenting new environmental challenges.

Similarly, the activity 'to clean' has evolved, now primarily reliant on water, sewage, and chemicals, along with the necessity for advanced water purification systems. Since the largest urban stock consists of buildings for housing and infrastructure, modelling the activity 'to reside and work' provides opportunities for innovative approaches to a circular economy in construction materials.

Furthermore, 'transportation and communication' demonstrate remarkable versatility, with vastly different requirements for material stocks and flows depending on the chosen modes - such as gasoline or electricity driven cars, boats, airplanes, or horses. Here again, the link between bulk and molecular level allows foresight and remedy: An urban metabolism approach with full balances of the activity to transport would have revealed the future accumulation of Pb in air, soil and water when leaded gasoline was introduced in the 1920s to enhance the antiknock properties of combustion engines.

Another example is the switch from transporting people to transportation of information, such as video conferencing instead of air travel. Analysis by MFA/SFA will reveal potential benefits while identifying areas requiring further improvements regarding sustainability. Today, such comprehensive assessments on the level of entire activities are quite rare.

3.1. Case study 1: Human activities in cities necessitate substantial flows of materials, long-term stocks, and efficient sinks to sustain their functions

A representative case of urban metabolism in the late 20th century is illustrated in Figure 1. System baundaries in space are the municipal boundaries, and in time the year of 1993. Additional examples, including contemporary cities of the 21st century, can be found in (ADB, 2014). Vienna serves as a model for many cities with 1 to 2 million inhabitants and a per capita gross domestic product (GDP) of approximately 25,000 €. Material flows and stocks are strongly influenced by GDP dynamics - whether in emerging or affluent economies, growing or shrinking urban environments - as well as by natural conditions (e.g., climate zones, desert vs. alpine regions, local resources) and techno-cultural characteristics (e.g., traditions of affluence vs. resource conservation and circular material use). Consequently, the specific figures for flows and stocks in Vienna apply only to similar cities within a particular time frame. Individual analyses are therefore necessary before drawing specific conclusions.

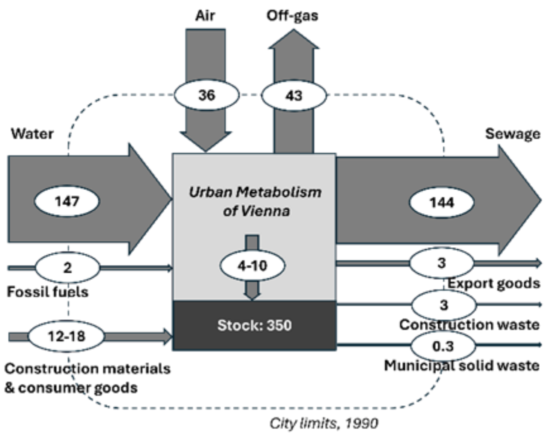

Figure 1. Per capita material flows [t/(c·yr)] and stocks [t/c] of the urban metabolism in the city of Vienna around 1990. Included are all flows and stocks of goods through private households, private and public service sector including administration, and most but not all industries (Brunner & Rechberger, 2017).

Given the rapid evolution of both anthropogenic systems (e.g., economic structures) and natural systems (e.g., climate change), it is advisable to periodically reassess whether the reported figures and conclusions remain applicable. The primary objective of this paper is to demonstrate an approach rather than to analyze a specific case. Therefore, the example of Vienna remains relevant despite potential discrepancies in numerical data. Over the past 30 years, Vienna's per capita GDP has doubled to €53,000, greatly increasing material flows and stocks, as shown in Figure 1. While the 1990 data may be outdated, key flows and stocks still shape the city's current urban system. Hence, the following conclusions of the Vienna study are still valid for most cities world-wide:

1. Mass Flow Considerations In Urban Metabolism: From a total mass flow perspective, water - and consequently the resulting sewage flow - constitutes the most significant material stream in a modern city. Water is essential not only for human sustenance ("to nourish") but even more so for sanitation processes ("to clean") (cf. Table 1). For hygienic reasons, water plays a crucial in collecting, concentrating and treating specific waste products from cities.

