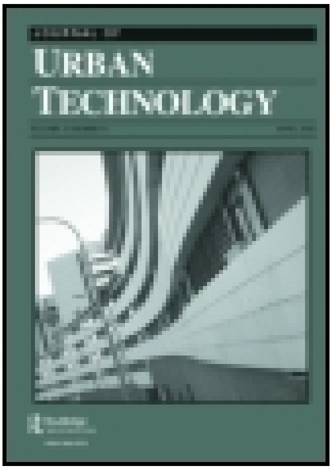

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Smart Urban Metabolism: Towards a Real-Time Understanding of the Energy and Material Flows of a City and Its Citizens

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ABSTRACT *Urban metabolism is a concept employed to understand the flow of energy and materials through urban areas. However, applying this approach at the city level has been limited by the lack of data at this scale. This paper reviews the current application of the urban metabolism concept and proposes the concept of a "smart urban metabolism" (SUM). Through integrating ICT and smart-city technologies, the SUM model can provide real-time feedback on energy and material flows, from the level of the household to the urban district. This is highlighted through an example of its application in the Stockholm Royal Seaport, Sweden.*

KEYWORDS *smart cities; ICT; real-time; urban metabolism; material flow analysis*

Introduction

In Europe, approximately 75 percent of the population lives in urban areas and this is forecast to increase to between 80 to 90 percent by 2020 (European Environment Agency, 2006). Furthermore, it is estimated that more than one-quarter of the territory of the European Union has now been directly affected by urban land use (European Environment Agency, 2006). These factors, coupled with the concentration of economic activities, high-intensity resource use, and massive deployment of fossil energy for human activities (Pincetl et al., 2012), suggest that cities have a major effect on the global environmental (Bai, 2007).

The need to place cities and urban development on the global sustainability agenda has been recognized by industry, governmental bodies, and environmentalists (Newman, 1999). A sustainable city has been defined as "an urban region for which the inflows of materials and energy and the disposal of wastes do not exceed the capacity of its hinterlands" (Kennedy et al., 2007: 44). In this context, cities have a significant role to play in reducing socioeconomic energy and material flows (Weisz and Steinberger, 2010). The urban metabolism concept has been suggested as fundamental to the development of sustainable cities (Niza et al., 2009; Kennedy et al., 2011). Through a holistic analysis of energy and material pathways, the urban metabolism concept allows one to "begin to conceive of management systems and technologies which allow for the reintegration

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of natural processes, increasing the efficiency of resource use, the recycling of wastes as valuable materials and the conservation of (and even production of) energy" (Newman, 1999: 220). However, as Baccini (1997) suggests, the transformation to a sustainable urban system may take up to two generations due to the slow changes in building and transportation networks.

At the same time as the urban metabolism concept is being called upon to contribute to sustainable urban development, the use of information and communication technologies (ICT) has become ubiquitous when envisioning the future of urban development. Hilty et al. (2011) have suggested that ICT can play a significant role in the service of sustainability by fostering "a transition to a less material-intensive economy" (Hilty, 2008: 153). The increasing use of ICT in cities has laid the infrastructure for the development of "smart cities." Komninos et al. (2012: 120) suggest that smart cities are places that generate "a particular form of spatial intelligence and innovation, based on sensors, embedded devices, large data sets, and real-time information and response." They are urban areas where data science and information-driven technologies are applied to areas, such as urban planning and infrastructure systems,[1] to more effectively coordinate socio-technical interactions. In terms of sustainability, the development of ICT-systems create many possibilities for urban-based technological innovation with a potential to reduce the negative environmental effects of consumption and production.

Recently, there has been increasing attention paid to the ability of ICT to better integrate into planning the information derived from tools used to measure the energy and material flows of cities (Chrysoulakis et al., 2009). Real-time monitoring, analysis, optimization, and visualization of energy and material flows in cities may allow urban planners to obtain new insights into the flow of energy and material in cities. Furthermore, the provision of this information to citizens through pervasive ICT technologies has the potential to influence pro-environmental behavioral change (Zapico et al., 2009).

Aims and Objectives

This paper addresses two questions that arise at the intersection of urban metabolism and smart-city research. First, how can the smart-city concept aid in measuring and influencing the energy and material flows of cities? Second, what are the potential benefits of integrating ICT, smart-city technologies, and urban metabolism tools?

The aim of this paper is to illustrate how the smart-city concept can be used to increase the utility of the urban metabolism concept as an element in the transition to sustainable urban development. It proposes the concept of a "smart urban metabolism" (SUM), which stems from the premise that by using ICT solutions to collect, analyze, and provide feedback on the flows of materials and energy caused by the actions of planners, industries, and citizens, in real time, it may be possible to optimize the energy and material flows of a city through more informed decisions. Furthermore, as part of this optimization, ICT may be able to offer a range of actions and automations on behalf of municipalities, industry, and citizens that could lead to more sustainable energy and material flows. In the following section, we provide an overview of the urban metabolism concept. The next section describes the SUM concept, highlighting its key features such as real-time high resolution data, continuous real-time analytics, and real-time feedback. This is illustrated by an example of the current implementation of the SUM concept in the development of the Stockholm Royal Seaport. Finally, the SUM concept is discussed in relation to its potential benefits and limitations.

Urban Metabolism: Approaches, Applications, and Limitations

The literature on urban metabolism represents the interests of a range of disciplines, including industrial ecology, urban ecology, ecological economics, political economy, and political ecology (Broto et al., 2012). As we endeavor to illustrate how the smart-city concept and ICT can be used to help measure and reduce the energy and material flows of a city, this paper views urban metabolism from an industrial ecologist's perspective.

The term "urban metabolism" has been labeled as a concept (Codoban and Kennedy, 2008; Minx et al., 2010; Kennedy et al., 2011) and a tool (Sahely et al., 2003; Keirstead and Sivakumar, 2012; Pincetl et al., 2012), and as a representative term for quantitative accounts of the overall inputs and outputs of energy, materials, and substances (such as water, nutrients, and pollutants) into and out of cities (Weisz and Steinberger, 2010).

Urban metabolism research "involves conceptualizing a city . . . as an organism and tracking resources that go into the system and products and wastes that leave it" (Bai, 2007: 1), providing a platform through which to consider sustainability implications (Pincetl et al., 2012). Urban metabolism is the stocks and flows of energy and materials in cities and their relationship with urban infrastructure (Kennedy et al., 2012), and has been defined as "the total sum of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al., 2007: 44).

