KTH Architecture and
the Built Environment

Smart Urban Metabolism
Toward a New Understanding of Causalities in Cities

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2015

ISBN 978-91-7595-737-1
TRITA-IM-PHD 2015:01
ISSN: 1402-7615

Printed by Universitetsservice US-AB, Stockholm, Sweden

Akademisk avhandling som med tillstånd av KTH i Stockholm framlägges till offentlig granskning för avläggande av teknisk doktorsexamen tisdagen den 16:e december kl. 14:00 i sal F3, KTH, Lindstedtsvägen 26, Stockholm, Sweden.

Acknowledgements

I would first like to thank my mentors, who gave me the foundation on which I stand today. Thank you Malcolm Lewis for kindly welcoming me to the CTG family, just based on that random phone call. Your memory is always shining in our hearts, they are lucky to have you in heaven. Thank you Greg Shank for creating the best work culture one could ever have wished for – the CTG Family. Thank you Jon Roberts for teaching me everything I know about modeling complex systems of systems, for your contagious love of research, and for teaching me how to draw my first Sankey diagrams. Thank you Chris Pyke for your mentorship and friendship. You provided the best possible conditions for a new engineer to learn and grow, taking me on the most exciting journey of my life – your compassionate leadership is always a source of inspiration. Last but not least, you inspired most of this work.

Dear Nils Brandt, thank you for so kindly welcoming me into your team, teaching me so much about this world, how to navigate through complex organizations, and providing me with the most fun research experience anyone could have asked for. Dear Olga Kordas, thank you for your ceaseless and compassionate help with my thesis and for your inspiring leadership. Dear David Lazarevic, thank you for all your help with this thesis and for teaching me about the essence of research. Dear Maria Malmström, truly thank you for all your help and support in this work, and thank you for all your efforts in creating a great workplace. Nils, Olga, David, Maria, without your efforts this thesis would never have gotten printed – thank you for all your support. Thank you my friend Aram Mäkivierikko for your kindness, brilliance, and for teaching me about altruism. Your talents have enabled so much good over the past decade, without your help, this would likely have remained solely a theory building thesis, and I'm looking forward to rejoicing for your success in your new chapter here at KTH.

Thank you all my dear friends for filling these years with the laughter and comradeship that made these years feel so much lighter than they really were: Louise Årman, Stefan Johansson, Anders Nilsson, Sophie Pandis Iveroth, Xingqiang Song, Pia Stoll, Kristin Fahlberg, Mari Appelgren, Omar Shafqat, Graham Aid, Rajib Sinha, Rafael Laurenti, Jagdeep Singh, JB Thomas, Isabelle Dubois, Olena Tatarchenko, Oleksii Pasichnyi, Kateryna Pereverza, Hongling Liu, Guanghong Zhou, Joseph Pechsiri, Emma Risén, and Markus Robért.

Thank you dear IE team for all your support and inspiring conversations throughout the year: Fredrik Gröndahl, Björn Frostell, Karin Orve, Kosta Wallin, Monika Olsson, Larsgöran Strandberg, Daniel Franzén, and Per Olof Persson.

Thanks to my colleagues at the City of Stockholm: Thomas Gustafsson for your vision; Christina Salmhofer for your kindness and faith throughout all these years; Maria Lennartson for always helping us to focus on the key issues; Jan-Ulric Sjögren and Örjan Lönngren for your tremendous passion and expertise; Michael Erman and Mika Hakosalo for leading the city into a new chapter; Anna-Karin Stoltz Ehn for your incredible wisdom and support; and Emilie Zetterström for all the wonderful opportunities, support, and laughter.

Thank you Peter Nõu, for your tremendous vision, wisdom, and belief in people. Thank you Allan Larsson, for your leadership, friendship, and bottom-up vision of the empowered citizens. Thank you Björn Nilsson, IBM, for being a truly caring project manager. Thank you Anthony Townsend for inspiring so much of this work and for kindly crossing the pond to be the opponent of the dissertation.

Thank you Berang Shahrokni for your heartfelt friendship and for helping me keep my sanity throughout all these years. Thank you Omid Sherafat for your compassionate guidance and inspiration to move forward.

I would also express my deepest gratitude to my family. To my brother Hammid for your patience, for your love, support, and for helping me keep perspective; my sister Sheyda for all your kindness, help with proofreading, and support throughout all these years; my father, Aziz, for being the best dad there is and teaching me everything about technology, buildings, and ethics; and my mother, Shahla, for your unconditional love, patience, support, and for always inspiring me with your spark for life.

Thank you … Elnaz.

List of Appended Papers

Paper I: Shahrokni H., Lazarevic D., & Brandt N. (2015). Smart Urban Metabolism: Toward a real-time understanding of the energy and material flows of the city and its citizens. Journal of Urban Technology, DOI: 10.1080/10630732.2014.954899

I conducted the case study research, data collection, data integration, analysis, concept development, and together with my co-authors undertook the literature review and paper writing.

Paper II: Shahrokni, H. & Brandt, N. (2013). Making sense of Smart City Sensors. In C. Ellul, S. Zlatanova, M. Rumor, & R. Laurini (Eds.), Urban and Regional Data Management, UDMS Annual 2013 (pp. 117–127). London: Taylor & Francis Group.

My contribution to this paper was planning the work, performing data collection, modeling, analysis, paper writing, and publishing.

Paper III: Shahrokni H., Årman L., Lazarevic D., Nilsson A., & Brandt N. (2015). Implementing smart urban metabolism in Stockholm Royal Seaport - Smart City SRS. Journal of Industrial Ecology, accepted for publication.

My contribution to this paper was idea development, planning the work, designing solution architecture, performing data collection, co-managing the research team, modeling, analysis, paper writing, and publishing.

Paper IV: Shahrokni, H., Levihn, F., & Brandt, N. (2014). Big meter data analysis of the energy efficiency potential in Stockholm's building stock. Energy and Buildings 78, 153-164. doi:10.1016/j.enbuild.2014.04.017

My contribution to this paper was idea development, planning the work, data collection, project managment, modeling, analysis, paper writing, and publishing.

Paper V: Shahrokni, H., van der Heijde, B., Lazarevic, D., Brandt, N., 2014. Big Data GIS Analytics towards Efficient Waste Management in Stockholm, in: Proceedings of the 2014 Conference ICT for Sustainability. Atlantis Press, Stockholm, pp. 140–147. doi:10.2991/ict4s-14.2014.17

My contribution to this paper was idea development, planning, performing data collection, supervising the project, paper writing, and publishing.

Abbreviations

API: Application Programming Interface

AR: Augmented Reality

Cap: Capita

CCI: Clinton Climate Initiative

CO2e: CO_2 equivalents

DH: District Heating

E-IOLCA: Economic Input-Output Life Cycle Assessment

GHG: Greenhouse Gas

ICT: Information Communication Technology

KPI: Key Performance Indicator

LCA: Life Cycle Assessment

MTCE: Metric Tons of Carbon Equivalents

PE: Primary Energy

SLCA: Social Life Cycle Assessment

SRS: Stockholm Royal Seaport

SUD: Sustainable Urban Development

SUM: Smart Urban Metabolism

UM: Urban Metabolism

Abstract

For half a century, urban metabolism has been used to provide insights to support transitions to sustainable urban development (SUD). Internet and Communication Technology (ICT) has recently been recognized as a potential technology enabler to advance this transition. This thesis explored the potential for an ICT-enabled urban metabolism framework aimed at improving resource efficiency in urban areas by supporting decision-making processes. Three research objectives were identified: i) investigation of how the urban metabolism framework, aided by ICT, could be utilized to support decision-making processes; ii) development of an ICT platform that manages real-time, high spatial and temporal resolution urban metabolism data and evaluation of its implementation; and iii) identification of the potential for efficiency improvements through the use of resulting high spatial and temporal resolution urban metabolism data. The work to achieve these objectives was based on literature reviews, single-case study research in Stockholm, software engineering research, and big data analytics of resulting data. The evolved framework, Smart Urban Metabolism (SUM), enabled by the emerging context of smart cities, operates at higher temporal (up to real-time), and spatial (up to household/individual) data resolution. A key finding was that the new framework overcomes some of the barriers identified for the conventional urban metabolism framework. The results confirm that there are hidden urban patterns that may be uncovered by analyzing structured big urban data. Some of those patterns may lead to the identification of appropriate intervention measures for SUD.

Key words

Big Data Analytics, Smart Cities, Sustainable Urban Development, Urban Metabolism

Sammanfattning

Under mer än ett halvt sekel har urban metabolism använts som ett verktyg i systemtänkande för att stödja övergången till en hållbarare stadsutveckling. Nyligen har informations- och kommunikationsteknologi (IKT) fått en växande roll för att stödja denna övergång. Denna avhandling syftar till att undersöka möjligheterna till att utveckla ett IKT-baserat ramverk för urban metabolism ramverk för att stödja beslutsprocesser i stadsutveckling som kan leda till ökad resurseffektivitet. För detta syfte formulerades tre mål. Först, att utreda hur det nya ramverket för urban metabolism kan stödja urbana beslutsprocesser. Därefter, att utveckla en IKT-plattform som kan hantera data av hög upplösning och utvärdera dess implementering. Slutligen, att identifiera möjligheter för effektivitetsåtgärder med hjälp av metaboliska data av hög spatial och temporal upplösning. Dessa mål uppfylldes genom litteraturstudier och fallstudier i Norra Djurgårdsstaden, kompletterat med mjukvaru-utveckling och analys av stora data. Det nya ramverket Smart Urban Metabolism (SUM), utvecklades i kontexten av ”smarta städer” och karakteriseras av möjligheten till analys och återkoppling av data med hög tidsupplösning (upp till realtid) och hög spatial upplösning (upp till hushåll/individ). Studien ledde till slutsatsen att det nya ramverket hanterar ett antal av de identifierade barriärerna som det konventionella ramverket för urban metabolism var behäftat med. Resultaten bekräftar även att det finns dolda processer och mönster i städer som kan upptäckas genom att analysera strukturerade stora data från städer. Av dessa mönster, kan ett antal leda till identifiering av nya och lämpliga hållbarhetsinterventioner för hållbar stadsutveckling.

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Preface

The research in this thesis began after I spent several years as a sustainability consultant at CTG Energetics in collaboration with the US Green Building Council. Having spent a large amount of time learning how to simulate buildings and cities to make priorities in sustainable urban development projects, the basis for this thesis started with my mentor Dr. Chris Pyke, posing the provocative question at the Copenhagen climate conference in 2009, COP 15: "What if you didn't need to simulate any more buildings? What if you could just know a building's performance statistically by having access to massive amounts of building performance data?". At first I couldn't grasp the idea and didn't want to understand, but then I realized just how profound his words were. From then on, I was looking for an excuse to advance sustainability through big data.

A delegation from the Clinton Climate Initiative was coming to Stockholm and asked if I wanted to join them to meet the local team. This was my first introduction to associate professor Nils Brandt and his amazing team at industrial ecology, and shortly thereafter he kindly extended an invitation for me to join them to deepen my skills in greenhouse gas accounting and sustainable urban development. The research began before the concept of smart cities had entered the mainstream, but smart grids were being discussed. I submitted a presentation called "Going from a Smart Grid to a Smart City" and shortly thereafter realized that smart cities was an emerging concept in its own right.

Starting with the challenging task of real-time evaluation of the goals of Stockholm Royal Seaport (SRS), my colleague, Louise Årman and I started exploring how this could be done. Little by little, through interactions with stakeholders and brainstorming sessions, a conceptual vision came together, but no perfect methodology was available. Urban metabolism was the closest, but it was not doing what we needed. Through a series of research and development applications and theory building, and the collaboration of more than 20 urban stakeholders, the practical and theoretical aspects of smart urban metabolism started taking shape. This goal was broken down into smaller, collaborative research and development projects that constituted a single-case study research platform, which led to the development of the Smary Urban Metabolism (SUM) framework.

At the end of this journey, I am excited to confirm Dr. Chris Pyke's suggestion back in 2009 – we now have the possibility of estimating building performance by drawing on more than 130 million data points representing 15,000 buildings in Stockholm. The projects on which the research platform was based are summarized here:

1) Clinton Climate Initiative Climate Positive Program, 2010-2011

A research and development task to develop a quantitative greenhouse gas metabolism tool to determine whether a climate-positive outcome can be reached, based on the Climate Positive Framework's system boundaries (Clinton Climate Initiative, 2013). This accounting tool was then tested in three pilot districts on three continents: Pedra Branca (Florianópolis, Brazil), Treasure Island (San Francisco, California), and SRS (Stockholm, Sweden).

2) Indicator development for Stockholm Royal Seaport 2010-2011

Based on the sustainability program of SRS (City of Stockholm, 2010), a list of possible qualitative and quantitative indicators for measurement and verification of the district's sustainability performance was developed (Årman et al., 2012a), as well as a number of over-arching key performance indicators (Årman et al., 2012b).

3) Urban Smart Grid Pre-study Work Package 5, December 2010-May 2011

This pre-study for the development of a smart electric grid in SRS was initiated and led by the local energy utility Fortum, and I led the fifth work package, with the goal of making the future smart grid compatible with the future vision for the smart city, in particular with regard to the necessary key performance indicators described above (Brandt and Nordström, 2011). As part of this study, an interoperability analysis was included.

4) Energy Awareness – Workstream 6 – Climate Potential, March 2012-September 2012

In this pre-study on the development of smart district heating in SRS, also led by Fortum, I led the work package that determined the potential greenhouse gas abatement potential of demand-response-based district heating in SRS and Stockholm (Paper IV) .

5) The Stockholm Royal Seaport Model – Information Management System, January 2012 – March 2012

Based on the previous studies, the Smart Urban Metabolism framework was formulated and I led the research in a pre-study to determine the barriers and opportunities across a large number of stakeholders who benefited from an integrating information management system (Paper II)

6) Smart City SRS, September 2012 – September 2014

To realize the vision developed in the pre-study of the information management system, I led an effort to create the necessary consortium. This resulted in 18 partners, who under the leadership of the City of Stockholm, IBM, KTH, and Fortum were granted a large-scale R&D grant from the government grant agency VINNOVA. I was a member of the steering group and led the research in "Work Package 3 – Calculation Engine" (Paper III)

1 Introduction

Cities are facing pivotal sustainability challenges over the coming decades (Rees and Wackernagel, 1996). Half the world's population, some 3.5 billion people, live in cities today and by 2050, the rapid rate of urbanization will have resulted in the need for cities to support roughly 6 billion people (Cohen, 2003). This has been projected to result in a 360% increase in energy use and a 310% increase in material use (Krausmann et al., 2008). With deteriorating natural resources (Robèrt, 2000) and rising energy and material consumption per capita, the ecological footprint of developed countries already exceeds their per capita carrying capacity (Wackernagel and Rees, 1996). Cities and, more recently, city districts have been recognized as the geo-political entities where the necessary shift towards sustainable urban development can and should be introduced (Rosenzweig et al., 2010; Sharifi and Murayama, 2013).