The second most critical flow is air, which role in oxidation, collecting, transporting, and diluting various urban waste products serves two primary functions: i. Urban energy metabolism still depends largely on the oxidation of fossil carbon, utilizing the oxygen present in air. ii. Air acts as a dilution medium for atmospheric emissions, including carbon dioxide, noxious gases, and particulate matter (dust/aerosols).

Today, air is widely used for running vehicles, heating homes, and powering industries. In the future, this use may decrease as renewable electricity replaces fossil fuels. However, since food (a non-fossil carbon source) still powers the human body, good airflow is still needed in homes and cities to maintain fresh air and healthy indoor conditions.

2. Construction Materials and Long-Term Urban Stock: Construction materials rank third in importance within urban metabolism due to their long residence time compared to water and air. While the annual balance of water and air remains constant, long-lived goods - such as construction materials, appliances, and furniture - constitute the major urban stock.

The case of Vienna (Fig. 1) illustrates that in the 1990s, the city's material stock amounted to several hundred tons per capita. Due to high economic growth, imports and exports of long-lived goods are not in equilibrium, leading to rapid stock expansion. Annually, 4 to 10 tons per capita are added to the urban stock, resulting in an average doubling time of 50 years. Growth rate and residence time affect how much material is available for recycling. However, when input exceeds waste output, recycling can't meet demand, requiring extra virgin materials. This imbalance is greater at the substance level. It poses challenges in recycling:

i. Legacy substances - such as mercury, cadmium, lead, and POPs - have been phased out due to their toxic properties, reducing their demand. However, their existing stock remains significant as they persist in long-lived products, including highly stabilized plastics, construction materials, and electrical appliances. As these materials transition into waste over the coming decades, the removal of hazardous substances during recycling will be crucial to ensuring the safety of new products manufactured from secondary resources.

ii. New substances, such as lithium for energy storage and graphene for electronic applications, are being introduced in rapidly increasing quantities. Due to the long lifespan of batteries and graphene-based components, their current output within urban metabolism remains relatively low compared to the accelerating input. Consequently, a significant time lag - often exceeding 10 years - exists between initial deployment and the feasibility of large-scale, economically viable recycling.

In cities, the growing amount of materials can be a useful resource in the future. If planned and managed well, these materials can help reduce environmental impact and improve resource availability. Managing materials throughout their life cycle can support more efficient, sustainable, and cost-effective urban development.

Table 1. Material flows, stocks and change of stocks in private households (PHH) for the activities to nourish, to clean, to reside and work, and to transport and communicate. Numbers apply to urban metabolism in Western Europe during the 1990ies. They differ from Fig. 1 (Vienna city) because they include only those flows that can be related to PHHs.

Activity	Input	Output			Stock	Δ Stock
		Sewage	Off-gas	Solid residues		
	Mg/c·y	Mg/c·y	Mg/c·y	Mg/c·y	Mg/c	Mg/c·y
To nourish	5.7	0.9	4.7	0.1	<0.1	
To clean	60	60	0	0.02	0.1	
To reside & work	10	0	7.6	1	100	+1
To transport & communicate	10	0	6	1.6	160	+2
Total flow & stock	86	61	19	2.7	260	+3

3. Circular vs. Linear Material Flows in Urban Metabolism: Beyond water, air, and construction materials, all other materials necessary for urban metabolism account for less than 10% of total mass. As illustrated in Figure 1, the majority of material flows through cities follow a linear trajectory, with only a small fraction operating within a circular system.

Before transitioning away from this linear regime, both the necessity and feasibility of circularity must be carefully assessed. For instance, in desert cities receiving less than 20 mm of annual precipitation, water recycling is justified despite high costs, given the extreme scarcity of freshwater. Conversely, in alpine cities with abundant freshwater resources exceeding 2,000 mm/yr, a linear water supply can serve as an efficient and sustainable economic and ecological solution. Importantly, circular material flows, compared to linear or spiral systems, is not inherently determined. It depends on various factors specific to a region, including available resources, system efficiency, and the overall context of the situation (Kirchherr et al, 2023).