Historical Development

Wolman's (1965) study *The Metabolism of Cities* was the first explicit application of the concept of metabolism to the city, modeling the metabolism of a hypothetical American city of one million people (Broto et al., 2012). The study showed that a city's impact on the environment went beyond its defined geographical or political boundaries; highlighting the regional and global scales of its environmental impact (Pincetl et al., 2012). Although there were several studies after Wolman,[2] the popularity of using the urban metabolism concept to assess questions concerning the flow of energy and materials waned during the 1970s and 1980s (Kennedy et al., 2011; Rapoport, 2011). During the late 1990s a resurgence of urban metabolism research was experienced, continuing to today (Kennedy et al., 2011). Review studies by Kennedy et al. (2007, 2011) and Holmes and Pincetl (2012) highlight the application of urban metabolism research in a number of major cities around the world.

More recently, ICT has been highlighted as a potential contribution to the future of urban metabolism research. Chrysoulakis et al. (2009) have demonstrated the combination of ICT and natural science methods (such as micrometeorological site studies, remote sensing measurements, and numerical modeling approaches) to provide quantitative measurements of flows (energy, water, carbon, and pollutants), and estimate their environmental and socioeconomic impacts and benefits.

Approaches: Production, Consumption, and Hybrid-Based Approaches

Several complementary approaches to understanding the flows of energy and materials through cities can be identified in the literature (Weisz and Steinberger, 2010; Kennedy and Sgouridis, 2011; Ramaswami et al., 2011; Baynes and Wiedmann, 2012) and are outlined below.

Production-Based Approaches

Production based approaches account for the energy, materials, and emissions produced within a city's boundaries, highlighting the importance of the economic and industrial activities within a city's boundaries (Weisz and Steinberger, 2010). Material flow analysis (MFA) is a tool used to analyze the stocks and flows of materials within a defined system. The strength of MFA is its application of the principle of mass-balance, which allows for the identification of hidden material stocks and flows accumulations (Kennedy and Sgouridis, 2011). These studies typically analyze the stocks and flows of specific substances (such as lead, copper, or phosphorus), or analyze important products and materials (Niza et al., 2009). However, such studies "do not explain the complete systems of material flows within a region or city" (Niza et al., 2009: 338).

Regarding energy flows, the direct energy production and consumption across all sectors of a defined territory can be determined by using top-down energy accounts (direct energy for all production sectors and the residential sector) (Baynes et al., 2011), or by using downscaled input-output (I-O) tables which can be used to identify the extent to which local businesses serve local households (Ramaswami et al., 2012).

Consumption-Based Approaches

Consumption based approaches account for the direct resource use of households and the indirect (upstream) resource use resulting from the purchase of goods and services consumed within a city (Weisz and Steinberger, 2010). This approach highlights the impact of a citizen's lifestyle patterns and behavior.

Consumption-based approaches typically use environmentally-extended I-O tables that are combined with expenditure/consumer surveys, allowing for the allocation of industrial energy use to goods and services categories and subcategories which have been purchased by the household (Weisz and Steinberger, 2010; Baynes and Wiedmann, 2012). This can be done for an "average" consumer at the national level, or divided into income brackets at the national level. Smaller survey samples can be made at the regional level to provide regional variation (Heinonen and Junnila, 2011). This follows the principle that "the total of a household's direct and indirect consumption includes the energy and materials used across all sectors in the production chain that supply the final demand" (Baynes and Wiedmann, 2012: 460).

Hybrid Approaches

Hybrid approaches have emerged that attempt to include both production and consumption perspectives. They utilize approaches such as: I-O analysis for "high-order" upstream phases, process life cycle assessment (LCA)[3] for direct emissions and important upstream phases to account for the carbon footprint of metropolitan consumers (Heinonen and Junnila, 2011), and MFA and life-cycle accounting for estimating the greenhouse gas (GHG) emissions including both direct energy consumption and indirect emissions in food, water, fuel, and concrete for a city (Ramaswami et al., 2008).

Applications in Urban Planning and Design

The majority of urban metabolism studies have been accounting exercises, used to provide indicators for assessing aspects of urban sustainability and to quantify GHG emissions of cities, such as measures of energy consumption, and material and waste flows (Kennedy et al., 2011). More recently, the urban metabolism concept has been applied in the context of sustainable urban planning and design, and policy analysis. Kennedy et al. (2011) have categorized these applications into four main areas:

- *Sustainability Indicators:* Urban metabolism studies are an important aspect in state-of-the-environment reporting, providing information pertaining to energy efficiency, material cycling, waste management, and infrastructure to assess a city's sustainability (Kennedy et al., 2011: 1968)
- *Quantification of GHG Emissions*: Urban metabolism studies provide a valuable input to the quantification of a city's GHG emissions, which is useful when cities aim to reduce their GHG emissions (Kennedy et al., 2011:1968–1970)
- *Mathematical Models for Policy Analysis:* Kennedy et al. (2011:1970) highlights that mathematical models, developed by the MFA community, have been developed for processes within the urban metabolism of a city, such as the stocks and flows of specific metals or nutrients at the urban or regional scale
- *Urban Design:* Urban metabolism studies have been used in an urban design context to redesign the flows of water, energy, materials, and nutrients through cities (Pincetl et al., 2012), using methods such as green building design, and sustainable transportation and energy systems (Kennedy et al., 2011: 1970).

Limitations in Conducting Urban Metabolism Studies

Lack of Data at the City Scale

It is generally acknowledged that there is a lack of data on energy and material flows at the urban/city level (Kennedy et al., 2007; Weisz and Steinberger, 2010; Broto et al., 2012). This lack of data is an issue for both production- and consumption-based approaches.

Baynes and Wiedmann (2012) suggest that the aim of the production-based approach is to characterize the city from actual data that represents local production and consumption, as opposed to assuming national or regional characteristics. However, the authors also note that this is restrictive due to the availability or scarcity of direct data sources and that leads to the use of top-down scaling and estimations (Baynes and Wiedmann, 2012). Traditionally, MFA has been predominantly applied at the national scale in the accounting of resource flows (Kennedy et al., 2007; Broto et al., 2012). Periodically available and harmonized datasets provided by statistical institutes are almost exclusively at the national level (Weisz and Steinberger, 2010). Kennedy et al. (2007: 57) suggest that "such practices may arguably be too broad and miss understanding of the urban driving processes." The application of MFA to cities has been limited by the lack of data at the city level (Kennedy et al., 2007; Ngo and Pataki, 2008; Minx et al., 2010). Hence, its application to cities has been labeled as "very new" (Hodson et al., 2012: 791). Although there is a need for basic empirical information on the physical and environmental characteristics at the municipal scale, there have been few comprehensive urban metabolism studies at this scale (Ngo and Pataki, 2008).

Baynes and Wiedmann (2012) suggest that in urban applications, the consumption approach only delivers an approximate representation of local economic structure and function. There is a loss of local specificity due to the lack of visibility of local businesses which serve visitors, local businesses which produce goods for export, and the information is lost on local improvements in production to serve local consumption, being replaced by the average production of the global economy (Ramaswami et al., 2012). Furthermore, since the environmentally extended input-output tables are based on monetary units (as opposed to physical units), models that use national input-output data do not reflect the price differences that exist between cities in the same country (Sugar et al., 2012).