The ability to introduce effective sustainability intervention measures into cities and districts is dependent on a systems understanding of their energy and material flows. Kennedy and Hoornweg (2012) note that "Understanding energy and material flows through cities lies at the heart of developing sustainable cities. Such flows are inherent in the study of urban metabolism". Urban metabolism is one of the primary methods in the Industrial Ecology toolbox (Ferrao and Fernandez, 2013) and is defined as "the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al., 2007). It provides a pragmatic approach to inform sustainable urban development processes and is being increasingly adapted by public bodies such as the World Bank, the EU Commission, and the California Energy Commission (Kennedy and Hoornweg, 2012). One of the recurring challenges in urban metabolism studies is the lack of data on metabolic flows at city scale (Weisz and Steinberger, 2010). While so-called intelligent buildings have become significantly more advanced in tracking energy and material flows on building level in recent decades, the same does not yet hold true for neighborhood or city level (Kennedy et al., 2011). Urban integration of internet and communication technologies (ICT) may provide solutions to this challenge.

Considered in the context of sustainable development, Hilty et al. (2008) suggested that ICT can be used to support a transition to a less material-intensive economy. In relation to IPCC's recommended GHG reduction target of 20% below the 1990 level by 2020, Farnworth and Castilla-Rubio (2010) concluded that ICT-based technology enablers, in theory, could support a 15% GHG reduction. Most of the ICT-enabled technologies studied to date are associated with the emerging concept of smart cities (Caragliu et al., 2009), a concept associated in part with abundant urban data (Townsend, 2013). On this note, it could be pointed out that urban metabolism studies depend on a substantial amount of urban data (Kennedy et al., 2007; Weisz and Steinberger, 2010). This raises the question of whether there might be some merit in coupling these two concepts.

Stockholm's new urban district, Stockholm Royal Seaport (SRS), is in fact reliant on both ICT as a sustainability enabler and urban metabolism to inform its sustainability performance and design (City of Stockholm, 2010). In 2008, the development of this new sustainable urban district in Stockholm commenced. While the first tenants moved in during 2013, the complete build-out is planned for 2030, resulting in 12,000 new apartments and 35,000 workplaces. Based on on-depth collaboration with key stakeholders in the area, a sustainability program for the district was developed (City of Stockholm, 2010). In October 2010 the city council voted to adopt the sustainability program as the guiding development document for SRS (City Council of Stockholm, 2010).

Despite being written before the concept of smart cities had become established (Söderström et al., 2014), the sustainability program exhibited most attributes associated with smart cities today, in particular with regard to data, monitoring, and feedback (Höjer and Wangel, 2014). The reason for the data-intensive nature of the sustainability program is because it was designed based on lessons learned from the policies that were implemented for the city of Stockholm's first sustainable urban district, Hammarby Sjöstad. In 2008, an evaluation was made of the influence of the district's environmental program (passed in 1996) on planning and environmental performance. An attempt by Pandis and Brandt (2011) to evaluate that district was hampered due to data scarcity and the authors concluded that it is impossible to evaluate and ensure the sustainability performance of eco-districts if they are not coupled with a robust monitoring and verification program (Pandis Iverot and Brandt, 2011).

The SRS sustainability program's key resemblance to the smart city concept is its goal of continuous feedback to the city, building owners, organizations, and households. Meeting this goal would result in the generation of massive amounts of new data that could indicate the district's progress towards sustainable urban development. This is perhaps best conveyed by the following sample of sentences from the sustainability program:

i. "Sustainability indicators should indicate the district's sustainability performance at different times and at different levels, such as household level, property level and district level." (City of Stockholm, 2010, p. 47).
ii. "Measurement and analysis of energy and material flows in real time will be possible within the framework of the Stockholm Royal Seaport innovation." (City of Stockholm, 2010, p. 49).
iii. "Residential and commercial buildings must contain user friendly systems for individual measurement, visualization, monitoring and control of energy,

water and waste, where costs and billing can be easily read." (City of Stockholm, 2010, p. 55).

iv. "Regular measurement and visualization of energy use and its impact on climate will be done in real estate, homes and businesses and for transport and infrastructure." (City of Stockholm, 2010, p. 21).

This is the context from which this thesis emerged. Early on, an idea was conceived to implement tools within industrial ecology, including systems thinking, material and energy flow analysis, and urban metabolism, to meet these goals. Upon further investigation, it became evident that the existing concept of urban metabolism and its practical means of implementation were inadequate to meet the goals of the sustainability program, and needed to be revised to support the sustainable urban development process in the context of smart cities.

1.1 Aim and Objectives of this Thesis

The work described in this thesis stems from the challenges of developing a method for real-time monitoring and follow-up of the SRS district's energy and material flows and sustainability performance. Urban metabolism is a suitable framework to meet this challenge, as it integrates biophysical sciences and technology with social sciences and explicitly identifies system boundaries, accounts for system inputs and outputs, and can be decomposed to study specific urban sectors (Princetl and Bunje, 2009).

However, previous studies of urban metabolism have mostly relied on statistical data with low spatial and temporal resolution (Kennedy et al., 2011), thereby resulting in limited potential for identifying effective intervention measures. This raises several questions, such as: Are real-time urban data available? Do new sensor networks have to be established? What are the problems associated with accessing and using real-time data? How can heterogeneous data be combined? How can real-time metabolic information be fed back to decision-makers?

The aim of this thesis was to explore the potential for an ICT-enabled urban metabolism framework to improve resource efficiency by supporting urban development decision-making processes.

The specific objectives in the work to achieve this aim and respond to the research questions were to:

i. Investigate how the urban metabolism framework, aided by ICT, could support decision-making in an urban development context.

ii. Develop an ICT platform for real-time, high spatial and temporal resolution urban metabolism data and evaluate its implementation.

iii. Highlight the potential for energy and resource efficiency improvements through the use of historical, high spatial and temporal resolution urban metabolism data.

1.2 Intended Audience

This thesis is primarily intended for three audiences. The first of these is sustainability system scientists and professionals such as industrial ecologists who rely on systems thinking to support the sustainable urban development process. The urban metabolism framework is one of the main tools found in the toolbox of industrial ecologists (Ferrao and Fernandez, 2013), and this thesis provides a revision of that framework. The second intended audience are ICT-oriented scientists and professionals active in the field of smart cities, in particular those seeking to research and develop smart city solutions to support sustainable urban development. This thesis demonstrates how they can implement smart city technologies and big data analytics in working towards sustainable urban development. The third intended audience is urban planners, policy makers, and professionals working on sustainable urban development projects. Many cities are adopting or planning to adopt smart city technologies and are struggling with how to monitor set sustainability goals. Since these concepts are still in their infancy, there is quite a lot of confusion and misconceptions, and little scientific research and evidence to inform public policies. This thesis provides a concrete, implemented case study and guidance on how to implement similar solutions. In a broader sense, researchers shifting towards the data-intensive paradigm of research, also known as the "the fourth research paradigm" (Wilbanks, 2009), may encounter interesting parallels between this thesis and their own research.

1.3 Scope

All the studies in this thesis are limited to the City of Stockholm and its eco-district, Stockholm Royal Seaport (SRS). The scope is limited to energy and material metabolism of districts, with particular focus on greenhouse gases. The metabolism of nutrient flows falls outside the scope of this thesis, but data on nutrients in wastewater are being collected for future studies. Similarly, the complete socio-economic metabolism falls outside the scope of this thesis, but some related social indicators are being collected for future studies.

2 Background

With a sense of the serious sustainability challenges (Rockström et al., 2009) that are created by the intertwined mega-trends of rapid population growth (Raven, 2002) and urbanization (Bugliarello, 2006), the path forward that remains is a substantial shift towards sustainable urban development (Steffen et al., 2001). This necessitates strategies based on a coordinated global effort by policy makers, planners, industries, research, and development in engineering, architecture, economics, ecology, biology, and humanities. Since the causal chains of urbanism are highly complex (Trantopoulos et al., 2011), these strategies should be developed, prioritized, and evaluated using a framework based on systems thinking (Davidson and Venning, 2011). Ferrao and Fernandez (2013, p. 8) see an opportunity for industrial ecology and urban metabolism to support a shift toward sustainable urban development, through both an intellectual framework and a toolbox of methods for decision-makers that "provide metrics […], allowing the individual to perceive the effect of her actions and providing her with the necessary feedback".

Urban metabolism allows for a better understanding of urban areas, enables their monitoring, and supports identification of appropriate interventions over time (Haberl et al., 2004). It is also the concept that this thesis is aiming to further develop and therefore it is necessary to at least cover the most essential background here.

2.1 Urban Metabolism – Concept, Framework, and Tools

Urban metabolism has been referred to as a metaphor (Gandy, 2004; Minx et al., 2010; Rapoport, 2011; Wachsmuth, 2012), a concept (Kennedy et al., 2011; Minx et al., 2010; Pincetl et al., 2012), an approach (Huang and Hsu, 2003; Pataki et al., 2006), a framework (Baccini and Brunner, 2012; Kennedy et al., 2011; Minx et al., 2010; Pincetl et al., 2012), a methodology (Chen and Chen, 2012), a tool (Holmes and Pincetl, 2012; Sahely et al., 2003), and a method (Princetl and Bunje, 2009). Approach, concept, metaphor, and methodology are used interchangeably in the literature, while framework and methodology typically denote a systematized process, and tools are usually the means of accounting towards implementing the frameworks. However, the literature is not always clear on these terms and citing them out of their original context can lead to misinterpretations. For the purposes of this thesis, these terms are aggregated into three distinct groups: concepts (encompassing the terms "approach", "method", and "metaphor"), frameworks, and tools (encompassing the term "tool"). This serves as a synthesis of the terms surrounding urban metabolism, some of which were identified in Paper I and Paper III.

The Urban Metabolism Concept

To date, more than 75 urban metabolism studies have been conducted, and more than 20 of these are comprehensive studies of cities (Kennedy and Hoornweg, 2012). The definition of urban metabolism used in this thesis was established by Kennedy and co-workers and is the most comprehensive definition to date: "The sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al., 2007, p. 44).

The urban metabolism concept is now being used not only to assess the sustainability performance of cities, but also to inform the design of cities (Baccini and Oswald, 2008; Codoban and Kennedy, 2008). Most studies have focused on the concept at the city scale (Kennedy et al., 2007; Lee et al., 2009; Newcombe et al., 1978), but some have focused on the neighborhood scale and even down to the building scale (Codoban and Kennedy, 2008; Kellett et al., 2012). However, there are not many urban metabolism studies at the neighborhood scale because of the challenges in finding data at that level (Codoban and Kennedy, 2008). Others use the concept to understand the continuum from buildings to the city scale (Agudelo-Vera et al., 2012).

For a more tangible understanding of the usefulness of the urban metabolism concept, Baccini & Brunner (2012, p. x) draw an analogy to human metabolism and medicine, noting that without answers to questions pertaining to knowing what, where, and how to measure, "a diagnosis is not possible, and no appropriate measures can be taken".

The Urban Metabolism Framework

While the increased adaptation of urban metabolism (Kennedy et al., 2007) advances the sustainable urban development process, Barles (2009) concluded that this field of interdisciplinary research is still fragmented due to its heterogeneous origins and is in need of consolidation. Towards this end, Kennedy and Hoornweg (2012, p. 780) conclude that:

> In order to mainstream urban metabolism, […] there needs to be a standardized, comprehensive urban metabolism framework, and some degree of agreement on which parameters, out of the many possible, should ideally be included in basic level reporting.

Therefore in 2010, researchers primarily from the industrial ecology community came together with the aim of standardizing the system boundaries and indicators. In parallel, González et al. (2013) incorporated urban metabolism into a sustainability impact assessment framework in the European FP7 project BRIDGE (sustainaBle uRban plannIng

Decision support accountinG for urban mEtabolism). One of its earliest tasks, to develop a framework for urban metabolism, was carried out by Princetl and Brunje (2009) for the California Energy Commission's Public Interest Energy Research Program (PIER). They evaluated several other frameworks to meet the requirements set forth by PIER and then developed their own "urban metabolism framework". In the process, they concluded that the framework was the best way for the PIER program to engage with its sectoral research (Princetl and Bunje, 2009). The benefits of the urban metabolism framework were aptly summarized thus by Princetl and Bunje (2009):

1. It explicitly identifies system boundaries.
2. It enables a hiearchical research approach.
3. It accounts for system inputs and outputs.
4. It can be decomposed to study specific urban sectors.
5. It requires an analysis of policy and technology outcomes with regard to sustainability goals.
6. It is an adaptive approach to solutions and their consequences.
7. It integrates social sciences with biophysical sciences/technology.

To systematize the implementation of urban metabolism frameworks, Baccini and Brunner (2012, p. 107) and Princetl and Bundje (2009, p.26) developed processes for the implementation of their respective frameworks. Baccini and Brunner (2012) note that these same steps have been repeatedly applied in numerous studies in Asia and America. The respective framework implementation processes are summarized in Table 1.