4. Anthropogenic vs. Geogenic Material Flows:
Today, anthropogenic (human-induced) flows of many substances surpass their natural (geogenic) counterparts (Klee & Graedel, 2004). This applies not only to organic xenobiotic compounds but also to numerous elements of the periodic table. For example, the flux of several heavy metals - such as cadmium (Fig. 2), lead, and mercury - is predominantly driven by human activities (Brunner & Baccini, 1981).

These excessive flows pose risks to water, air, and soil quality. In some regions, heavy metal concentrations are steadily increasing in soils, creating localized contamination hotspots that threaten agricultural viability. This raises a critical question: Where do these material flows ultimately end? The fate of substances depends on the availability of natural sinks (e.g., sea, sediments, atmosphere, space) or engineered conversion and containment systems (e.g., incinerators, biochemical processes, landfills). The challenge lies in ensuring that these sinks can safely transform or isolate pollutants over long time periods, preventing adverse environmental and health impacts.

5. Shift in Urban Emissions and Environmental Policy: In most modern urban areas, emissions from household consumption activities now exceed those from industrial, commercial, and trade production. The cumulative impact of numerous small sources has become a significant contributor to urban pollution, particularly in the release of metals such as copper and zinc, as well as various organic compounds.

This shift necessitates a fundamental change in environmental protection policies. While historically, industrial production facilities were among the largest polluters, today's regulatory focus must increasingly address dissipative pollution stemming from everyday consumer activities. This need is especially pressing in high-density urban environments, where aggregated emissions from millions of individuals significantly impact air, water, and soil quality.

6. Dynamic Residue Flows and the Need for Monitoring Systems: Due to the phenomena described in Sections 1 to 5, the type, volume, and composition of urban residues - including municipal solid waste, construction debris, sewage sludge, and off-gas emissions - are subject to rapid and continuous change. To effectively manage these evolving material flows, it is essential to develop advanced monitoring and early warning systems. These systems help predict both beneficial accumulations - which present opportunities for recycling ("urban mining") - as well as harmful concentrations that could pose future environmental risks.

Material Flow Analysis (MFA) is a fundamental tool for early detection and optimization of urban metabolism, as it adheres to the mass balance principle: Over time, input, stock, and output must remain in equilibrium - no matter can be lost. While Life Cycle Analysis (LCA) is useful for assessing environmental impacts, it often overlooks small, hard-to-measure flows that gradually accumulate or dissipate over extended periods.

To enhance urban resource management and sustainability, long-term modelling and simulation of supply, stock, and disposal processes are indispensable. These tools enable cities to anticipate future material shifts, improve resource efficiency, and mitigate environmental burdens, ultimately leading to a more resilient and sustainable urban metabolism.

Table 1 with the main flows and stocks of goods through households serves well for planning of water supply, and sewage collection and treatment. For managing of municipal solid wastes, these figures are instrumental for optimizing collection and treatment systems such as recycling systems, collection routes, Waste-to-Energy (WtE) capacities, flue-gas treatment, and landfill volume). The main advantage of the numbers in Fig. 1 is that the output figures are related to input and stock. In waste management, often output figures (collected wastes) are used only, thus no assessment of future waste development is possible.

The large per capita material flows and stocks presented in Case Study 1 do not inherently pose a problem. A sustainable economy can be maintained if resource availability is sufficient and if emissions and effluents remain environmentally compatible. However, challenges arise when resources become scarce or when metabolic residues - such as municipal solid waste, sewage, off-gas, and industrial by-products - cannot be effectively recycled or accommodated within adequate environmental sinks (Tarr, 1996).