High Data and Resource Requirements of Urban Metabolism Studies

Notwithstanding the lack of data at the city level, undertaking urban metabolism studies entails very high data requirements due to the systems approach of the urban metabolism concept (Minx et al., 2010). There is a requirement for completeness in the description of metabolic flows needed to detect environmental problem shifting associated with policies, and a need for global system boundaries and consumption-based accounting due to the globalization of production and consumption chains (Minx et al., 2010). The consequence of such an undertaking is a significant time and resource burden when conducting urban metabolism studies.

Analysis of the Evolution of a City's Urban Metabolism

Due to the significant amount of data required to conduct an urban metabolism study, follow-up studies are seldom conducted. Yet follow-up studies are required to understand how the urban metabolism of a city has evolved over time. Kennedy et al. (2007) have highlighted the few studies that show how the urban metabolism of cities have evolved. For instance, Warren-Rhodes and Koeing's (2001) update of Newcombe et al. (1978) of Hong Kong between 1971 and 1997; Newman's (1999) study of the change in per capita energy and material flows in Sydney between 1970 and 1990; and the study of Toronto's urban metabolism between 1987 and 1999 by Sahely et al. (2003).

Difficulties in Identifying Cause and Effect Relationships

The long period between urban metabolism studies of the same city means there is a lack of analyses of the causes that change the energy and material flows of a city. Indeed, there has been little attention paid to the socioeconomic and political driving forces of energy and material flows and the function of an urban system and its environmental performance (Chrysoulakis et al., 2009; Broto et al., 2012). There is a need to consider and understand the agents involved in materials flows, to question their management methods, and to consider the economic and social consequences of these flows (Barles, 2010). Furthermore, there is a need to know how urban metabolisms change in the short and long-term as a result of changing policy instruments and planning decisions.

The Potential Contribution of the Smart City Concept to Urban Metabolism Studies

The aforementioned limitations of urban metabolism studies are all related, in some way, to the collection and analysis of data. ICT has the potential to contribute to addressing these limitations, especially when the application of ICT is envisaged within the smart-city framework.

Caragliu et al. (2011: 70) suggest that a city is smart "when investments in human and social capital and traditional (transport) and modern (ICT) communication infrastructure fuel sustainable economic growth and a high quality of life, with a wise management of natural resources, through participatory governance." One significant component of smart cities is the "utilization of networked infrastructure to improve economic and political efficiency and enable social, cultural, and urban development" (Hollands, 2008: 308). "Infrastructure" refers to the ICT component (mobile phones, computer networks, Internet services, etc.) and the business, housing, leisure, and lifestyle services in which they are used (Caragliu et al., 2011). Technologies commonly used in smart cities include smart meters, sensor networks, automated control systems, and cyber-physical systems.

The co-development of ICT and infrastructure systems has led to the development of solutions to improve the environmental sustainability of cities such as smart grids, smart district heating and cooling, smart logistics, smart buildings, intelligent transportation systems, and smart industrial symbiosis. ICT can allow for radical increases in the volume, speed, and complexity of processing information (Zapico, 2014), and enabled solutions often contribute to strategies for decoupling environmental impact from economic growth, often achieved through the increase in efficiency provided by ICT (Hilty et al., 2011).

The integration of ICT in cities, such as sensor networks, real-time heterogeneous data-sources, and real-time analytics creates the possibilities of obtaining a better understanding of energy and material flows in urban environments. This can have several effects; the automation of data collection and analysis, the customization of targeted feedback, and the potential for this information to be used in smart infrastructure systems to augment energy and material flows to achieve a city's environmental objectives.

Additionally, approaches such as sustainable interaction design or sustainable human compute interaction (HCI)[4] (DiSalvo et al., 2010), eco-visualization[5] (Holmes, 2007), and augmented reality[6] (Azuma et al., 2001) can be used to convey to various stakeholders (planners, local utilities and building owners, and households) the most relevant information required to fulfill their objectives. For instance, pervasive technologies (Fogg, 2002), such as computers and smart phones, can be used to provide trigger features to help citizens change attitudes and behaviors to make them more efficient (Zapico et al., 2009). Climate pervasive services, such as ICT applications, can assist in changing personal attitudes regarding climate change and/or change behavior towards reducing GHG emissions (Zapico et al., 2009). Presenting the results of urban metabolism studies on the environmental impact of household consumption to the households themselves highlights a proactive approach to reducing the energy and materials flows through a city.

The Concept of a Smart Urban Metabolism

The aim of the SUM concept is to provide knowledge on energy and material flows *as close as possible to reality* by collecting and analyzing real-time user generated data sources. The SUM concept can be classified as a hybrid approach as it attempts to include both production and consumption perspectives. ICT infrastructure is used to collect data on energy and material flows from utilities, and sensors and smart meters installed in households, businesses, and public spaces. These data streams are collected in an information management system and analyzed by a real-time calculation engine which can provide feedback related to sustainability indicators set by the city, building owners, and citizens themselves.

Accordingly, the SUM concept advances the conventional urban metabolism concept and uses ICT and smart-city technologies to derive a real-time dynamic understanding of urban energy and material flows. This may provide planners, organizations, and citizens with a better basis for decision-making through an increased awareness of their system consequences. Furthermore, it has the potential to enable the automation of relevant decisions and the optimization of the metabolism of a city. Its key features are:

- it is based on the integration of high quality, siloed, heterogeneous data streams in urban environments
- it processes these flows in a real-time calculation engine to provide real-time data on energy consumption, GHG emissions, water consumption, material consumption, and waste production
- it continuously illustrates these flows to city officials, organizations, and citizens through feedback tailored to each stakeholder level.

Real-Time, High Resolution Data

The SUM concept attempts to improve data quality, both with regards to *resolution* (from city level down to citizen level data) and *frequency* (from monthly data up to real-time data), and to reduce the number of assumptions and simplifications required when using statistical data. This requires an information management system (IMS) to store and manage data on the flows of energy and materials at varied spatial resolutions. Flow data is collected on the lowest level possible, starting at households, then aggregated to the building level and finally to the district level (See Figure 1). These flows, detailed in Table 1, include:

- local flows of energy and materials related to electricity consumption, heating and cooling consumption, water consumption, transport (private, public, and freight), fuel consumption, waste generation, goods and services consumed, on-side energy production, and materials consumed in construction and maintenance
- regional flows of energy and materials related to energy production (electricity and heat), water treatment and distribution, and waste management
- global flows of energy and materials related to resource extraction, goods manufacture, food production, and transport (flights and goods shipping).