Table 1. Conventional urban metabolism framework processes as presented by Baccini and Brunner (2012, p. 107) and Princetl and Bundje (2009, p. 26)

Step	Baccini and Brunner	Princetl and Bundje
1	Definition of task (outcome)	Define the boundaries of a community.
2	Setting objectives	Define the metabolic commodities and processes of the community.
3	Definition of the system	Quantify the anthropogenic metabolism of the community.
4	Rough balancing to testing whether the chosen system is appropriate for the objectives	Assess the metabolic relationships between human activities and the natural environment in the community.
5	Mass balancing of goods and substances	Measure the metabolic relationships between the community and hinterlands outside its boundaries.
6	Evaluation and interpretation of results (loop back to system definition and iterate until desired results are reached)	Identify strategies for improving the metabolic efficiency and reducing waste in the community.
7	Drawing conclusions	Collaboratively develop policy solutions that address identified strategies.
8	Reporting	-

The Urban Metabolism Tools

An urban metabolism tool is an accounting system that can manage, quantify, and process metabolic flow data. This could be a single accounting tool or a combination of different tools, each of which is specialized in a part of the metabolism. One typical characteristic of urban metabolism tools is their integrative nature, i.e., their ability to integrate a variety of data sources and provide a systems perspective, based on a relevant theory (Holmes and Pincetl, 2012). Accounting tools range from paper-based in simpler models to spreadsheet-based, or tailored software in more advanced models.

Urban Metabolism – A Brief History

In an analogy between a city and a living organism, and with the aim of addressing contemporary challenges of water supply, waste management, and air pollution, the urban metabolism concept was pioneered by Abel Wolman in 1965. He proposed that "The metabolic requirements of a city can be defined as all materials and commodities needed to sustain the city's inhabitants at home, at work and at play" (Wolman, 1965). With the aim of minimizing water and air pollution and addressing water scarcity, Wolman quantified the flows of energy, water, materials, and waste in a conceptual North American city.

Urban metabolism studies have seen two schools of thought, the first of which, pioneered by Odum (1988, 1983), described urban metabolism in terms of energy equivalents (emergy). In a review of the research on urban metabolism, Kennedy et al. (2011) describe the second school of thought as a broader approach that expresses the city's flows of water, materials, and nutrients as mass fluxes. This school of thought is associated with material flow analysis (MFA).

Since it seeks to optimize the material flows of economic systems (Graedel, 1994), MFA is one of the main tools of industrial ecology (Socolow, 1994). It is the study of material flows of materials into, through, and out of economic systems (e.g., cities) within a specified temporal and spatial boundary, and it allows for a better systems understanding of potential intervention measures for purposes such as sustainble development (Ayres and Ayres, 1999; Kytzia et al., 2004; Voet, 1996). It was pioneered in the late 1960s, a few years after Wolman's work, by Ayres and Kneese (1969) as a response to the limited economic view of contemporary environmental concerns. They developed a mathematical framework and quantified the material flows and waste products in the United States to highlight the interdependency of production-consumption and externalities such as waste and pollution.

It would take more than 20 years before substantial developments were made in MFA. They emerged particularly in the seminal work by Baccini and Brunner (1991), who further developed a methodology based on the first law of thermodynamics, the principle of energy-mass conversation, to describe the metabolism of the anthrosphere and its elements, and embedded this process in a framework (presented in Table 1).

The current mainstream way of representing urban metabolism stems from the second school of thought and is based on material and energy flow analysis (MEFA) (Kennedy et al., 2011; Haberl et al., 2004), where energy flows are measured in a unit of energy such as joules and mass flows are measured in weight or volume.

A very significant contribution to the field in recent years was made by Kennedy and co-workers in work comprising comprehensive literature reviews, case studies, and theory building (Kennedy et al., 2007; Codoban & Kennedy, 2008; Kennedy et al., 2010; Kennedy et al., 2011; Kennedy, Demoullin, et al., 2012; Kennedy, Baker, et al., 2012). Kennedy et al. (2007) also established the most recent definition of urban metabolism, which is used in this thesis. Most of their contributions came after the turn of the millennium, which coincided with a resurgence of the field after two slower decades (Kennedy et al., 2011). Since then, the field has grown considerably and today there are more than 75 papers and two books dedicated to the subject area (Chrysoulakis et al., 2014; Ferrao and Fernandez, 2013).

Along with the evolution of the field of urban metabolism, the following sections introduce an emerging and technology-enabled research paradigm that is advancing research in many fields, with particular relevance to urban metabolism research. In section 2.4, the specific connection between urban metabolism and ICT is then reviewed.

2.2 The Fourth Research Paradigm

The fourth research paradigm refers to data-driven research that does not always start with explicit research questions, but instead revolves around big data exploration of "unknown unknowns" (Hey et al., 2009a), meaning unknown answers to unknown questions. Large datasets representing reality have become accessible to researchers in an unprecedented way. This means that scientific advances are no longer confined to designing well-defined experiments and evaluating them through hypothesis testing. While conventional research retains its essential role, there is a new operating space in research where immense and complex datasets need to be analyzed for hidden and hard-to-discover patterns and relationships from the viewpoint of a multitude of collaborating disciplines (Abbot, 2009). Within this paradigm, Hey et al. (2009b) identified the evolution of two new branches in each discipline, taking ecology as an example. One computational branch focused on more advanced ecological simulations and one eco-informatics branch focused on collecting and analyzing ecological information. This indicates that data-intensive science will be a core component of a large number of future scientific advances (Wilbanks, 2009). However, the ability to navigate through oceans of data is a skill to be acquired, as noted by Bell et al. (2009).

Along this line of thinking, Cleveland (2001) introduced data science as an independent discipline, with data scientists mastering three domains: computer science and data management expertise, mathematical and statistical expertise, and specific subject matter expertise (e.g., urban metabolism). Founded on this combined expertise, the research approach of data scientists can be summarized in three phases: data capture, data curation, and data analysis (Hey et al., 2009a). The following paragraph describes the three previous research paradigms that served as mankind's methods for understanding the surrounding world.

The first paradigm was used in observational and experimental research to describe tangible natural phenomena. This was the kind of research that led to the model of the universe developed by the astronomers of ancient Greece (Hey et al., 2009b). It was followed by the second research paradigm, based on theories such as Newton's laws of gravity, Kepler's laws, and Maxwell's equations of electromagnetism (Jiang, 2011). The third research paradigm can be referred to as computational sciences that enabled predictions of future scenarios, i.e., simulations (Root and Schneider, 1995). Many of the scientific advances in recent decades have rested on discoveries based on the third research paradigm. As predicted by Moore's law (Schaller, 1997), there have been great technological advances in data storage and processing power is growing exponentially, which has created new possibilities for researchers.

The fourth and emerging paradigm is described as big data exploration. Scientist need new tools to learn how best to navigate and explore the massive amounts of data that are being made available from heterogeneous data sources and sensor networks (Lynch, 2009). This led Strawn (2012) to differentiate between traditional scientific research (traditional biology, traditional astronomy, etc.), and new scientific research (new astronomy, new biology, new social sciences, etc.) enabled by information technology.

As pointed out by Hey et al. (2009b) with regard to eco-informatics, data-driven disciplines, in particular sustainability science and industrial ecology, could be served by actively seeking paths to advance into the fourth paradigm of research. The floods of urban data enabled by increased fusion of ICT in cities and research methodologies pertaining to the new paradigm may enable the continuous disovery of new efficiency measures concealed from the previous research paradigm.

2.3 ICT in Cities – A Driver of Sustainable Urban Development

The United Nations recently called on local governments to rely more on ICT to build institutional capacity in their integrated efforts for sustainable urbanization (United Nations, 2014) and ICT is gaining an increasingly central role in the sustainable urban development literature (Farnworth and Castilla-Rubio, 2010). Mitchell (2000) categorized ICT's contribution to sustainability into five domains, which can be summarized as:

1. **Dematerialization**

   Replacing material systems with electronic counterparts, such as mail with e-mail or bank buildings with online banks.

2. **Demobilization**

   Replacing travel with telecommunications and increasing work from home or local work hubs.

3. **Mass customization**

   Moving away from the heritage of the industrial era's standardized (and often waseful) "one size fits all" approach, and instead offering demand-oriented services. An example of this is intelligent car sharing services (such as Zip cars), where the car type needed is made available when and where it is needed, as opposed to year-round ownership of one car type. A similar example is real-time, demand-driven public transportation services.

4. **Intelligent operation**

   This is the most "new" of the intelligence-embedded, demand-response technologies associated with smart cities today, i.e., the fusion of sensors, actuators, and algorithms with water, energy, and transportation infrastructures. This allows for more efficient and real-time operation of city infrastructures and sectors. This is not limited to intelligent decisions made by computers, but refers to decision-making processes in general.

5. **Soft transformation**

   Soft transformations refer to the enhancements and adaptations of the existing built environment through relatively non-intrusive ICT inclusion in the building stock, public spaces, and transportation infrastructure of neighborhoods and cities, to transform legacies of the industrial era. This can also include the relationship between public planning efforts and ICT.

A further simplification of all these ICT-enabled urban interventions would be to say that they may ultimately improve urban resource efficiency or the ability to "do more" (house a larger population) with less resources. Here it should be emphasized that efficiency and sustainability are not necessarily the same. More recently, Hilty et al. (2008) reaffirmed that ICT could support a transition to a more sustainable and less material-intensive economy. Based on this work, Kramers et al. (2013) developed a framework to assess the implementation of ICT-based solutions in sustainble urban development projects. Their framework is based on Mitchell's five ICT-enabled categories of urban sustainability interventions and the household functions developed by Höjer et al. (2011).

2.3.1 Smart Sustainable Cities

The more prevalent context of ICT in cities is captured by the emerging concept of smart cities (Caragliu et al., 2009). It is within this context that a further adaptation of the urban metabolism framework is enabled. Smart cities add a new dimension to the infrastructures of urban areas by integrating ICT in the fabric, life, and culture of the city. There is a gradual integration of sensors, actuators, intelligent agents, and pervasive feedback mechanisms within the existing infrastructure of cities and virtually all aspects of economic and social activity.

Numerous studies have since confirmed the ICT-enabled sustainability intervention measures in cities (Ahola et al., 2010; Hilty et al., 2011). More recently, work on smart sustainable cities has taken the concept of smart cities further by explicitly incorporating the concept of sustainability:

> A smart sustainable city is an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations (Cavada et al., 2014, p. 6).

Finally, a concept with particular relevance to this thesis is that of urban computing (Kindberg et al., 2007). Based on the following definition by Zheng et al. (2014, p. 9:3), an ICT-enabled evolution of the conventional urban metabolism framework could be regarded as an ecological and socio-economic application of urban computing:

> Urban computing is a process of acquisition, integration, and analysis of big and heterogeneous data generated by a diversity of sources in urban spaces, such as sensors, devices, vehicles, buildings, and humans, to tackle the major issues that cities face, e.g., air pollution, increased energy consumption, and traffic congestion.

This intention of integrating heterogeneous urban data and analyzing them for sustainability interventions is closely related to that of an ICT-enabled evolution of urban metabolism. Zheng et al. (2014, p. 9:3) underscore that urban computing is based on "unobtrusive and ubiquitous" sensor systems that are coupled to urban data management and feedback mechanisms. The aim is to create value for related stakeholders, improving the urban environment, urban infrastructure, and quality of life. Just as urban metabolism studies strongly rely on interdisciplinary collaborations, Zheng et al. (2014) point out that urban computing requires the collaboration of computer science with transportation, civil engineering, industrial economy, ecology, and sociology. Through such collaboration, Zheng et al. suggest that urban computing enables a better understanding of "urban phenomena" to such a degree that it could serve as a basis to predict some future events.

A realized vision of urban computing as detailed above would lead to the generation of unprecedented amounts of urban data, demanding an ability to manage large amounts of data and master data-intensive research, or in other words, the skill sets of the fourth research paradigm. However, Townsend (2013) cautioned that no matter how much data would be generated and analyzed, the results will provide little insight if they are not based on the relevant models and theories of the built environment. Based on this logic, the three previous sections, on urban metabolism, the fourth research paradigm, and ICT in cities, need to converge in a discourse about urban metabolism and ICT.

2.4 Urban Metabolism and ICT

The first documented vision for fusing the concept of urban metabolism with ICT was made made by Townsend (2000) in the article "Life in the Real-Time City: Mobile Telephones and Urban Metabolism". This identified that ICT is fundamentally transforming temporal and spatial constraints of communication between humans: "The "real-time city," in which system conditions can be monitored and reacted to instantaneously, has arrived" (Townsend, 2000, p. 89).

Townsend (2000) recognized a disconnect between the prevailing urban design methodologies, which are concerned with physical scales that are several orders of magnitude higher than the intervention level of mobile communication technologies. Already around the turn of the new millenia, Townsend (2000, p. 102) arrived at a conclusion that seems to carry stronger weight the more advanced cities become, cautioning that "Without good models for understanding urban systems, no amount of data will produce useful analysis for guiding real-world decisions". Since then, two other articles have started to explore the future role for ICT in the urban metabolism concept.

First, Hoornweg et al. (2012) recognized the potential role that ICT and smart cities could play for urban metabolism studies and arrived at a number of insights. These insights highlighted the potential of ICT to manage highly disaggregated urban metabolism data in order to enable smarter decisions by governments and citizens. Second, Trantopoulos et al. (2011) proposed a roadmap with three components to enable better measurement and prediction of urban metabolism. These components are digital traces of anthropogenic activities, integration with large-scale simulation models, and sensors and ICT enabling real-time feedback of human activity. Trantopoulos et al. arrived at the concept of an urban nervous system that links urban infrastructures with each other, stakeholders, and citizens, and noted that such a nervous system would require relevant feedback systems.

Despite the potential highlighted in the aforementioned conceptual studies, only one study has so far implemented the integration of remote sensing data into an urban metabolism model (Chrysoulakis et al., 2009). Their sensing focused primarily on air quality data (particles, NO_X, VOCs, etc.) and meteorological data (air pressure, temperature, wind, humidity). However, they discuss how other types of urban activities could also be sensed to support decisions in urban planning. This discussion resulted in a call for a "bottom-up" approach in urban metabolism, aided by ICT in terms of modeling, monitoring, and decision-support systems to arrive at a systems understanding of the impacts of industries, urban infrastructures, and households. Given this, no studies to date have implemented an ICT-based urban metabolism model to study energy and material flows in urban areas.

3 Methodology

This thesis aimed to contribute to the theories associated with industrial ecology, specifically that of urban metabolism. The selected methodology for working towards the outlined objectives was adapted from Design and Development Research (DDR) methods (Peffers et al., 2007), traditionally employed in the context of developing models and tools that are problem-driven and ICT-based. Within the taxonomy of research, it falls within the research and development category comprised of tool and prototype development, as described by Nunamaker and Chen (1991). In this sense, DDR can be considered a bridge between theory and practice.