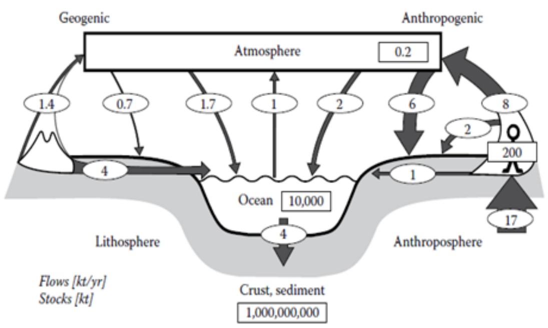

Figure 2. Global Cadmium (Cd) Flows [kt/yr] and Stocks [kt] in the 1980s: anthropogenic flows exceeded geogenic flows, leading to accumulation of Cd in the environment, particularly in soils. Industrial processes such as mining, smelting, material processing, and waste incineration released significant quantities of volatile cadmium, which were subsequently transported via atmosphere and water to soil and the sea. Cd stock within the anthroposphere exhibited an annual growth rate of 3%, exacerbating future environmental exposure risks. Careful management strategies will be essential to ensuring that still growing anthropogenic Cd stocks do not contribute to future environmental contamination (Brunner & Baccini, 1981).

A shift in focus is required: Recent debates have centred on resource scarcity, driven in part by the rapid introduction and consumption of new substances, such as lithium and other critical metals vital for the transition to renewable energy systems. As technology advances, however, it is possible that lithium - currently a key component in energy storage systems - may become obsolete, replaced by more economic, innovative materials with higher energy densities and faster storage capabilities.

Thus, resource scarcity can be addressed not only through expanded prospecting and mining but by advancing technologies, too. Strategic planning and research into next-generation materials will be essential for ensuring the long-term sustainability of urban metabolic processes.

3.2. Case study 2: Designing Urban Metabolic Processes Under Environmental Constraints - The Case of Cadmium

In addition to the classical challenge of resource scarcity at the front end of the supply chain, there exists a less frequently discussed but equally critical issue at the back end: the absence of adequate sinks for safe disposal of materials. This challenge is particularly relevant in the case of cadmium (Cd), a substance widely used for energy storage before lithium emerged as the dominant battery material. Historically, cadmium served multiple industrial and consumer applications: As a corrosion-resistant coating for metal surfaces, as a yellow and red pigment in paints, as an additive in plastic materials, such as polyvinyl chloride (PVC), to extend the lifespan of window frames and construction pipes.

During the second half of the 20th century, vast amounts of cadmium were introduced into the urban metabolism through consumer products, industrial applications, and infrastructure development. As a result, a large and growing stock of cadmium accumulated within private households and urban infrastructure, posing long-term challenges in material management and environmental sustainability.

This trajectory shifted when it was discovered that cadmium (Cd) concentrations were steadily increasing in soils, sediments, water, and air, posing a significant risk to both ecosystems and human health. Without appropriate countermeasures, Cd levels could surpass ecotoxicological thresholds and violate health standards, particularly in urban environments where accumulation is most pronounced.

In response, many countries implemented regulatory frameworks to limit Cd usage, particularly addressing its dissipative applications - those that lead to uncontrolled environmental dispersion without feasible recovery or safe disposal in a final sink.

These measures aimed to prevent Cd contamination, ensuring that waste management and material recovery strategies could prevent its long-term accumulation in the environment. MFA and the urban metabolism approach are highly effective tools for ensuring the sustainable management of cadmium (Cd) in cities. These methodologies provide a transparent and reproducible framework to trace Cd flows and stock in goods and substances, covering the entire lifecycle from supply to final disposal in sinks.

Figure 3 and Tables 2 and 3 illustrate this linkage, based on data from a hypothetical city of approximately one million inhabitants. As systems boundaries, city limits and the range 1980-1990 have been used for the MFA. Basic material and substance data and methodology is given in (Brunner and Rechberger, 2017). The visual representations in Figure 3 detail Cd flows per capita, tracing the movement of Cd from private households (PHH) through municipal solid waste (MSW) collection and waste-to-energy treatment, leading to environmental dissipation.