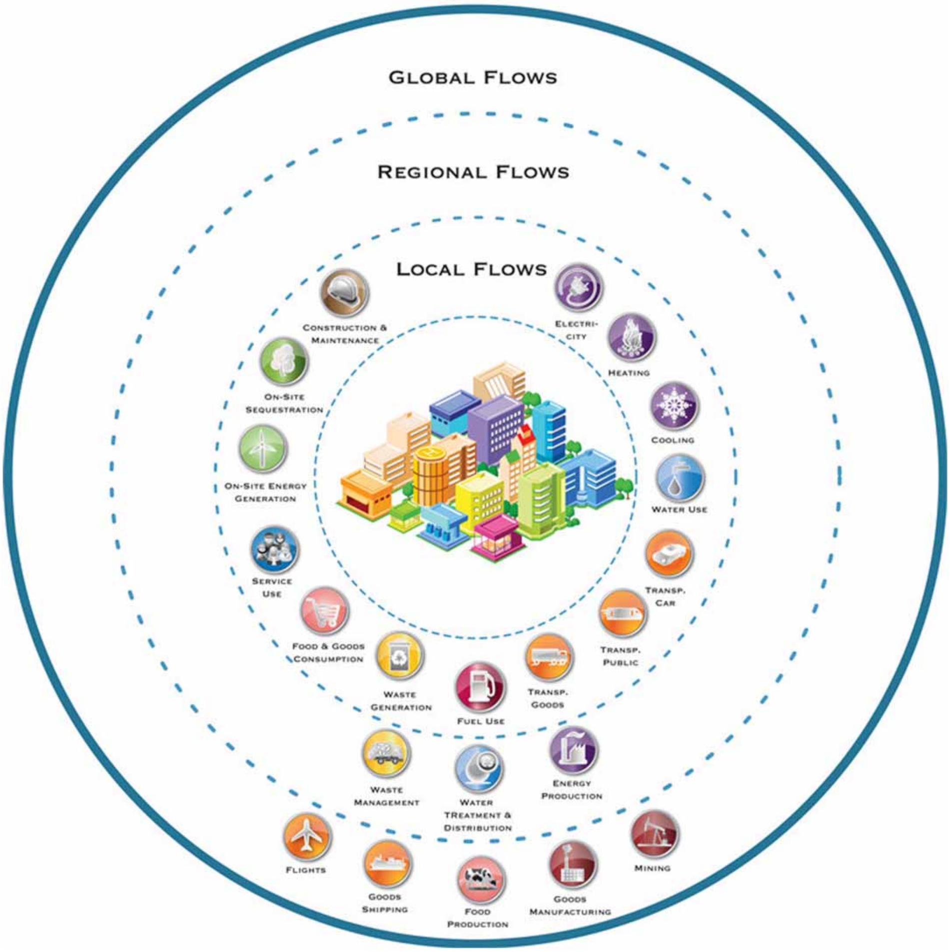

Figure 1: Smart Urban Metabolism data flows (adapted from Shahrokni and Brandt, 2013).

There are several smart-city technologies able to supply user-generated data of these flows. Utilities have the ability to collect a significant amount of information as part of their business activities through implementation of smart grids and smart metering technologies, such as two-way automated metering infrastructure (AMI). The data provided by these meters is commonly referred to as siloed data, as the utilities that collect this data retain them in in-house "siloes." At the household level, AMI technologies can provide instantaneous individual and aggregated information on electricity, heat, water, and waste flows. These technologies can be used to impose caps on consumption and also enact various revenue models at the request of the consumer to control costs. AMIs can also provide information for the flows of residential buildings and of public spaces in urban districts. In addition to conventional flow meters, some information can be obtained from data mining invoices. For example, at the regional level, material flows in the construction and maintenance sector can be mined, primarily, from invoices on material purchases (Brunge, 2013).

Table 1: Possible data sources for developing a smart urban metabolism

Flow		Data Points	Data Owners
Local Flows	Electricity, Heating Cooling, Water Use, On/Site Generation	Billing Meters, Submeters	Energy Utility, Building Owner, Homeowner
	Transportation—Car, Public, Goods, Fuel Use	GPS, GSM, Road Tolls, Vehicle Registrations, Taxi Logistics, 3rd Party Apps, Surveys, Public Transit Logistics System, Traveler Card Swipes, Package Tracking Numbers, Road Tolls, Billing Systems	Car owner, Telco's, Transportation Authority, Taxi Companies, App Developer, Statistics Bureaus, Package Tracking Numbers, Road Tolls, Gasoline Station Billing Records
	Waste Generation	Weight of waste fractions, Weight of organic waste	Municipality, Waste Management Companies Customers (Homeowners, Building Owners)
	Food & Goods Consumption, Service Use	Credit Card Statements, e-Bills, Digitized Receipts, Sales Statistics, Economic Input-Output LCA	Citizens (Card owners), Finance institutions, Shops, Scientific Journals
	On-Site Carbon Sequestration	Municipal Tree Inventory, Carbon Sequestration Volume	Municipality, Energy Utility
	Construction & Maintenance	Construction Materials Purchased, Re-Used, Recycled Content, Shipping Distance, Fuel Use for Construction	Construction Developer, Sub-Contractors, Logistic Centers
	Energy Production	Public Electricity Use (E.g. Parks), Public Transportation Electricity Use, EV Charging Electricity & Location, Electricity Generation Fuel Mix, Grid Failures, Peak Load Reduction, Local Heat/Cooling Production to the Grid	Energy Utility
	Water Treatment & Distribution	Water Use by Building and Neighborhood, Sewer Water Generation, Sludge Water to Biogas Generation, Water Treatment and Distribution Electricity, Water Quality and Nutrients in Treated Water, Heat Recovery from Sewer Water	Water Utility
	Waste Management	Waste Management Transportation.	Waste Management Companies, Municipality, Refurbishing and Second Hand Organizations
		Recycling Rates of Waste, Weight of Waste Fractions, Waste Stream Assessment,	
Global Flows	Mining, Goods Manufacturing, Food Production, Goods Shipping	LCA Databases	Open Data and LCA Databases
		Economic Input-Output Databases	
	Flights	Airport Flight Data (Real-Time), Airline Carbon Disclosures, Company Travel Expenditures, Resident Travel Expenses	Public Data, Airports, Airlines, Local Companies and residents