Nunamaker and Chen (1991) proposed a multi-methodological approach (requiring the combination of several different methods) to ICT-based research. They recognized that research within some fields, such as engineering, is so broad that it has to rely on a wide array of methods, and this holds true in particular for the study of ICT-enabled evolution of urban metabolism. They called this type of research "Management Information System" (MIS) research, conducted as "system-integration" types of projects that fuse multiple methods over the distinct main phases of "concept", "development", and "impact" (Nunamaker et al., 1991).

In this thesis, the DDR framework (Richey and Klein, 2014), comprising six phases, was implemented with five research methods. The five research methods consisted of literature review, single-case study research, urban metabolism, software engineering research, and big data analytics associated with the fourth research paradigm.

3.1 The Six Phases of the Design and Development Research Framework

The DDR framework consists of six distinct phases (Ellis and Levy, 2010). Within each phase, a number of outcomes and methods relating to the research questions are identified. These phases revolve around ICT development, where the ICT tool/platform is referred to as the "artefact":

1. Identify the problem.
2. Describe the objectives.
3. Design and develop the artefact.
4. Test the artefact.
5. Evaluate test results.
6. Communicate test results.

These phases correspond to those conducted in this thesis. Each phase is associated with specific methods to arrive at its objectives, as summarized in Table 2. The methods used in this thesis were:

- The urban metabolism concept (Kennedy et al., 2011) – The fundamental concept for understanding the urban energy and material flows stemming from technical and socio-economic processes.
- Literature review – To identify and limit barriers to conventional urban metabolism; plus an additional literature review to position the case of SRS in the context of sustainable urban development, smart cities, and the fourth research paradigm. The literature review was used to adapt the conventional urban metabolism framework to overcome its limitations.
- Single-case study (Yin, 2009) – Application of the framework in the context of a single case – SRS and its 18 stakeholders. This is a relevant method when studying a new phenomenon with rich contextual data (Pandis Iveroth, 2014).
- Software engineering (Kitchenham et al., 2002) – To design and develop the necessary software architecture and algorithms to enable urban metabolism studies aided by ICT.
- Big data analytics (Hey et al., 2009a) – To identify urban patterns, correlations, and processes that may lead to the discovery of new urban sustainability intervention measures.

Table 2. The Design and Development Research (DDR) framework and the methods associated with each phase used in Papers I-V of this thesis

	Phase	Applied Research Methods	Paper
1	Identify the problem	Literature review Case study research	I, II, III
2	Describe the objectives	Literature review Case study research	I, III
3	Design and develop the artefact	Literature review Case study research Urban metabolism Software engineering research Big data analytics	II, III
4	Test the artefact	Case study research Software engineering research Urban Metabolism	II, III,
5	Evaluate test results	Case study research Urban metabolism Big data analytics	IV, V
6	Communicate test results		I, II, III, IV, V

3.1.1 Phase 1 – Identify the Problem

Research that is appropriate for the DDR framework meets one of the following three criteria: i) There is an emerging problem that no tool or model can address; ii) the emerging situation itself is so poorly understood or complex that it requires a better tool to increase knowledge and understanding about it; and there is a problem that can be managed by an ICT solution originally designed for a completely different domain (Richey and Klein, 2014).

The problem addressed in this thesis meets all three criteria: i) The problem comes from the limitations of the conventional urban metabolism framework, which is an inadequate methodology for meeting the goals set for the SRS urban district. These goals require continuous monitoring of local sustainability performance, as well as empowering all stakeholders, including citizens, with appropriate sustainability feedback. ii) The complex system of systems that urban areas represent are only vaguely understood today, and more refined tools and data are needed to move towards a better understanding of the causalities that govern cities. iii) Real-time feedback, big data mining, and better decision-making are today successfully deployed in many other domains. One example is Formula 1 racing cars, where ICT has become a key driver to increase performance, with hundreds of sensors, actuators, supported by big data analytics, providing insights fed back in real time. Similarly, the DDR on which this thesis is based explores how similar ICT can become a key driver in improving the performance of urban areas.

Single-case study research was used to arrive at a deep understanding of the sustainable urban development process and goals for the urban district SRS (Paper I; Paper III). The second method used in this phase was literature reviews (Paper I; Paper III). As background, literature reviews were conducted on sustainable urban development and smart cities, while for the problem formulation and theory building work, literature reviews were carried out on urban metabolism and the fourth research paradigm. In particular, the review of existing frameworks for urban metabolism helped formulate the problem and define the gap between the sustainability requirements in SRS and the toolsets found in conventional urban metabolism frameworks.

Single-Case Study Research as a Method

Case study research can be conducted with multiple cases, embedded cases, or a single case (Yin, 2009). Single-case studies are particularly effective when studying a newer phenomenon that requires ample amounts of case-contextual data enabling an in-depth analysis of factors that would remain inaccessible in a more general study (Eisenhardt, 1989; Yin, 2009). In this thesis, it provided necessary insights with regard to sustainability policies, their dependence on the large and complex network of actors, their interactions, and incentives. Arriving at such an in-depth understanding is the principal objective of case study research (Woodside, 2010). The research included numerous stakeholder workshops, questionnaires, interviews to identify what synergies each stakeholder has with the sustainability goals, what data they could generate to evaluate those goals, and how those data could be shared and used within the project.

SRS was particularly well-suited for a single-case study for a number of reasons, similar to those identified by Pandis (2014) for the first eco-district of Stockholm. First, it is the first place that has enabled the ICT-enabled approach to urban metabolism. Second, it is coordinated with a unique sustainability program that unites the public, academia, and private stakeholders to arrive at ICT-enabled sustainable urban development goals. Therefore, a single-case study could shed light on barriers to stakeholder collaboration, in particular with regard to data sharing. Lastly, the SRS is a Clinton Climate Initiative 'Climate Postitive Candidate' (Clinton Climate Initiative, 2013) and is of high interest to many sustainable urban development projects in their early stages, for which a single-case study could provide key insights.

There are two principal limitations of single-case studies. The first is that the researcher may lack the necessary objectivity by becoming too engaged and opinionated with regard to the case (Benbasat et al., 1987). This limitation holds true for this case, but was partly reduced because the research on which the thesis is based was carried out as a team effort. Another criticism of the single-case study is that it cannot become generalizable from a statistical perspective and its contribution to scientific knowledge has therefore been questioned. Flyvbjerg (2006) refers to this as a misunderstanding and argues that generalizability is one of many characteristics of scientific research. However, within the post-positivist paradigm, the generalizability criterion is replaced by a transferability requirement. This means verifying whether conclusions from a sample lead to lessons learned that are of use for a larger population (O'Leary, 2013). In the field of urban metabolism, many studies can be in fact be considered single-case studies (Chen and Chen, 2012; Duvigneaud, Paul, Denaeyer-De Smet, 1977; Newcombe et al., 1978; Sahely et al., 2003), which in turn have been essential for meta-analyses that have led to theory-building in the field (Kennedy et al., 2011).

3.1.2 Phase 2 – Describe the Objectives

The second phase of the DDR framework was to define the objectives that support the aim. These three objectives have already been described in the section "Aims and Objectives" and were developed through single-case study research within SRS and literature reviews of the two contexts of sustainable urban development and smart cities, the research framework of urban metabolism, and the ICT-enabled fourth research paradigm.

3.1.3 Phase 3 – Design and Develop the Artefact

The problem formulation and identification of research questions and objectives served as the foundation for the core phase of the thesis, the design and development phase (Paper II; Paper III). The main results of this phase were the development of an refined framework of urban metabolism, called "Smart Urban Metabolism" (SUM), and a supporting ICT platform (Paper I; Paper; II; Paper III). These results were contingent on six outcomes, each of which was associated with a method.

The first outcome was to identify the current limitations on the urban metabolism framework with regard to sustainable urban development and explore the opportunities presented in smart cities based on the fourth research paradigm. This was done as a targeted literature review of these four domains.

The second outcome was to develop a new framework for urban metabolism based on the findings from the literature. The primary methods included here were theory building on the urban metabolism methodology (systems thinking, material and energy flow analysis, system boundaries, etc.), combined with opportunities arising in the fourth paradigm research (sensing and big data analytics) (Paper I; Paper III).

The framework could not be regarded as complete without confirming that its necessary data sources exist or can be made available. Therefore the third outcome was based on single-case study research to identify potential data sources for implementation in urban districts (Paper I). This involved several workshops, interviews, and meetings to locate existing siloed data sources.

The fourth outcome was to develop an ICT platform that could support the new framework using DDR methods (Nunamaker et al., 1991b). There were three main phases involved in this:

1. Building a conceptual model that described the platform's requirements and functionalities (Paper I).
2. Based on the conceptual model, designing and analyzing one or multiple alternative system architectures (Paper II).
3. Developing a first prototype, using agile development methodology (Maruping et al., 2009) (Paper III).

The ICT platform consists of three main components: data model, integration platform, and calculation engine. The calculation engine, which was the fifth outcome, was developed based on principles of urban metabolism. The sixth and last outcome of this phase was developing feedback mechanisms (Paper III), which was based on DDR methods and interviews with stakeholders.

3.1.4 Phase 4 – Test the Artefact

Once the platform was developed, it was necessary to demonstrate that it meets the requirements and functionalities described in its design. This validation was achieved through four distinct outcomes. Ellis and Levy (2010) add that a critical part of this phase is to validate that the platform actually works in the context of the problem it was intended to solve, pointing out that the researcher bears the responsibility for ensuring that it "is indeed applicable in the proposed context and can demonstrate some viable results in addressing the problem" (Ellis and Levy, 2010, p. 113).

The first outcome of Phase 4 was of an organizational nature. It was based on developing the necessary partner consortium, identifying incentives, establishing agreements with data providers, and identifying feedback needs of the different stakeholders in SRS, all of which were based on single-case study research (Paper I; Paper III). The second outcome was more technical and was based on integration of real-time data sources and collection of necessary static data, using methods from DDR (Paper II; Paper III). The research methods used here were drawn from software engineering research. Once the data had been integrated, it was possible to verify the results from the real-time metabolic flow calculations, comprising the third outcome based on urban metabolism (Paper III). The fourth and last outcome of this stage was to test the different feedback solutions that had been prototyped, and this was also based on software engineering (close to human-computer interaction (HCI) research) (Paper III).

3.1.5 Phase 5 – Evaluate the Test

Once the new framework had been designed, developed, and tested, it was evaluated with two outcomes in mind. The first of these was a qualitative evaluation of the single-case study that can support researchers and practitioners when implementing the framework in other locations (Paper III). The second outcome was to evaluate whether or not the framework and, in particular, the big data generated from it can address the problem formulated in the thesis and uncover new sustainability intervention measures. This was based on urban metabolism research within the fourth research paradigm (big data analytics) (Paper IV; Paper V).

3.1.6 Phase 6 – Communicate Results and Conclusions

The last phase was to contribute to the body of knowledge through proper communication and dissemination of results and conclusions. This was done through a number of conferences and presentations to different audiences of stakeholders, researchers, and professionals, locally and internationally. In addition to the presentations, there were a number of reports and publications in scientific journals and conferences, which are summarized in this thesis, as well as additional papers that are being prepared.

4 Results

This chapter presents the results obtained, structured based on the three thesis objectives. It begins by presenting findings from the literature review of existing urban metabolism studies and then describes the resulting Smart Urban Metabolism framework that overcomes some of the barriers of conventional urban metabolism. Next, it describes the design and development of the supporting ICT platform, including its data model, integration platform, metabolic flow calculation engine, and various feedback interfaces to different stakeholder groups. The lessons learned from the case study implementation and its obstacles are then presented, along with recommended implementation processes for future implementation of the SUM framework. Lastly, two case studies on utilizing the resulting big data from the SUM framework to explore resource efficiency measures in the city are presented. The relationships between thesis objectives, results, and papers are outlined in Table 3.

Table 3. Summary of results obtained with respect to the three main objectives set for this thesis work

Objective	Results	Paper
Investigate how the urban metabolism framework, aided by ICT, can be utilized to support decision making in an urban development context.	Current limitations of the urban metabolism framework in the context of urban development identified	I
	Smart Urban Metabolism framework developed	I, III
Develop an ICT platform for real-time, high spatial and temporal resolution, urban metabolism data and evaluate its implementation	1. ICT platform developed (development described, preliminary exemplified feedback solutions presented)	I, II, III
	2a. Solutions to implementation obstacles in SRS context described	III
	2b. Solutions to the real-time operation obstacles in the SRS context described	II
Highlight the potential for efficiency improvements through the use of historical, high spatial and temporal resolution, urban metabolism data	3.1 Energy efficiency in Stockholm analyzed	IV
	3.2 Waste collection efficiency of Stockholm analyzed	V

4.1 Urban Metabolism Limitations and New Potentials Enabled by ICT

This section presents the findings on the limitations of the urban metabolism concept based on the literature. As a response to these limitations, a new concept is introduced based on the opportunities that are enabled by ICT.

4.1.1 Current Limitations of Urban Metabolism in the Urban Development Context

While urban metabolism has reached a milestone in its maturation (Kennedy and Hoornweg, 2012), its influence on sustainable urban development is still restricted due to a number of limitations. Therefore, further development is required on the framework in order for it to support the necessary transitions towards sustainability. Paper I and Paper III identified the following four limitations (L) with the urban metabolism approach:

L1: Lack of data at the city scale. This is a primary reason why there are still only a limited number of comprehensive urban metabolism studies (Hodson et al., 2012; Ngo and Pataki, 2008).

L2: The high resource requirements needed to conduct urban metabolism studies. Due to the necessity for complete and accurate data on the metabolic flows, collecting, organizing, and harmonizing all the necessary data is a work-intensive and challenging process (Minx et al., 2010).

L3: The limited studies on the evolution of a city's urban metabolism. The urban metabolism framework is sometimes used for climate action planning (Kennedy and Sgouridis, 2011). These plans are not necessarily effective policy instruments, since they often remain as snapshots in time. In most cases they are not coupled with a monitoring program and, when they are, those programs are usually inadequate to describe whether or not climate targets were met and why (Boswell et al. 2010).