Estimations for Cd in non-PHH products and urban Cd stocks remain approximate and are not comprehensively documented. These figures primarily apply to affluent urban societies but tend to be lower in emerging economies. Furthermore, cadmium stock dynamics are subject to rapid change, driven by technological advancements and waste management improvements, particularly in the transition towards a circular economy.

Cadmium Exploitation and Urban Fluxes in the 1980s: In 1980, global Cd exploitation amounted to 17,000 metric tons per year. Given that slightly less than half of the global population lived in urban areas, approximately 10 g Cd per capita per year was used in cities. Of this amount, an estimated 6 g Cd per capita per year entered private households (PHH), while the remainder was used in industrial production, the service sector, and public infrastructure.

Cadmium Outputs from PHH: Analysis of MSW shows Cd concentrations ranging from 8 to 12 mg per kg MSW, roughly eighty times higher than the average concentration in the Earth's crust (0.1–0.2 mg Cd per kg). Given an average MSW generation rate of 250 kg per capita per year in the 1980s, the Cd flux from PHH to waste-to-energy (WtE) plants amounts to 2.5 g/c·yr - equivalent to a total 2.5 metric tons per year in a city of one million residents. Remarkably, this quantity represented one-fourth of the city's total Cd demand.

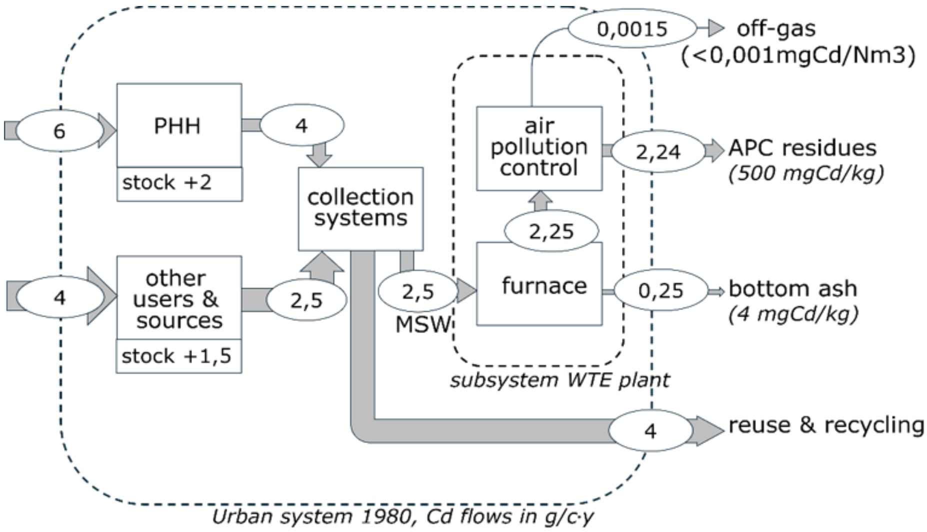

Figure 3. Cd flows in g/capita and year through private households (PHH) and waste management systems in Europe between 1980 and 1990 (data from Brunner and Rechberger, 2017). About 3.5 g/c·yr of the total Cd flow of 10g/c·yr used in urban systems is added to the stock, 2,5 g/c·yr of Cd is collected by MSW, and a large fraction of 4 g/c·yr is separately collected and recycled (batteries). In WtE plants, athmophilic metals such as Cd, Sn, and Hg are diverted to the flue gas, and must be removed by advanced Air Pollution Control (APC) technology. Hence, the highly toxic APC residues could become key residues for Cd recycling (cf. Tab. 3).

During MSW incineration, Cd partitioning occurs as follows: 10% of Cd is retained in bottom ash (cf. Fig. 3), and 90% is released into raw flue gas.

Table 2. Per capita Cd flows through a city: Numbers apply to urban metabolism in Western Europe during the 1980-90ies with advanced APC. (cf. Brunner and Rechberger, 2017).