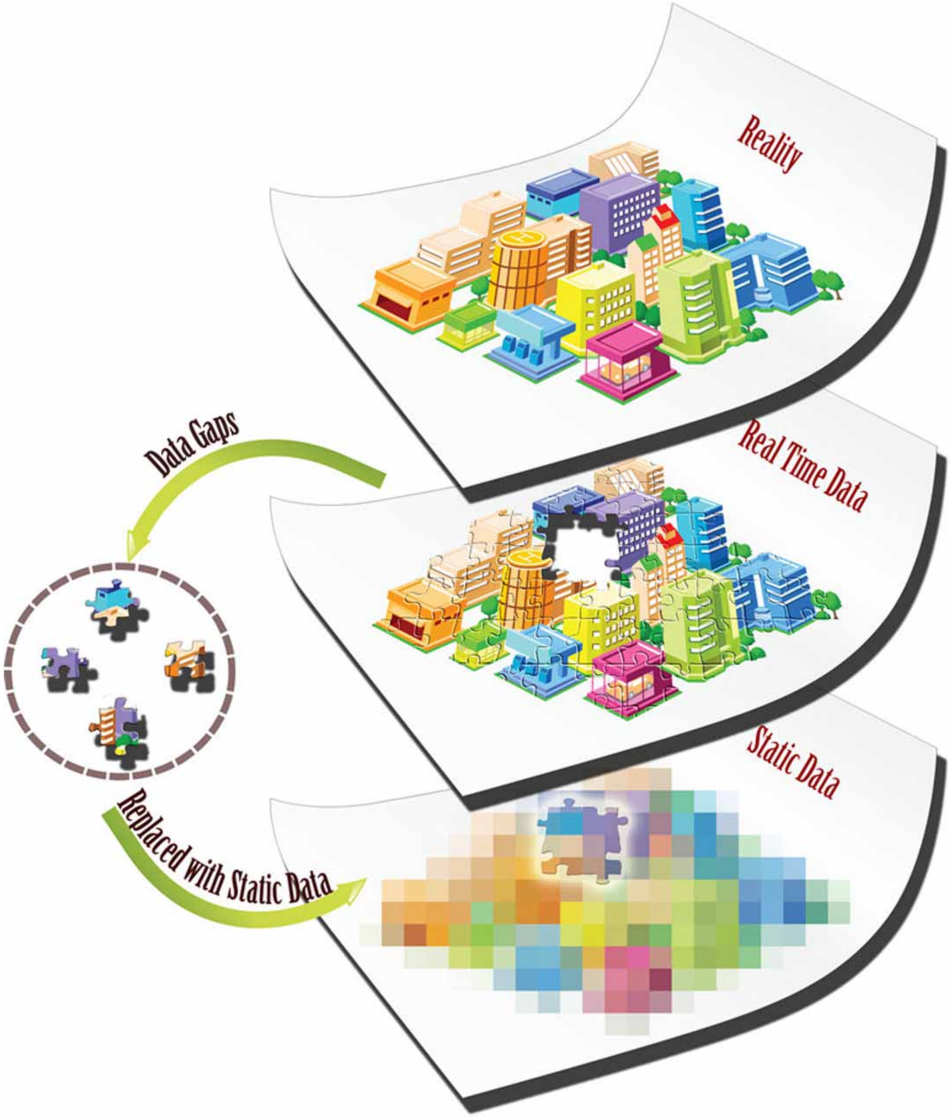

Figure 2: Solving the problem of data gaps through the prioritization of data layers.

Sensors provide a notification of an observed event and describe the event according to a suitable ontology (Filipponi et al., 2010). In-house sensors can provide data on energy and water-using appliances. Flow data at this resolution can be used to provide a basis for understanding how energy and material flows are influenced by user behavior. Sensors can also be integrated into buildings, public spaces, and infrastructure systems such as energy (electricity and heat), water and waste management systems, and public and private transportation systems.

The key data parameters required to determine the real-time urban metabolism of a city include: measurement data (e.g., water volume, energy use), time signature (time signature of the measurement), and identification data (meter

ID linked to location and owner). To coordinate the flow of data, all key data owners (see Table 1) are required to agree to provide their data, according to specified standards, to the SUM IMS, which stores data from city departments, utilities (energy, water, waste), transportation agencies, construction developers, smart meters, and sensor in one location. One significant issue which must be addressed is obtaining this data from all the relevant stakeholders and the associated issue of privacy. These aspects are detailed in the discussion.

There are a number of reasons to expect numerous, and potentially significant, data gaps such as an absence of a well-established sensor or AMI network, if residents opt out of providing data due to privacy concerns, or sensor/meter malfunction. One solution to filling these data gaps is to have a prioritization of data layers (See Figure 2). If high quality real-time data is not available, it can be substituted with estimated or statistical data.

Moving from vision to practice, there are a number of issues related to emission factors, system boundaries, data structure, ontology, heterogeneous data (data from varying types of sensors and meters), and multiple sensors tracking the same flow. These aspects are described in Shahrokni and Brandt (2013).

Continuous Real-Time Analytics, Feedback, and Interactivity

In contrast to conventional urban metabolism approaches, the SUM model combines data collection and integration into a single phase. Furthermore, data collection and integration phases required for follow-up studies continuously take place due to the real-time nature of the SUM model. A potential consequence is the reallocation of resources from data collection to analysis and policy development. Data is processed by a calculation engine, for instance described in Shahrokni and Brandt (2013) that continuously processes the data streams, and transforms them into key performance indicators (KPIs) tailored to several levels of feedback.

At the **city or urban district level**, the aim of applying SUM is to assist in urban planning and reduce the urban metabolism of an urban area. SUM can provide real-time feedback for sustainability indicators (such as energy use intensity targets, GHG emission targets, renewable energy targets, etc.), and identify the reasons why such targets are not being met. This information may aid planners in answering questions such as “Has the city/urban district achieved its sustainability targets, and if not, why not?” At the **building level**, the aim of applying SUM is to assist stakeholders, such as building owners and utility providers, to identify the energy and material flows within their control which have a significant environmental impact. This information can aid building owners to answer questions such as “Which part of my building portfolio causes the greatest environmental impact and should be retrofitted first?” At the **household level**, feedback regarding energy consumption, water consumption, GHG emissions, and waste production can be provided to individual households based on their activities. The aim of applying SUM at this level is to provide a visualization of environmental information through human-computer integration technologies, such as augmented reality, to promote awareness of the environmental consequences of one’s consumption and to promote pro-environmental behavioral change. This information may aid citizens in answering questions such as “What are the environmental consequences of taking the bus or car today?”

Insights from the correlation of trends, patterns, and the visualization of the system consequences of decisions, may lead to a more efficient and perhaps more sustainable metabolism through identifying areas which require actions from the city/urban district, organizations, and citizens. There also exist possibilities for the automation of infrastructure systems and household appliances to reduce the urban metabolism of a city. Furthermore, this also enables new insights of city dynamics by correlating this new spatial and temporal data between water, energy, waste, transportation, and other drivers. SUM can, therefore, overcome the aforementioned limitations of conventional urban metabolism approaches in understanding and evaluating the effects of local policies. The following section outlines one way to implement the SUM concept, through its application in a new urban development in Sweden; the Stockholm Royal Seaport (SRS).