L4: Difficulties in identifying cause and effect relationships. Due to their static nature, conventional urban metabolism studies cannot describe the dynamic relationship between environmental performance and urban patterns (Alberti, 1999). A way to understand this dynamic relationship of metabolic flows has therefore been called for by Minx et al. (2010). Conversely, there is a need to understand how urban stakeholders affect these flows and their corresponding economic and social consequences (Barles, 2010). Furthermore, there is a need to know how urban metabolism changes in the short and long term as a result of changing policy instruments and planning decisions (Kennedy et al., 2007). To overcome these barriers, this thesis proposes the development of an ICT-enabled real-time urban metabolism concept, namely Smart Urban Metabolism.

4.1.2 The Smart Urban Metabolism Concept

The concept of Smart Urban Metabolism aims to provide a deeper knowledge of energy and material flows in urban areas that better reflects reality, by integrating and analyzing real-time, high spatial and temporal resolution urban metabolism data (Paper I; Paper III). This integration is based on heterogeneous data sources such as sensors and smart meters from utilities, organizations, buildings, apartments, and ICT devices of citizens. Hence, the SUM concept advances the conventional urban metabolism concept based on urban ICT and smart city solutions, to enable a real-time and dynamic understanding of the urban energy and material flows at a continuum of urban scales, from city to citizen. This understanding may provide actors with a better basis for decision making through increased awareness of the consequences of their decision system. Such actors include urban planners, utilities, organizations, building owners, and citizens. By virtue of better continuous understanding of metabolic flows, SUM could support the automatization of relevant decisions towards optimization of the metabolism of a city. The key features of the SUM concept are:

i. It is based on the integration of siloed, heterogeneous, high spatial and temporal resolution real-time data on metabolic flows.
ii. It analyzes these flows in a real-time calculation engine to provide real-time data and feedback on metabolic flows of energy, emissions, water, materials, and waste.
iii. It enables continuous and tailored feedback of these flows to urban decision makers, including city officials, organizations, and citizens.

The limitations of the conventional urban metabolism concept (L1 through L4) listed in section 4.1.1 are addressed by the SUM concept in the following respects:

L1 in SUM: It overcomes the (perceived) lack of data at the city and district scale by integrating existing and siloed urban sensors.

L2 in SUM: While the initial set-up of the SUM concept will most likely be even more resource-intensive than the work required for conventional urban metabolism, subsequent studies are carried out with virtually no added data collection efforts. This allows researchers to focus more on understanding and researching the data, rather than collecting data.

L3 in SUM: Since little additional resources are needed for studying the evolution of the metabolism and the SUM concept is inherently continuous, this limitation is overcome.

L4 in SUM: The SUM approach, through high resolution data, provides substantially better insights into correlations and patterns in the city, which can lead to better interventions, although it cannot yet be claimed that it leads to a true understanding of causalities that govern cities. However, there is a belief that research on big data is indeed intended to go beyond correlations to causations (Pietsch, 2013).

To summarize, the novelty of this concept is that it is based on the full spectrum of temporal and spatial resolution data on metabolic flows. SUM simultaneously assesses spatial ranges from a region or a city down to a household or an individual, and temporal ranges from past decades to past minutes (Paper I; Paper II; Paper III), thereby enabling a better understanding of causalities that govern cities (Paper I, III), which in turn can lead to the identification of new intervention measures towards sustainable urban development (Paper IV; Paper V).

The differences in these frameworks can be categorized into nine aspects. These are: levels of intended decision makers, temporal resolution, spatial resolution, data quality, monitoring of targets, continuity, resource requirements, feedback, and exploration of causalities in urban areas (subject of further discussion in the next chapter).

4.1.3 Smart Urban Metabolism Framework

The SUM framework builds on the conventional urban metabolism framework developed by Baccini and Brunner (2012), Princetl and Bunje (2009), and Kennedy and Hoornweg (2012). The system boundaries of the SUM framework rely on those proposed in the systems perspective of Kennedy and Hoornweg (2012), which integrate the Eurostat material flow analysis (Eurostat, 2015) with methods for energy, water, substance, and material flows. The procedure of implementing the framework is of necessity different, however.

The process of implementing the conventional urban metabolism framework proposed by Baccini and Brunner (2012) and Princetl and Bunje (2009) was summarised in Table 1. The SUM framework differs from that process with regard to data collection, stakeholder integration, and data management. The SUM process comprises the steps listed below and depends on the aim of the SUM study. If the aim goes beyond monitoring and feedback to identifying intervention measures, then steps 10 and 11 apply. If the aim also includes monitoring of implemented interventions in real time, step 12 applies.

1. **Define stakeholder goals and interests**. For instance, a local government may ask: “What intervention measures should be applied, and where, to reduce energy dependency on fossil fuels?”
2. **Define corresponding key performance indicators (KPIs) and metrics**.

These are defined such that they can inform each stakeholder of the achievement of their goals.

3. **Define the system**. Develop local system boundaries for the urban flows and related sub-systems. Verify the accuracy of the proposed system with stakeholders.
4. **Identify real-time data sources.** Document relevant data (real-time and static) currently collected by the local government, local utilities, local organizations, and in existing and planned buildings. If these are insufficient to represent the KPIs, identify what additional sensors need to be deployed, and by whom.
5. **Set up a consortium of data owners.** Data rights and responsibilities are managed in a consortium agreement, ensuring data owners that their data will not be managed outside the consortium and what partners will be allowed what access.
6. **Develop an integration platform.** Designed in collaboration with each data owner's IT department for access and integration of their data.
7. **Develop a metabolic flow calculation engine.** This generates the KPIs based on the system boundaries set. Verify outputs.
8. **Develop interfaces (**Application Programming Interfaces, **APIs)**. These manage user access to specific KPIs for feedback in the various interfaces.
9. **Design and develop feedback/visualization interfaces.** These should be developed with stakeholders and according to their interests and goals.
10. **Conduct sub-system in-depth analytics**. Identify intervention measures by studying big metabolic flow data to identify patterns, correlations, clusters.
11. **Evaluate and report findings**. Evaluation in collaboration with stakeholders.
12. **Follow-up results of interventions in real-time**. If merited, conduct a second sub-system analysis to achieve an understanding of associated causalities.

An overview of the SUM framework and steps 4-11 is provided in Figure 1. In most cities, a wealth of real-time data is already being collected by various organizations and agencies (Figure 1: A. Urban sensors), such as energy utilities, waste utilities, water utilities, traffic agencies, building managers, and power grid managers. However, most of these data are used for billing purposes, not to support efficiencies in the city. Once the three first steps of the SUM framework are completed (define stakeholder goals, define KPIs, define system), the next task is to integrate these siloed and heterogeneous data streams and, if necessary, add additional sensors relating to the goals. These data streams are then integrated into an integration platform (Figure 1: B. Integration platform). To understand the metabolic flows, hybrid emission and flow factors (Figure 1: C. Real-time and static emission/flow factors) are combined with the integrated sensors data, and are then structured and stored in a data model (Figure 1: D. Smart Urban Metabolism data model), a sufficiently detailed representation of the city. The data model sends the structured urban sensor data and the flow factors to the calculation engine, which processes and returns the results in real time (Figure 1: E. Metabolic flow calculation engine).

From here, the resulting metabolic flows can be fed back (Figure 1: F. Feedback KPI APIs), for up to real-time feedback through designed interfaces/visualizations corresponding to their goals (Figure 1: G. Real-time feedback). These inform decision-makers by visualizing the system consequences of their decisions. In addition, there is long-term feedback to decision makers. Stored real-time data enable big data analytics of sub-systems, with the aim of uncovering system inefficiencies to identify intervention measures (Figure 1: H. In-depth sub-system feedback – Big data analytics). Both the real-time and the in-depth feedback are communicated through various means to stakeholders or decision-makers (simplified as: Figure 1: I. Local government city officials, J. Building owners/Organizations, K. Households/Citizens).

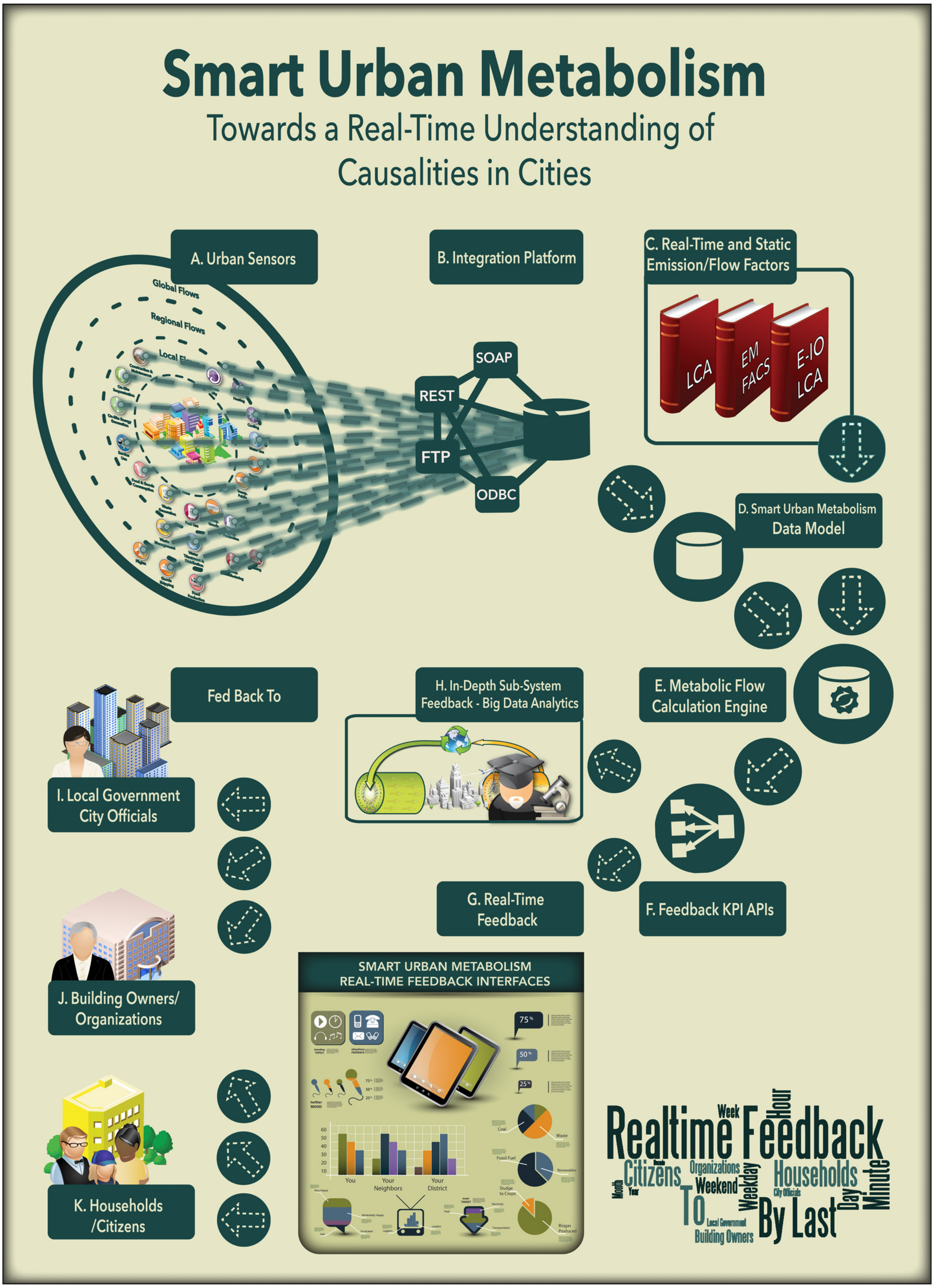


Figure 1. Overview of the Smart Urban Metabolism framework developed in this thesis. Please refer to the section above for a description.

4.2 ICT Platform Development, Implementation, and Evaluation

This section describes the ICT platform and is divided into two sub-chapters that present the methods needed to develop the platform. Developing the integration platform and data model primarily relied on software engineering (Paper II), while the calculation engine drew from principles of urban metabolism (Paper I; Paper III).

4.2.1 ICT Platform Development

Given the continuous characteristic and data-intensive nature of the SUM concept, it must rely on an operational ICT platform (Figure 2). This ICT platform consists of two internal standard elements, an information management system (IMS) and a calculation engine. The ICT platform is coupled with external, case-specific feedback interfaces.

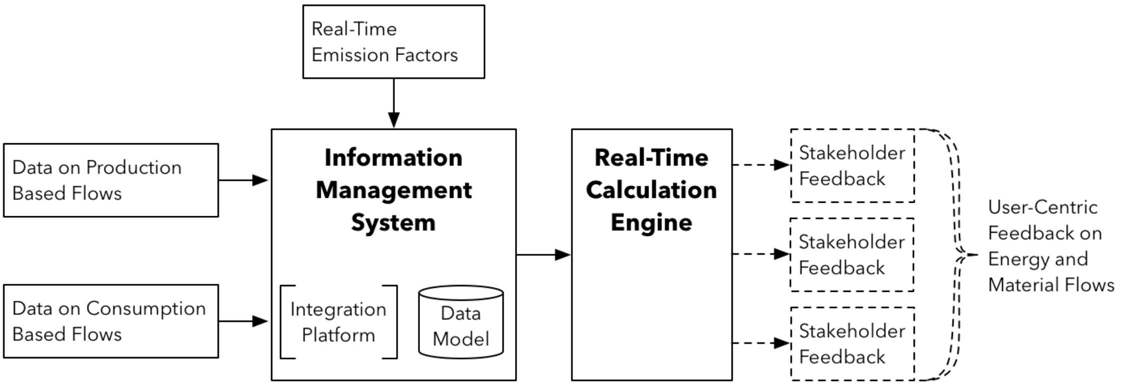


Figure 2. Schematic ICT platform for smart urban metabolism.

As illustrated in Figure 2, the information management system in turn consists of an integration platform and a data model, which are further described in the following section.

Information Management System

The IMS consists of two components, an integration platform and a data model. The integration platform integrates and transforms production- and consumption-based metabolic flow data, as well as real-time emission factors (Paper II). These are stored in a data model that represents the city.

To develop the integration platform, the first step is to determine exactly what type of data (flow type, frequency, and delay) will be integrated. It is safest to arrive at a consensus to convert data to SI units and also to make all conversions in one place. This practise avoids calculation errors, because a metric such as domestic hot water could otherwise be expressed in cubic meters, liters, or kWh of energy. While such considerations may seem trivial, they need to be carefully managed to avoid errors, since the ICT platform involves more people influencing data than would e.g., a spreadsheet. The data integration can be done in different ways, which are perhaps best described by the two extremes. The first extreme is where all data owners are required to send data to a single API as defined by the SUM development team. The other extreme is that the SUM development team fully customizes each integration to each data owner's current system, with minimum effort for their IT departments.