Urban input	(g/c·yr)	
total input	*10*	
input into PHH		6
input into rest of economy		4
Urban stock	(g/c·yr)	
total net addition to stock	*3.5*	
addition to PHH stock		2
addition to stock rest of economy		1.5
Urban output	(g/c·yr)	
total output	*6.5*	
MSW & WtE residues to landfill/recycling		2.5
MSW flue gas emissions		0.0015
recycling output from PHH		1.5
output from the rest of the economy (landfilling of construction waste, recycling)		2.5

Prior to 1970, APC systems were relatively rudimentary, relying primarily on basic cyclones and scrubbers. While these systems were effective in removing bulk particulate matter, they were not optimized for capturing fine particles containing volatile elements, such as Cd, Sn, and Pb. As a result, only 10% of Cd emissions were removed during flue gas treatment, leading to significant atmospheric pollution. In the vicinity of MSW incinerators, elevated concentrations of Cd, Pb, Zn and other heavy metals were observed, contributing to widespread contamination of soil and vegetation. This posed serious risks to human health and farm animals, jeopardizing agricultural sustainability.

The situation worsened with the widespread use of polyvinyl chloride (PVC), where Cd was a primary plastic additive. Waste incinerators faced several challenges: A rising influx of Cd-containing materials; a drop in flue gas pH due to hydrochloric acid (HCl) emissions from PVC degradation; and an increase in heavy metal volatility, as Cd and other metals formed chloride compounds, which were more prone to atmospheric dispersal. Due to the harmful effects of Cd emissions from waste incinerators, new air pollution regulations were introduced, mandating stricter controls to significantly reduce concentrations of Cd, Pb, Hg and others in off-gas emissions.

During the 1970s, Cd pollution was a critical environmental issue, with approximately 2 g/c·yr being released into the atmosphere and soils. This led to extensive soil contamination. The adoption of advanced APC technologies, such as electrostatic precipitators (ESP), bag filters, alkaline scrubbing, and DENOX systems, has since resulted in a dramatic reduction in Cd emissions. Today, state-of-the-art WtE plants emit only 1,5 mg/c·yr Cd. For a city with one million inhabitants, advanced APC devices translate to a thousandfold decrease - from about 2 tons of Cd emissions per year to under 1.5 kg annually.

Figuring out what constitutes a "sustainable" level of Cd emissions in clean flue gas poses significant challenges. A simplified approach, outlined in Table 3, assumes that urban areas are surrounded by similar regions and that atmospheric Cd import from neighboring cities balances with export to adjacent areas. This equilibrium assumption becomes plausible when considering the continuous growth of urban populations and centers, especially over a long period of 1,000 years.

Within this conceptual framework, Cd emitted by an urban system would theoretically be rained out and deposited within city boundaries. The Cd "lost" to neighboring areas would equal the Cd "gained" from them, contingent on neighboring cities showing a comparable urban metabolism. This approach offers a simplified yet effective means of assessing cadmium flows within urban ecosystems.

In Table 3, four different transfer coefficients (TCs) for cadmium (Cd) are linked to the corresponding Cd emissions and flows into soils over a 1,000-year period. With a TC of 0.1, 10% of the incoming Cd in MSW is transferred to clean flue gas; at a TC of 0.0001, this reduces to just 0.01%. This corresponds to 0.2 mg and 0.0002 mg of Cd per Nm^3 of clean flue gas, respectively. If this flue gas is deposited and dispersed across the 200 km^2 urban settlement area, approximately 1 mg of Cd would accumulate in 1000 years per m^2 of soil.

"Sustainable" emissions must preserve soil functions over extended times. This is particularly relevant for Cd, as it has low mobility in soil and tends to accumulate. The critical question is whether anthropogenic inputs significantly alter geogenic concentrations.

According to Table 3, over a millennium, a WtE plant working with a TC of 0.0001 would add approximately 1 mg of Cd per m² of urban soil, assuming the city is surrounded by other urban areas with similar Cd emissions. This contribution amounts to less than 1% of the existing Cd stock in soil. Therefore, it can be concluded that such a minor increase stays within natural ranges, preserving soil properties and functions over very long time periods.