Smart Urban Metabolism in Practice: The Stockholm Royal Seaport

This section describes the application of this concept in the SRS urban development in Sweden. The SUM concept is currently being applied as a research and development project called Smart City SRS, funded by the Swedish government grant agency VINNOVA and 18 partners representing city, industry, academia, and citizens. The project is applied in the first construction phase of the SRS, which includes 682 households, located in four blocks. Ten construction developers are involved in the construction which started in 2011, with move-in dates anticipated between 2012 and 2014. The prototype developed for the SRS is but one approach to the implementation of the SUM concept. The prototype employs a hybrid approach, with the real-time calculation engine being able to process production and consumption data (See Figure 3).

The current focus of the SRS prototype is to understand the GHG emissions resulting from the consumption of electricity, heat, water, and the production of waste in the SRS. Indeed, Björklund and Finnveden (2005) have suggested that energy use is often a good indicator of other environmental impacts. Furthermore, GHG emissions are associated with many of the flows in Figure 1. Since much of the data on energy flows has been collected, future research will be focused on developing real-time emission factors for other environmental impacts categories which can then be coupled with these flows.

From the production perspective, the system boundaries are the geographical boundaries of the SRS urban district. From a consumption perspective, the system boundaries are extended to include indirect GHG emissions which occur outside the SRS boundaries, either exported or attributed to the citizen's consumption.

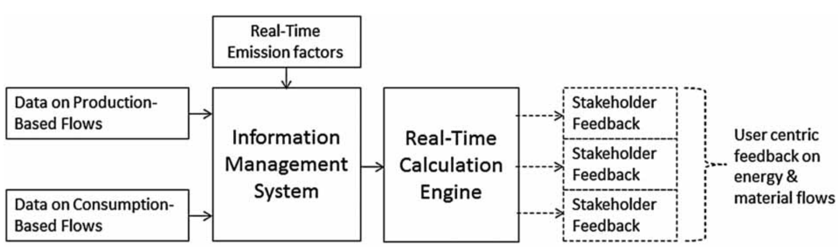

Figure 3: Data flows in the Stockholm Royal Seaport model.

However, the SRS currently does not collect or integrate consumption data. The implementation of the SUM concept has commenced in three phases: (1) obtaining data, (2) development of a calculation engine and data processing, and (3) development of feedback tailored to individual stakeholder requirements.

Data Collection and Integration

To narrow the scope for the pilot, real-time data (in varying frequency) has been collected for the following flows: electricity production and consumption, district heat production and consumption, water production (treatment, pumping, and distribution) and consumption, waste water production, household waste generation, bulky waste generation, waste management, and transportation. Most of these flows are collected at a household level, which can then be aggregated to the building and urban district levels.

In the SRS pilot, real-time siloed data (from smart meters) for electricity consumption, district heating, water use, and waste flows at the household level has been obtained from utility providers. Additionally, in-house sensors have been installed to generate data on electricity, potable water, and domestic hot water. Household waste sensors are being installed, that measure household waste weight by fraction through scales and radio-frequency identification tags. Furthermore, waste management companies specify a number of data points such as fraction, weight, address, time, and waste management facility. While integrating data streams may be perceived as a trivial task, substantial resources have been spent on developing a common communication framework for data integration, and there are still new challenges for each new data source. Where data gaps exist, statistical data has been used from previous studies on the district (See Johansson et al., 2013).

Calculation Engine

The focus in the SRS pilot has been to develop a platform for determining the real-time energy use and GHG emissions from electricity consumption, district heating, transportation, and waste management for the SRS. To this end, an IMS and calculation engine have been developed to collate and process all real-time flow data and calculate real-time GHG emissions.

In conventional GHG accounting exercises (see Kennedy and Sgouridis, 2011), GHG emissions have been based on average annual emission factors for each flow, i.e., fuel, electricity, heat. In the SRS pilot, data for electricity and district heating production are available at hourly and monthly frequencies, respectively. GHG emission factors for energy production technologies have been sourced from the life-cycle assessment database (See Gode et al., 2011). These emission factors have been coupled with hourly data on the electricity production and imports from the *Nord Pool* Nordic electricity grid (Swedish National Grid, 2012; Kristinsdóttir et al., 2013; Stoll et al., 2014). These real-time GHG emission factors are coupled with the real-time electricity flow for each household, and district heating flows for each building (then allocated to each household) to provide real-time GHG emissions for each household. Further research will develop real-time emission factors for other environmental impact categories, such as eutrophication and acidification potential.