Once established, the integration would most likely take the form of a REST or SOAP API, or a script (such as "cron jobs") running on each side reading and writing to an (S)FTP server, or a direct ODBC connection. Depending on security requirements, the nature of the necessary systems, requirements of flexibility, and so forth, these architectural decisions need to be made on a project-by-project basis and, in some cases, on an integration-by-integration basis. Researchers and other professionals conducting SUM studies may not necessarily have as much direct control of the data collection process as they might have had when conducting conventional urban metabolism studies. This emphasizes the need for clear documentation on behalf of the system integrators.

The integration platform has an API layer for external access. Through authorization for specific entities (district, building, apartment, etc.), stakeholders can access outputs from the data. By asking for an entity during a time period, the API responds with all relevant indicators for external feedback and visualization purposes.

Once the data streams have been integrated and clarified, they need to be structured, organized, and related in a data model that represents the city (whether a relational or semantic data model is chosen (Kotoulas et al., 2012)). While there are a number of existing quasi-standard data models (such Open Street Maps), there are several aspects relating to the metabolic flows that these existing models will not be able to represent, in which case new data modeling might be needed.

New data modeling would most likely require systems thinking together so that the flows, conversions, and KPIs can be appropriately represented. It may also raise some detailed geographical system boundary types of questions such as: What is the smallest geographical unit (apartment, room, citizen)? If a green space between two different buildings is maintained, how should the maintenance flows be divided (equally, proportionally by capita, by area, etc.)? Should aggregations be linear, or should the system boundaries be different for a household, a building, and a district (since the purpose of their activities are different)? When answers (or assumptions) have been found to most of these systems thinking questions, the data model can be considered to be prepared to respond to the requirements for implementation of SUM. The various types of data populating the data model are presented in Paper III.

Calculation Engine

To transform integrated and structured urban data into interconnected metabolic flows, a calculation engine needs to be designed and developed (as described in more detail in Papers I-III). The SUM calculation engine executes two primary types of calculations: flow coefficient calculations and flow aggregations. Flow coefficient calculations generate metabolic flows from metered data, e.g., acidification potential based on domestic hot water use. Another example would be share of renewable energy metabolism by combining the real-time consumption with real-time production emission coefficients for district heat and for electricity (based on their current respective grid mixes). Flow aggregation calculations aggregate flows spatially (levels from citizen/apartment to district) and temporally to deliver KPIs. This could be total water use for a block or a district during the last month, or the greenhouse gas emissions of a household during the last week. For each sensor, the data model needs to know whether or not to use it for aggregations, since there can be multiple sensors measuring the same flow, leading to double counting (Paper II), in which case one is selected for aggregation while both can be used for KPIs on that level. To support this, a coefficient library needs to be established, integrated, and maintained, so that it is representative for the location of the study. Outputs of the calculation engine are evaluated by comparing control calculations with manual calculations in other tools which generate the same results. To inform decisions, these metabolic flow outputs then need be fed back in a relevant context.

4.2.2 Results from ICT Platform Implementation in SRS

The results presented in the following are derived from implementation of the ICT platform in the context of the urban district SRS (Paper I; Paper II; Paper III).

Data Integration and KPIs

In stakeholder workshops, the indicators deemed most important by the stakeholders and reflective of the sustainability program of SRS were: kg CO2e/capita, kWh primary energy/capita, energy use intensity (kWh/m^2), and share of renewable energy use (%). There were several organizational barriers to data integration, as described in Paper III, with the most challenging barrier being that of incentives and business value for the data of industry partners. After extensive efforts to overcome these barriers, the calculation engine was then verified by comparing its automated KPIs to manually derived control calculations. Throughout the testing, the only differences that were encountered were rounding errors. The system boundaries for the selected KPIs in the Smart City SRS are described in Paper III.

Feedback

Once data had been identified, integrated, structured, and computed as metabolic flows, they were able to reach fruition in supporting decision-making processes through feedback. There are two major types of feedback in the context of the SUM framework, real-time feedback and in-depth feedback of sub-systems based on big data analytics. The feedback presented here is only the direct outcomes of the Smart City SRS project (Paper III) and, apart from the real-time SUM Sankey diagrams, only represents examples of feedback that the SUM framework can generate. Given resource constraints, these were developed based on experimentation to meet local needs and are in various stages of development. The interfaces presented here were aimed at four different stakeholder groups: 1) system scientists, 2) city officials, 3) building owners, realtors, and architects, and 4) citizens.

Feedback Stakeholder Group 1: System Scientists – Real-time SUM Sankey Diagrams

As an integral part of the SUM framework, a real-time SUM Sankey diagram was developed that illustrates the metabolic flows of an apartment, building, and district in real time (Figure 3). The data on mobility and transportation data currently use the statistics layer of the calculation engine and the other consumption flow data are updated in real time. For production data, electricity and district heat production is updated in real time, while emissions factors for waste and water are static. The ability to follow three concurrent Sankey diagrams over time, representing the same flows at different spatial scales, creates new opportunities to identify patterns and correlations that may provide insights about the causalities that govern the metabolism of cities.

Feedback Stakeholder Group 2: City Officials – Building Monitoring App

The work described in this thesis orginated from a desire to achieve sustainability targets and to measure and verifiy target achievement from the SRS sustainability program. Therefore, a simple app was developed with this in mind. It allows city officials to determine whether the buildings being built are meeting their performance targets and to benchmark them against the neighborhood average (Figure 4). It also verifies that the APIs are working correctly and that the calculation engine is generating the predicted outputs. This app was designed by a project participant.

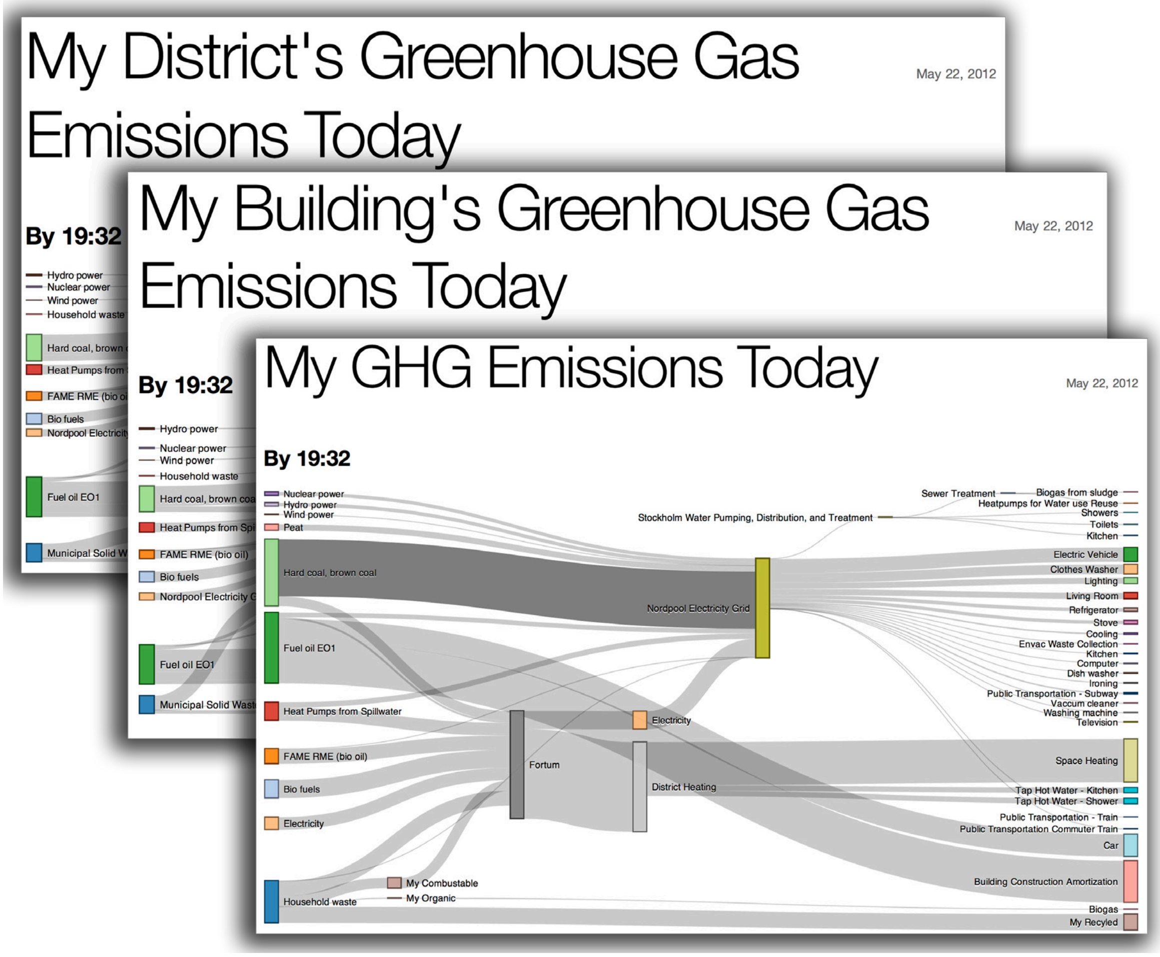
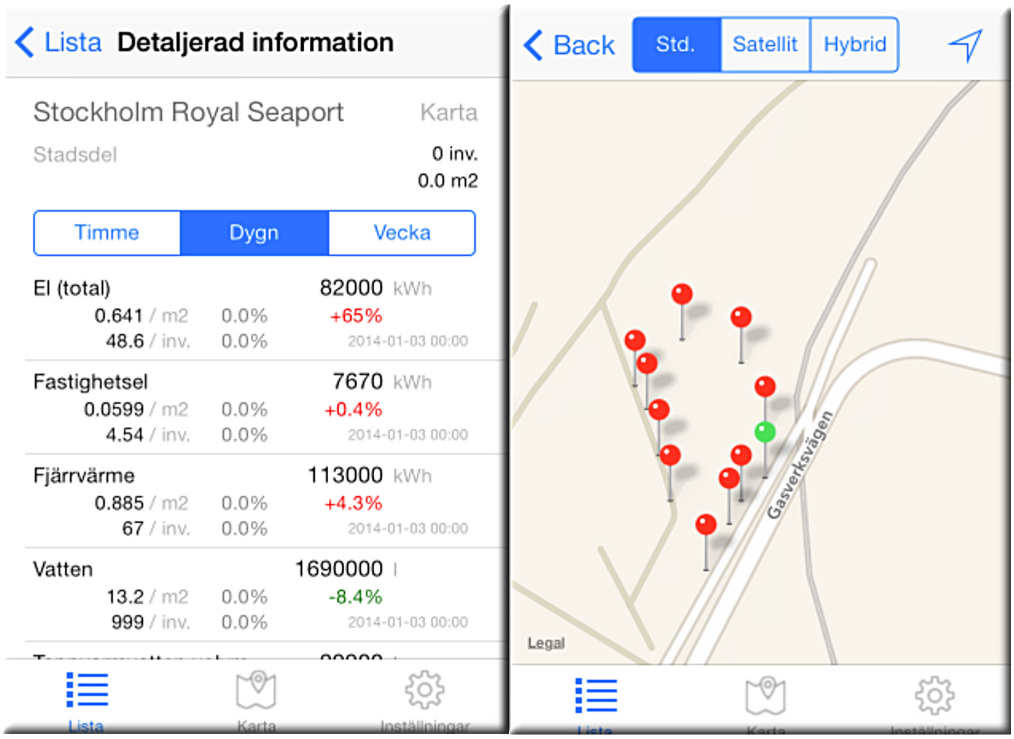


Figure 3. Example of feedback to system scientists through real-time Sankey diagrams on the district level, building level, and household level, at the same time. Please refer to Paper I for further description (reproduced from Paper I).



Stockholm Royal Seaport
Stadsdel
0 inv.
0.0 m2

El (total) 82000 kWh
0.641 / m2 0.0% +65%
48.6 / inv. 0.0% 2014-01-03 00:00

Fastighetsel 7670 kWh
0.0599 / m2 0.0% +0.4%
4.54 / inv. 0.0% 2014-01-03 00:00

Fjärrvärme 113000 kWh
0.885 / m2 0.0% +4.3%
67 / inv. 0.0% 2014-01-03 00:00

Vatten 1690000 l
13.2 / m2 0.0% -8.4%
999 / inv. 0.0% 2014-01-03 00:00

Figure 4. Building monitoring app (in Swedish) for city officials (reproduced from Paper III).

Feedback Stakeholder Group 3: Building Owners, Realtors, and Architects – smARt Viz

On building level, one of the most obvious and widely adapted practises is that of building portfolio management (Volk et al., 2014), working towards optimized portfolio-wide energy use, and in some cases also emissions. Another use for feedback could be for marketing and promotion of green buildings. One pre-study to the Smart City SRS project was a visualization-oriented study called "On-Site Visualization" (led by the Interactive Institute in collaboration with the author), which investigated the possibility of using Augmented Reality to visualize sustainability data with the purpose of providing the right feedback, at the right place, and at the right time. This was later called smARt Viz and two prototypes were developed.

The first prototype was intended for citizens to enable feedback on household waste generation based on the SUM platform. Household waste is measured by household, fraction, and waste in real time. This prototype enabled the visualization of paper, plastic, and combustible waste (Figure 5a). Later, in dialogue with the US Green Building Council's Research Program (Paper III) in relation to their Green Building Information Gateway, they proposed an ability to respond to the question: "What's the greenest building near me?" The SUM calculation engine was enhanced to enable it to answer that question and the Interactive Institute, together with Greenelizer (Paper III), made a prototype that works in a neighborhood in a district, as illustrated in Figure 5b and Figure 5c.