Table 3. Cd flow analysis of WtE in a city of 1 million population and 200 km^2 settlement area: Cd emissions for different APC technologies (transfer coefficients TC from 0.1 to 0.0001) and corresponding environmental soil loadings (between 1000 and 1 mg/m^2 per 1000 years) show, that environmentally sound WtE is possible. TC of 0.1 means that 10 % of Cd in MSW input is transferred to gas. Modern WtE has TCs for Cd of ~0.0005.

WtE transfer coefficient TC to flue gas for Cd	Cd emission in flue gas to atmosphere	Cd flows to soil in 1000 years
	mg/Nm^3	mg/m^2
0.1	0.2	1000
0.01	0.02	100
0.001	0.002	10
0.0001	0.0002	1
Cd stock in natural soils: ~ 130 mg/m^3		

Modern APC technologies, with TCs for Cd ranging from 0.001 to 0.0001, meet these sustainability criteria. However, this assessment is only valid for WtE plants adhering to the highest APC standards and subject to independent regulation and rigorous emissions monitoring.

The results presented in Table 2 and Figure 3 have applications not only for environmental protection but also for resource management. From a mass perspective, the primary solid product of incineration is bottom ash, amounting to 250–300 kg per 1,000 kg of MSW. This bottom ash holds 4 mg of cadmium (Cd) per kg, making Cd 20 times more abundant in bottom ash compared to traditional geogenic construction materials. If bottom ash is used as a substitute for geogenic materials, careful monitoring of heavy metal accumulation is essential. To ensure best and environmentally friendly use, it may be helpful to optimize incinerator technologies to minimize metal content in bottom ash (Mehr et al., 2021).

Given the high volatility of Cd, its concentrations in APC residues from WtE plants are even higher, reaching around 500 mg/kg. These residues are comparable in Cd content to electric arc furnace filter dust (500–1,000 mg Cd/kg), which is commonly recycled today. Consequently, the filter residues from WtE plants exhibit significant recycling potential, which has only recently gained attention. Using the urban metabolism framework, this recycling potential can be evaluated over long timeframes, providing insights into stock accumulation and future resource availability. Metals such as Cd or zinc (Zn) from WtE filter residues can feasibly be recycled, offering a sustainable approach to resource management.

In the 1970s, MSW was often used to produce compost for application on agricultural fields, vineyards, and other lands to enhance fertilization and soil quality. However, simple balance calculations demonstrate that applying materials like MSW, containing 10–12 mg Cd/kg, can pollute soils with initial Cd concentrations of 0.2 mg Cd/kg within relatively short timeframes (decades), leading to hazardous conditions for agricultural production. Today, modern practices focus on separately collecting “clean” residues from activities aimed at nourishing, to create soil amendments that remain beneficial even over prolonged use. Comprehensive Cd balances for the entire urban system highlight sources, pathways, and sinks of this metal, enabling early detection of hotspots and timely intervention.

The holistic urban metabolism framework offers a reliable approach for tracking materials and substances, relying on the principle of balance: what enters a process must eventually exit. Therefore, it must address residues as a critical aspect. When goods from PHH are collected and processed via WtE, composting, or recycling, some fractions inevitably remain unrecyclable due to contamination. These residues do not “disappear.” In fact, the more separation, incineration, and recycling efforts are undertaken, the more visible these side products become. Waste management systems must therefore ensure the provision of safe final sinks for such contaminated residues. In our case study, for instance, approximately 10 metric tons of Cd that are not recycled must be securely disposed of for extended periods in designated "final sinks."

The concept of final sinks is well-established for substances such as fossil carbon and its resulting CO_2 (linked to climate change), chlorofluorocarbons (associated with ozone depletion), and a few others. However, this issue deserves broader attention as it applies universally to all substances within the anthroposphere: ultimately, all substances require a final sink. MFA proves to be a valuable tool for illustrating the necessity of final sinks, as highlighted by Kral, Vyzinkarova, and Brunner (2015).