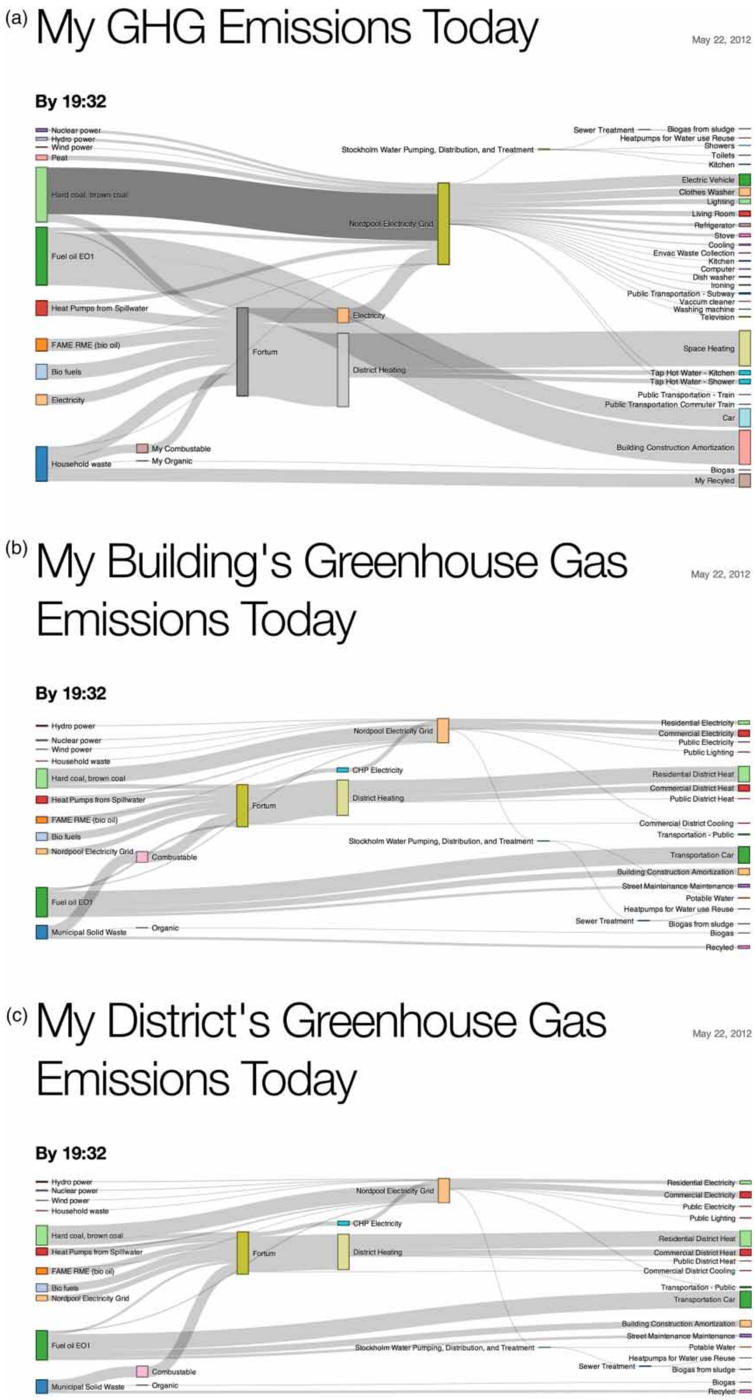

Figure 4: (a) Visualization of a household carbon metabolism at a given time through the use of Sankey diagrams. *Note: The figure illustrates cumulative GHG emissions from midnight until 19:32.* (b) Visualization of a building carbon metabolism at a given time through the use of Sankey diagrams. *Note: The figure illustrates cumulative GHG emissions from midnight until 19:32.* (c): Visualization of the district's carbon metabolism at a given time through the use of Sankey diagrams. *Note: The figure illustrates cumulative GHG emissions from midnight until 19:32.*

Feedback

Indicators developed in the calculation engine need to be tailored to the various users at the urban, building, utility, and household levels. In the pilot-study, real-time data on district heating, domestic hot water, domestic waster household electricity, building electricity, household waste, bulky waste, and the electricity grid have been integrated. The district heating grid uses the energy utilities simulated values as opposed to a real integration. For transportation, statistics from a previous study (Johansson et al., 2013) are used in lieu of measured data, with an aim to integrate real-time transportation metrics during the pilot study.

To convey the system consequences of decisions, Sankey diagrams have been developed to visualize a given flow through the city systems at a given level. These diagrams can be produced at various spatial resolutions, from the household level to the city level. Figure 4 shows the GHG emissions within a household (utilizing household sensors data) (Figure 4(a)), at the aggregated level of a single building (Figure 4(b)), and at the aggregate level of the SRS urban district (Figure 4(c)).

In Figure 4(a), the carbon metabolism of a single household is illustrated for energy use, water use, and waste generation, at a given time; the width of the flows conveys the GHGs in grams. This diagram shows that in the current moment, given the current grid mix, the majority of the emissions are generated from space heating and domestic hot water. The left-hand side of the diagram illustrates the energy sources used by the household and the right-hand side highlights the end uses. For example, the GHG emissions associated with the combustible household waste which has been incinerated in a combined heat and power plant to obtain heat energy can be seen. Roughly half of this is converted to useful energy which is used as space heating in the household. The electricity that is co-generated by the combustible household waste is transmitted to the electricity grid and powers home appliances. A very small portion of that electricity is also used to pump and treat the potable water used in the apartment's fixtures. The Sankey diagram runs at real-time, reflecting the actions performed by the household and is provided with hourly updates on the electricity grid mix and monthly updates on the district heating mix. To maintain privacy, this household-specific feedback is only available to the households themselves. However, households can compare their GHG emissions to the average GHG emissions of other households in the building. Figure 4(b) can be used by building owners to identify the GHG emission performance of their building stock, and Figure 4(c) can be used by urban planners to identify the GHG emission performance in relation to the city's environmental goals.

While Sankey diagrams are often used by researchers, more intuitive indicators and visualizations can be developed for the diverse needs of other stakeholders. These indicators are stored as a set of functions in the calculation engine, such as GHGs per square meter and primary energy per square meter. Building owners can use these indicators to benchmark and compare their building stock with others. Furthermore, city officials may be interested in comparing a building's performance in relation to the environmental goals of the district, such as in the SRS where the intensity of energy use is required[7] to be below 55kWh/m2*year.

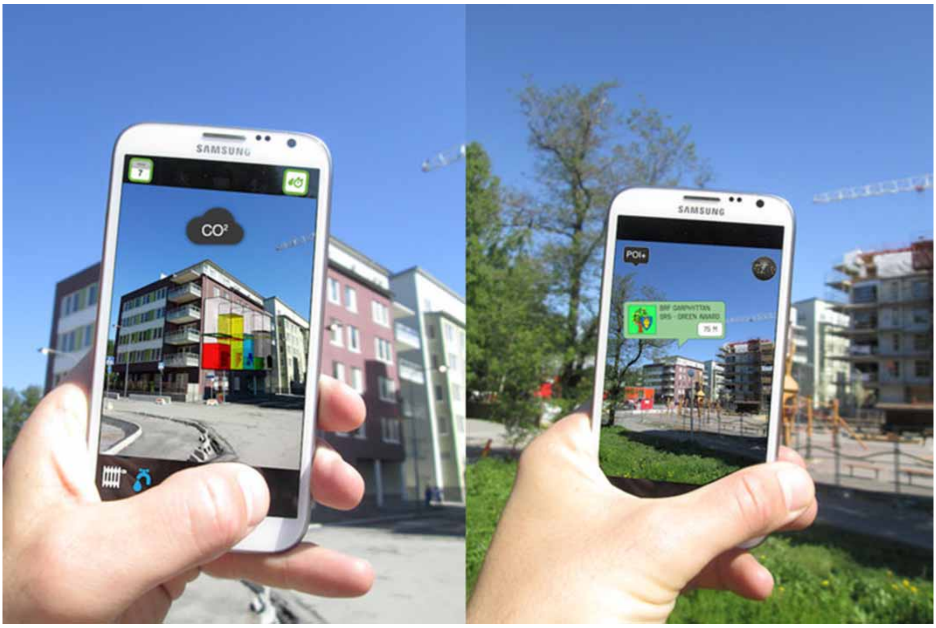

Figure 5: Augmented Reality solutions using the Smart City SRS platform.
Note: The image was taken from the smART Viz application developed by the Interactive Institute and Greenelizer.

There data can also be used for other forms of feedback that are tailored to specific stakeholder groups. Figure 5 illustrates the development of augmented reality applications that allow citizens to see the energy use of a building. These applications could be used by building portfolio managers, realtors, or architects, and answer questions such as, "What is this building's performance compared to the neighborhood average?"