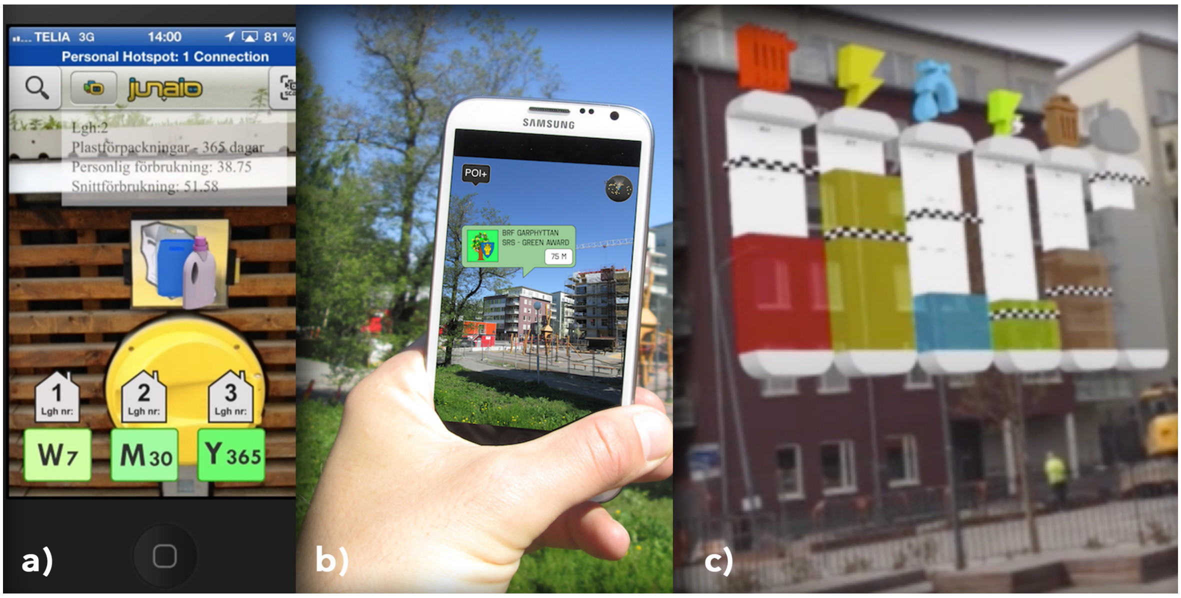

Lgh:2
Plastförpackningar - 365 dagar
Personlig förbrukning: 38.75
Snittförbrukning: 51.58

Figure 5. Augmented reality solution smARt Viz. a) Household-specific plastic waste feedback compared with the neighborhood average (where 'less than full' means less than the neighborhood average). b) Visualization of the "greenest building near me". c) Actual performance compared with the neighborhood average when getting closer to the building. Visualizations developed in collaboration with the Swedish ICT's Interactive Institute and Greenelizer (reproduced from Paper III).

Feedback Stakeholder Group 4: Citizens – Smart City SRS Dashboard

A key distinction of SUM compared with conventional urban metabolism is that it enables feedback to households and citizens, although such feedback has to be carefully designed, as a response to citizens' desire to get sustainability feedback in a context that is relevant to their daily lives. In collaboration with a Master's student (Ectors, 2014), a personal informatics dashboard was developed. The dashboard integrates 25-30 different real-time data sources, including sustainability metrics, to provide residents of SRS with actionable real-time information. It also includes weather, with actionable information such as "Bring an umbrella" (Figure 6a) or, if a high relative temperature drop is identified, "Bring warm clothes". The dashboard includes routing options for public transport, road congestion, and traffic cameras, and it can be set to send a text message alert if these problems result in a need to wake up earlier in order to reach a destination on time. On the sustainability side, beyond the grid mixes and the KPIs, there is also a recommendation engine that compares the electricity use from the day before with the grid mix production, and instructs residents on how they could have shifted their loads to adapt to the grid and lower their emissions (Figure 6b).

The dashboard also feeds back the real-time neighborhood mood via Twitter analytics near the residents (Figure 6a). The Twitter mood analytics calculations are based on a recent study that analyzed three emotions in a word library of 13,915 words (Warriner et al., 2013). Each word is assigned a value of 0-10 for the respective feeling and each tweet is the weighted mean of all its words (e.g., 0 sad, 10 happy). Based on these words, the Twitter mood is continuously fed back and monitors the "pulse" of the local area quite well. It works particularly well with regard to sports and politics.

Local criminal activity in the vicinity of a resident's home over the past three days is also fed back. As the crime database is populated over time, it could also serve as a source of predictive analysis that could correlate crimes to locations, dates, times, and perhaps also the Twitter mood (e.g., intersections and dates with an increased risk of incidents). Integrated with this is the City of Stockholm feedback mechanism for reporting issues in and around in the city. Among social data streams, these were those integrated to the dashboard within the limited time of the Master's thesis[1].

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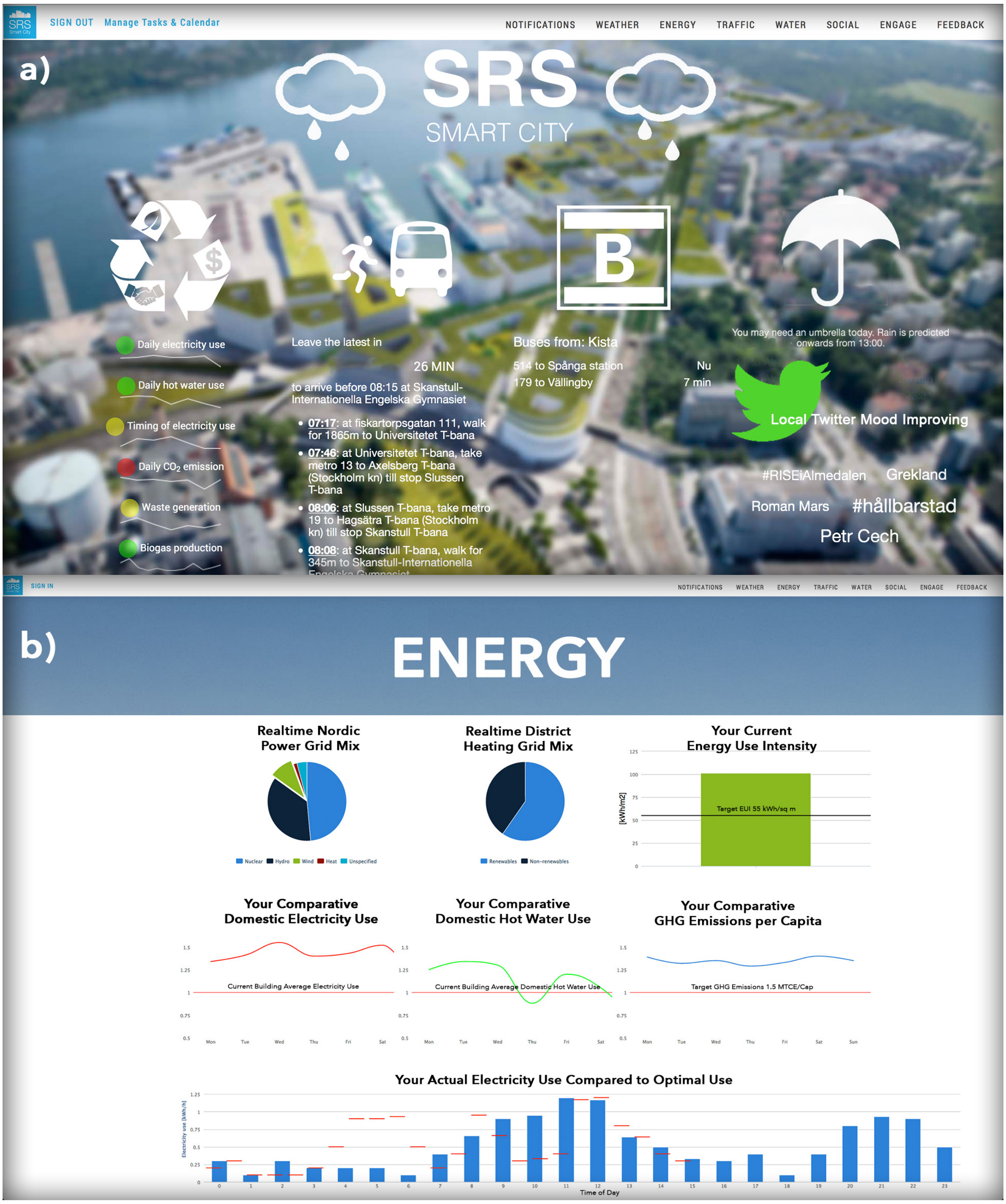
[1] Ectors received KIC InnoEnergy's best thesis award for 2014.



Leave the latest in

26 MIN

to arrive before 08:15 at Skanstull-Internationella Engelska Gymnasiet

- 07:17: at fiskartorpsgatan 111, walk for 1865m to Universitetet T-bana
- 07:46: at Universitetet T-bana, take metro 13 to Axelsberg T-bana (Stockholm kn) till stop Slussen T-bana
- 08:06: at Slussen T-bana, take metro 19 to Hagsätra T-bana (Stockholm kn) till stop Skanstull T-bana
- 08:08: at Skanstull T-bana, walk for 345m to Skanstull-Internationella Engelska Gymnasiet

Buses from: Kista

514 to Spånga station	Nu
179 to Vällingby	7 min

You may need an umbrella today. Rain is predicted onwards from 13:00.

Figure 6. a) Dashboard notification center and b) sustainability section. For link and further description, please refer to Ectors (2014). Reproduced from Paper III.

4.2.3 Evaluation of the SUM Tool in SRS

The following section provides an overview of the challenges and obstacles to implementation of the SUM tool in SRS (Paper II; Paper III).

Implementation Obstacles

The SUM implementation encountered several obstacles that are described in detail in Paper III and summarized here. These implementation obstacles were identifying incentives and establishing trust for data sharing, and designing relevant feedback.

Identifying Incentives and Establishing Trust for Data Sharing

A significant challenge was to convince stakeholders to share business-sensitive data. There are three functions in a given organization that need to work together to make this succeed (provided no legal issues are at stake): 1) Management, 2) Business Development, and 3) The IT Department. The SRS case study initially focused on obtaining commitments from high-level managers. However, business developers also had to give their approval. In most cases they would ask about the short-term benefit to them from collaborating and sharing data.

To overcome this obstacle, it was suggested to the stakeholders that, if their data enabled societal benefits, this could potentially translate into a business opportunity for them. This was solved by highlighting that if their data unlocked or enabled societal benefits and efficiencies, they could probably use this for business development. The IT departments of data providers presented a different challenge. They were overburdened with numerous business-critical tasks, and could only support this project in their spare time. Since the plan was contingent on data integration, this challenge delayed the entire project significantly. An early strategic decision was made not to proceed with the other development without all the data being on hand and the “data hunt” was part of a data collection and integration effort of outreach and reminders. The rationale was that moving along without all data providers’ data could disincentivise them from sending any real data, which would almost completely diminish the value of the project.

After almost twelve months, this strategic decision was reversed and data for the entire district were simulated by the research team so that the feedback interfaces could be developed and tested. This allowed the project team to tangibly demonstrate the uses of the SUM platform and actually increase motivation for stakeholders to send data. As each data provider sent data, these gradually replaced the simulated data.

Designing Relevant Feedback

Much effort went into developing KPIs for citizens. For the city, utilities, and building managers, it was easier to communicate KPIs, while the case of the citizens was more challenging. Their honest opinion was that the four KPIs currently generated did not necessarily pique their interest in further visualization and feedback (Paper III). They suggested that “If these four indicators for my household were shown in a larger context that directly related to my daily decisions, I might consider using them". That key end-user feedback indicates the need for sustainability scientists to acknowledge that sustainability issues might only constitute a fraction of daily attention spans. The conclusion was that to achieve the aim of increasing awareness and empowering citizens about the sustainability consequences of decisions, this awareness needs to find its small place in relation to all their other everyday commitments and responsibilities. The dashboard developed was one limited attempt at providing such feedback.

In summary, to overcome these obstacles, it is recommended that managers of stakeholders engage their business development and IT staff at an early stage and that a dialogue is maintained with citizens about how they prefer to receive their sustainability feedback.

Operational Obstacles

During operation, typical software engineering challenges arose. These ranged from failed integrations, the occurrence of data gaps (Paper II), and misinterpreted data values to incomplete datasets (Paper III). Implemeting SUM relies on engaged stakeholders, and the primary reason for these challenges was their resource limitations. Most of these issues occurred outside the project duration and therefore outside the budget. Some integrations failed due to staff changes on the data owner side and the ICT platform side, while others failed due to system changes on the data provider side. Due to the failed integrations, large data gaps occurred for some data providers, making it difficult to get a good evaluation of the metabolism of the district.

To overcome these obstacles, continuous dialogue was required to establish and restore the integrations. Another challenge that arose was that the district heating data for the buildings in the study area were provided by an aggregate meter that included data from other buildings and from the construction site. To overcome this issue, a sub-metering company that was not an original project member was contacted. Based on agreements from the citizens, this company agreed to provide the correct data from their sub-meters. A lesson learned from this is that projects implementing SUM should budget for a longer maintenance period than the actual project development cycle.

Furthermore, the information management platform was changed four times and each time the integrations had to be re-done. The technology provider had to change all its servers in the middle of the project and, in this process, some integrations were lost and had to be rebuilt. After the project, the project participants and I developed a local test environment to continue development of the platform and, once that had been tested, the integrations needed to be moved to a production server. When analyzing the data, data gaps were discovered and the data suppliers were asked to send data again.

4.3 Resource Efficiency Potential

Successful implementation of the SUM framework leads to the generation of stored and structured big metabolic flow data of high spatial and temporal resolution. The combined historical big data from stakeholders enable in-depth studies into sub-systems that may uncover previously inaccessible insights. Stakeholders could then initiate studies to identify intervention measures and solutions to their needs, through in-depth big data analytics of metabolic sub-systems. Two such studies that were conducted within the scope of the Smart City SRS project with Stockholm-wide data are presented in the following section.