Currently, the need for sinks within the context of urban metabolism has primarily been acknowledged for bulk waste materials. Even modern cities necessitate landfills for the disposal of non-recyclable goods. However, it has yet to be adequately addressed at the more critical level of specific substances. To facilitate a zero-waste society, all toxic legacy substances must be transformed in something harmless or stored in a safe final sink "forever".

4. Conclusion

Throughout cultural evolution, agricultural settlements transformed into urban centers with intricate infrastructures interlinking people, materials, energy, and information. This "anthroposphere" is embedded within and exchanges resources with the environment. "Urban metabolism," a subset of this anthropogenic system, encompasses the flow of materials and energy driven by four basic human activities: to nourish, to clean, to reside and work, and to communicate and transport. While fundamental human needs such as food, shelter, communication, and health have remained relatively constant over time, the means have continuously evolved due to cultural, technological, economic, and resource-driven changes.

Over the past 150 years, urban areas have undergone rapid development. Most people now live in cities due to urbanization, leading to growth in population density, resource use, and information flow. Concurrently, material stocks in cities have grown, representing valuable future resources. The environmental burdens associated with this growth, particularly during the 19th and 20th centuries, have since been addressed, with a strong focus on fossil carbon emissions and climate change. Looking ahead, emerging technologies such as artificial intelligence, renewable energy, robotics, the circular economy, and social engineering may once again revolutionize urban metabolism in unprecedented ways.

This paper presents two case studies focusing on two critical aspects: (1) the economic level of goods and (2) the substance level, which determines the value of goods. Substances can affect a good's value positively or negatively. For example, cadmium (Cd) diluted within the urban system can cause severe environmental and health problems, whereas concentrated Cd can be economically recovered as a valuable resource.

The combination of these levels is crucial for success. While economic accounting tables provide abundant data about goods, substance data is scarce. Linking information about goods and substances through process balances is essential for efficient data acquisition. Urban metabolism research must therefore involve experts from disciplines such as economic theory and practice, product analysis and safety, and environmental science. Currently, only a few research groups approach urban metabolism comprehensively.

In the future, attention to urban metabolism will be imperative as it offers opportunities to enhance urban economies. Early recognition of challenges, like the buildup of valuable or hazardous stocks, enables proactive decisions. The combination of MFA and SFA allows issues to be identified early, avoiding delays in addressing problems like pollutant accumulation in soils. Without modeling, valuable accumulations of metals and substances in urban stocks remain unnoticed and unexploited.

Modeling flows and stocks of materials, substances, and energy is a first step to optimize a city's metabolism. Material transformations require energy, presenting synergies in large cities, particularly in recycling and waste management (Brunner, 2011). Urban mining can recover raw materials from recyclable stocks on a large scale. Integrating metal recycling facilities with waste energy utilization - such as using this energy for heating, cooling, or powering the city - is a promising approach to improve sustainability. The MFA/SFA approach is highly instrumental for assessing the effects of new products or technologies on urban metabolism. The introduction of new means to fulfil human needs such as a change towards vegetarian diet or electric cars will have a substantial impact on urban metabolism. MFA/SFA are strong analytical tools to assess such impacts on resources and environment.

Although urban metabolism has great potential, it is not widely used yet. This is due to limited data, the complexity of creating full models, and a lack of experts who can simplify city systems into clear flows and stocks. Building detailed models of material and substance movement in cities is still difficult. Adding social and economic data to these models is also important to support policy and sustainability planning. The real value of these models is in showing resource limits and environmental risks early. As cities grow and resource use increases, research in urban metabolism is more important than ever. Achieving future urban sustainability will depend on researchers who are ready to explore this complex field and create real solutions.

Author Contribution Statement

P.H. Brunner conceptualized and wrote the paper, reviewed the literature, and was responsible for the work that resulted in the MFA/SFA methodology and data used for this study.

Data Availability Statement

The data used for this paper has been taken from (Brunner & Rechberger, 2017) and (Baccini & Brunner, 2012).

Declaration of Competing Interest

The author declares no conflict of interest.

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