The SUM Concept: Benefits and Limitations

A User-Generated Approach to Urban Metabolism

Traditional urban metabolism approaches often suffer from a lack of data at the city scale, nor can they offer feedback at a fine enough resolution for actors to realize the consequences of their actions in terms of energy and material flows. Indeed, Chrysoulakis et al. (2009) have noted that understanding the links between socioeconomic driving forces, the function of the urban system, and its environmental performance requires a bottom-up approach. The principle difference between the SUM concept and the conventional approach to urban metabolism studies is that through the use of real-time data, the SUM concept allows for dynamic and interactive feedback on how actions and behavioral patterns influence energy and material flows in urban areas.

The SUM calculation engine processes a combination of statistical and user-generated data to measure the production and consumption of energy and materials within a city. One benefit of using ICT to collect, process, and disseminate user-generated consumption data is the high resolution of energy and material flows. At the household level, sensors can record energy and material flows based on the actions performed in individual households. Smart meters can provide an aggregate of this behavior at the household level. When this data is aggregate to the building or urban district level, it can be compared to statistical production data from utilities.

User-generated data can also allow a greater interactivity between the user and the feedback they are given on the potential environmental impact of their decisions. Through processing this dynamic real-time data, the SUM concept is envisaged as a first step towards providing those who seek to know (individuals, building owners, utilities, municipalities, and cities) feedback on the system consequences of their decisions. This can lay the foundations to better inform decision situations, which may also allow us to overcome the isolation from the system consequences of our choices.

Benefits

The SUM concept uses ICT to collect data and analyze real-time data and has the potential to overcome some of the limitations of conventional urban metabolism studies. First, the use of ICT such as sensor networks, smart meters, and data mining can automate data collection, thus providing a greater level of detail at the city scale than conventional urban metabolism studies. Second, this automated data collection and analysis can help to reduce the high resource requirement associated with urban metabolism studies. While establishing the networked infrastructure, reaching agreements on data collection and ownership involves significant expense, that is, a one-off capital investment that can then provide continuous, real-time data flows. Third, once the data collection infrastructure, information management system, real-time calculation engine, and stakeholder feedback interfaces have been established, the SUM tool provides continuous information on energy and material flows. This information can then be used to study the evolution of a city's urban metabolism over time. Fourth, an analysis of the evolution of an urban district's metabolism can help reveal the cause of change in the urban metabolism. For instance, while scenario modeling may aim to look at the potential future reductions of GHGs due to the implementation of certain policy instruments, disaggregated real-time data can be analyzed *ex post facto* to identify the real-world consequences of these policy instruments.

Limitations: Data-Dependent Model

As the SUM concept is dependent upon user-generated data, there are a number of issues concerning the data ownership, the development of business models to secure data from business, organizations, and citizens, and privacy, which are central to the acceptance and success of the SUM concept. Hence, gathering data not only concerns technical issues, but relates to several socio-technical issues concerning the role of data and information flows in society.

For calculation engines to run, data are required from a variety of sources (sensors, AMI technologies, utilities, Stockholm City, building owners, open data sources) that are owned by different stakeholders. A question that arises is "who owns what data?" This largely depends on prevailing laws and partner agreements. The Smart City SRS project benefits from the fact that it is a new urban development, with legislative enforcement of building performance. Developers must provide Stockholm City with evidence, measuring performance for two to five years after construction, demonstrating the achievement of the city's environmental goals. Hence, most buildings are designed with ambitious measurement and verification plans. Currently, there is ongoing work in the SRS to develop business models to support the future development and maintenance of the Smart City SRS platform. This will take the form of an information market place where data and services can be bought and sold by anyone. This will allow for utilities and organizations to make their data available while providing an incentive for them to do so.

Potential Ways Forward

Providing the information collection and processing infrastructure, the SUM concept provides some of the building blocks of an innovation ecosystems (See Komninos, 2011) where researchers, software developers, and entrepreneurs can develop apps to meet the needs of targeted user groups. In bottom-up (i.e., living lab, people driven) innovation ecosystems, open and crowdsourcing platforms can be used to transfer the responsibility of producing information and interfaces to citizens; moving from a statistical to a user-generated approach to data collection and feedback.

This user-generated approach can be envisaged in several non-mutually exclusive ways. For instance, one possibility may be to develop a "planning-centric" approach. In this case, mobile apps could allow anonymous user-generated data on the consumption of food, goods, services, and transportation to be crowd-sourced. This would be done to populate the IMS, benefiting city planners, by allowing them to collect anonymized data "as close to reality as possible." However, such an approach is dependent upon citizens/users opting in to allow authorities to access their data.

Another possibility is to develop "citizen/user-centric" approaches to benefit users. In this situation, data does not need to leave the user. It is possible to develop apps that embed the SUM calculation engine logic, thereby connecting the user to real-time statistical data (e.g., grid mix) and real-time emission factors. User-generated data can be retained on the mobile device itself, and still allow the users to get feedback on the environmental impact of their activities. Providing such environmental information through various augmented reality solutions and gamification, persuasive services may be used to promote pro-environmental behavior. The benefit of such an approach is to empower individuals with feedback on the environmental consequences of their actions.

Conclusion

Kennedy et al. (2011) note that the urban metabolism concept is applied in a number of contexts, including sustainability reporting (sustainability indicators), inputs to urban GHG accounting, dynamic mathematical models for policy analysis, and urban design. However, limitations of applying urban metabolism concept in urban planning contexts include: intensive data collection and analysis, a lack of data at the municipal/urban district scale, and a lack of follow-up studies that allow for a comprehensive understanding of how the urban metabolism of a city evolves.

This paper proposes the SUM concept, an integration of the urban metabolism concept with ICT and smart city technologies to provide user-generated automated data collection, real-time analytics, and feedback that can be tailored to various stakeholder needs—from the household to the urban planner. Real-time data collection and analytics on the energy and material flows of an urban district can be used by urban planners to follow up on a city's environmental goals, by utilities and building owners to optimize their energy and material use, and by households as information of the environmental impact of their consumption and as a means of aiding them to achieve their own environmental goals.

The real-time data collection and analytics also provides the basis for an innovation ecosystem to foster the bottom-up development of applications to use and visualize environmental information and collect user-generated data on the consumption of food and transport.

Notes

1. Energy, transport, district heating, waste management.
2. See Kennedy et al., 2007, for a summary of these studies.
3. Assessment of the potential environmental impact of product/service systems using energy and mass flows for the main production and supply chain processes.
4. The study of the relationship between humans and technology (computers): Hilty et al., 2011.
5. Data driven animations that display ecological information in real-time (such as consumption statistics of key environmental resources) for the goal of promoting ecological literacy: Holmes, 2007.
6. Improving and enhancing ones' perception of their surroundings by combining sensing, computing, and display technologies: Olwal, 2009.
7. As part of a contract between the building owner and Stockholm City.

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