4.3.1 Case 1 – Energy Efficiency of Stockholm's Building Stock

The City of Stockholm has set a greenhouse gas (GHG) emissions target of 3 tonnes per capita by 2020 (City of Stockholm, 2014) and continuously updates its climate action to steer in this direction. This case study (Paper IV) evaluated the energy efficiency potential in the city using the big district heating metering data from more than 80% of the building stock (roughly 15,000 buildings and 130 million metrics) in Stockholm, which gave new insights into the energy use of the city. A preliminary analysis of the energy efficiency potential revealed that roughly one-third of the energy use could be reduced, corresponding to 144,000 metric tonnes of GHG per year. The greatest reduction potential was attributed to buildings dating from the construction period 1946-1975, while the worst performing buildings were identified as those constructed between 1926 and 1945, contradicting commonly held beliefs (Paper IV). This study was partly continued as a Master's project in collaboration with the Department of Industrial Economics, KTH, as part of the Smart City SRS project (Heijde, 2014)[2]. Here a retrofitting plan was developed that indicated the retrofitting potential of buildings (types, vintages, and locations). The resulting retrofitting map is depicted in Figure 7. This map has interesting implications for the energy efficiency of existing building stocks, as it can be used to show what retrofitting measures should be implemented in what building types (or even buildings), to reach city-wide efficiency and climate targets with the lowest societal investment costs. It will be the subject of extensive future research and development.

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[2] Heijde received the best Master's Thesis award for 2014 from KIC InnoEnergy, as well as Vattenfall's Energy Prize

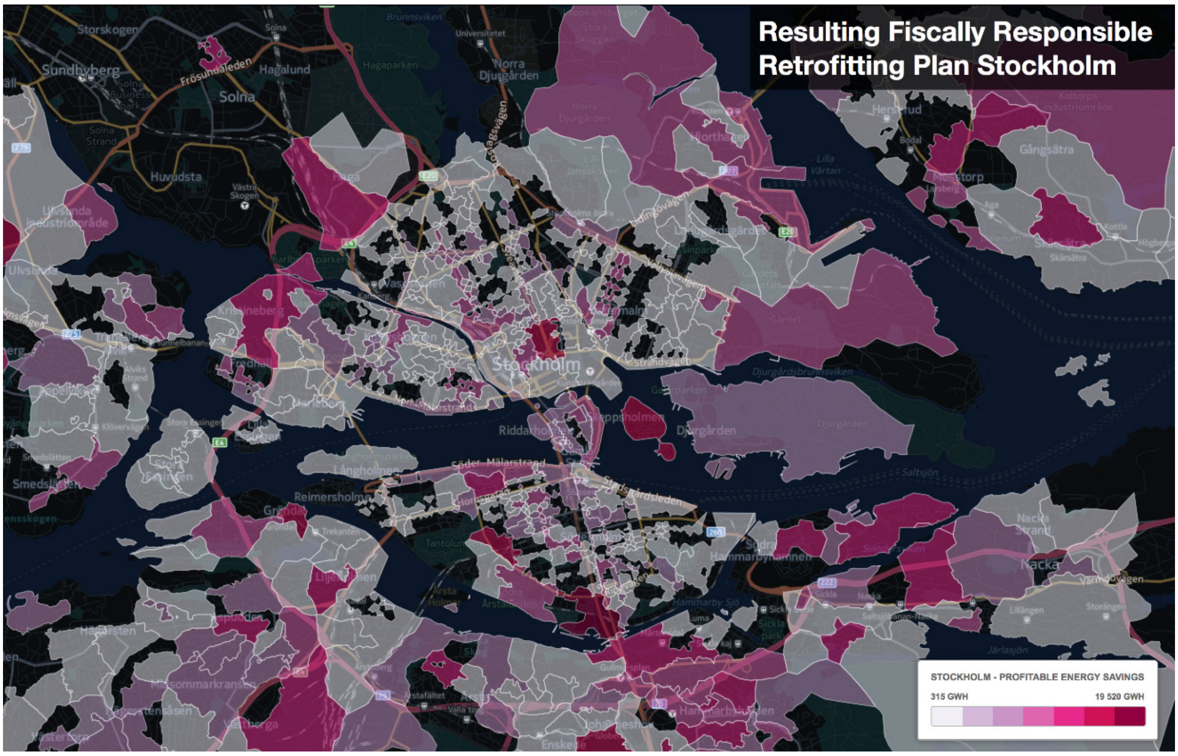

Figure 7. Proposed retrofitting plan aggregated by zip code. Blank areas (holes) are areas where the energy efficiency investments did not pay back quickly enough.

4.3.2 Case 2 – Transportation Efficiency of Stockholm's Waste Collection

This case study utilized big metabolic flow data on waste collection for the City of Stockholm to evaluate the state of waste management and collection processes, to identify potential inefficiencies, and to suggest potential improvements. The study was based on a large dataset consisting of roughly half a million entries on waste fractions, weights, locations, and trucks across 30 waste management companies. The data went through an extensive curation process, followed by batch geocoding of the curated entries.

The result was a series of waste generation maps presenting the current waste generation and collection patterns, with indicators assessing kg waste collected/km. Substantial inefficiencies were revealed, one preliminary finding being that in a short time span, multiple trucks were circulating in the busy streets of Södermalm, performing the same job (Figure 8), collecting bulky waste from customers spread out across the district. Subsequent analysis revealed that a better public procurement process which zoned the city and, when possible, allowed the waste management companies to determine when they collect could reduce time on the road and vehicle miles traveled by 49%.

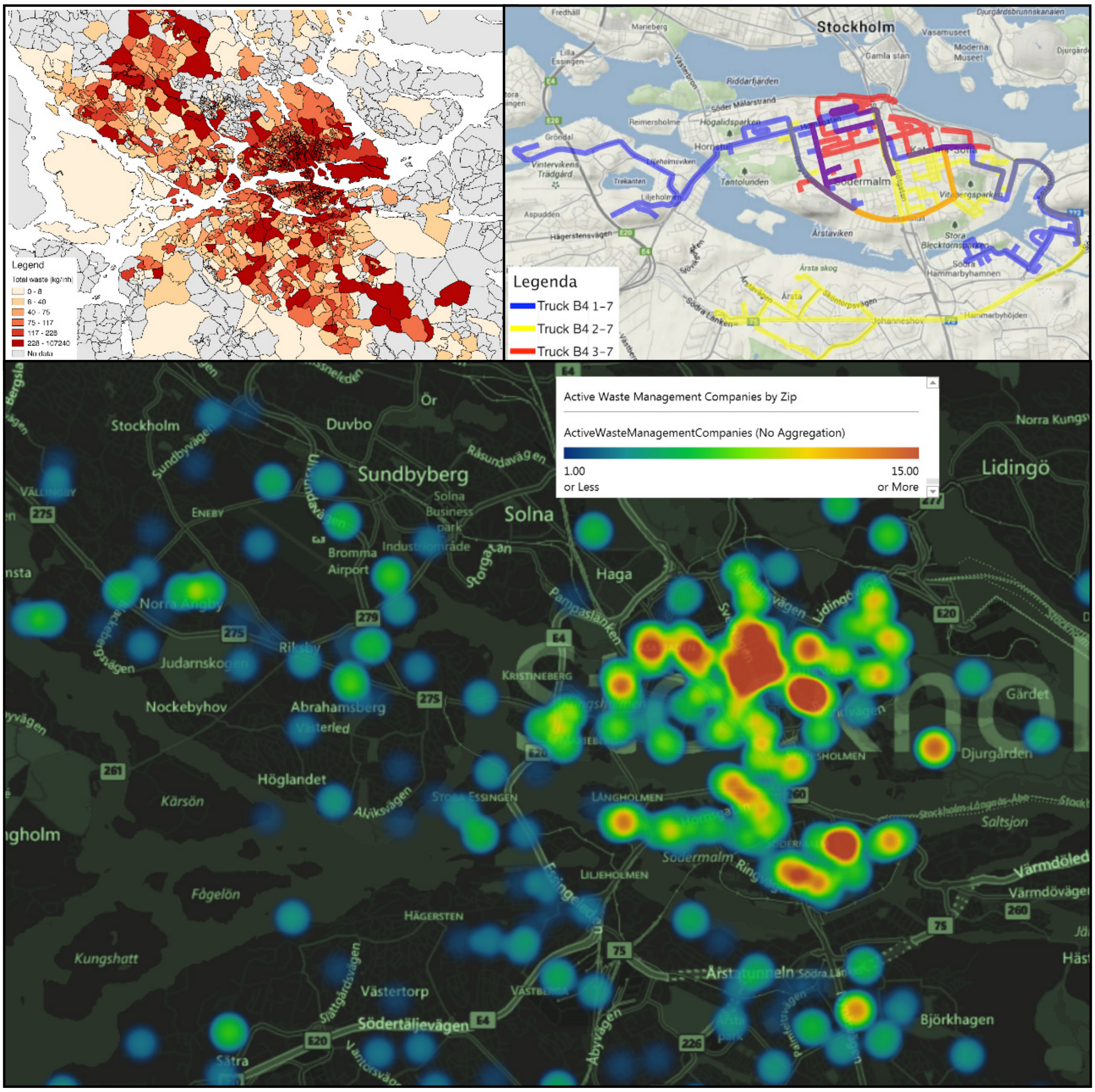

Figure 8. Upper left: Total bulky waste generation in Stockholm, Upper right: Redundant collection trucks on the same roads (Reproduced from Paper V). Bottom: Spatial density of active waste collection companies.

5 Discussion

The discussion is structured around four aspects of the thesis: the results, the methodology, the implications of SUM for industrial ecology, and recommended areas for future research. The results are discussed in four regards (R): by comparing the benefits of the SUM framework with the conventional urban metabolism framework (R1); by evaluating the limitations of the SUM framework (R2); by evaluating the development of the feedback interfaces (R3); and by evaluating the potential of high spatio-temporal urban metabolism data to identify new sustainability intervention measures (R4).

5.1 Benefits of Smart Urban Metabolism Compared with Conventional Urban Metabolism (R1)

To provide an overview of the key benefits of the SUM framework compared with the urban metabolism framework, Table 4 compares these in terms of several functional aspects (A through I in Table 4).

Table 4. Comparison of the Smart urban metabolism framework with the conventional urban metabolism framework

Functional Aspect	Conventional Urban Metabolism	Smart Urban Metabolism
A. Intended Stakeholders	Local governments Local industries	Local governments Local industries Local businesses Local citizens
B. Temporal Resolution	Decade Year	Decade Year Month Day Hour Minute / Second
C. Spatial Resolution	City District	City District Neighborhood Block Building Household Citizens
D. Data Quality	Statistical/average metabolic flow data Statistical/average emission factors	Statistical/average metabolic flow data Statistical/average emission factors Metered/real-time flow data Metered/real-time emission factors
E. Monitoring of Targets	Possible but impractical	Integrated for city/district/building/household level
F. Continuity of research	"One-off' studies	Continuous platform for on-going academic research
G. Resource Requirements	Medium	High in first implementation, marginal for subsequent studies
H. Feedback	Reports on urban metabolism	Big data analytics report of metabolic flows HCI feedback to public officials, local stakeholders, and citizens
I. Exploration of Causalities in Urban Areas	No, Sankey diagrams may lead to the visual identification of correlations	Yes, big data analytics on structured high spatial and temporal metabolic flow data enable the exploration of urban causalities.

A: Intended Stakeholders

Conventional urban metabolism is primarily intended to facilitate decisions by local policy makers and large local industries (Kennedy and Hoornweg, 2012). The SUM framework addresses most stakeholders in the city, including local governments and industries, but also building portfolio managers, building owners, households, citizens, and employees. By providing each stakeholder with individualized and relevant feedback, most stakeholders, including citizens, who are of particular interest for the sustainable urban development process, can be empowered to make more informed and possibly more sustainable decisions.

B, C, D: High Spatial and Temporal Resolution Data, High Data Quality

Conventional urban metabolism studies primarily target the city or district levels, over decades or years, with varying data quality and underlying assumptions, to integrate different datasets. The SUM framework increases the spatial and temporal resolution of data and the quality.

Conventional urban metabolism studies of e.g., energy, water, and greenhouse gases are based on statistics (Newcombe et al., 1978) on average areas of residential, commercial, and public spaces, with average end-use distributions per type, e.g., waste generation statistics on households and commercial spaces, with statistics on waste distribution of municipal solid waste. Transportation flows are estimated based on vehicle-kilometers per citizen (and sometimes employees), and average mode splits for the city, region, or nation are then used to assume how those total vehicle-kilometers are distributed. Construction emissions are usually averaged based on life cycle assessments (LCA) per unit area of soil remediation and construction. Data on consumption of food, goods, and services are derived from statistical expenditure surveys.

For greenhouse gases, in conventional urban metabolism studies average grid mixes are selected for electricity and cooling. If heating is also supplied by a local or district heating grid, that grid mix is factored in too. For automobiles, national statistics on the vehicle fleet are used to derive fuel economy values and emissions. For waste, LCA studies on waste collection, processing, and management are typically used. Consumption of food, goods, and services is usually accounted for by hybrid models with Environmental-Input-Output LCA.

In SUM, flows of electricity, heating and cooling, waste generation, and construction are measured in quasi-real time on the consumption side and, to an extent, transportation is also measured in this way. On an opt-in basis, household expenditure on foods, goods, and services is accounted for. On the production side, some emissions factors are real-time emissions factors (Paper II), while others remain as statistical emissions factors. The real-time emissions factors are those where data on grid mixes or fleet mixes are available in real time. In SRS, this includes the electricity grid mix, the district heating grid mix, and the current vehicle fleet mix on the roads (through real-time, camera-based road tolls).

E, F, G: Monitoring of Sustainability Targets, Continuity, and Resource Requirements

Urban metabolism studies were originally conducted by applying systems thinking to urban statistics and initially summarized with pen and paper (Ayres and Kneese, 1969), later aided by computational software tools (Huang et al., 2006). In practise, they were resource-intensive (Ferrao and Fernandez, 2013), "one-off" studies that in most cases were started from scratch in subsequent studies. To date, only three cities have been the subject of longitudinal monitoring of sustainability performance over time (Kennedy et al., 2007): Hong Kong (1971 and 1997), Sydney (1970 and 1990), and Toronto (1987 and 1999). Moreover, it is difficult to gauge how comparable the outputs of the follow-up studies are with regard to assumptions and data quality. This is an area where the SUM framework provides a particular advantage, since it is not a mere snapshot study. The SUM framework is associated with higher initial resource requirements to establish, but once implemented, it becomes an integral part of the local data infrastructure. Therefore the short- and long-term monitoring of sustainability targets becomes an integral component of the SUM framework. By virtue of its coupled information management system that preserves the transparency of the data, even with changing data streams over years, it facilitates like-for-like comparisons over time. Therefore, the framework enables continuous feedback, knowledge creation, and research.

H: Feedback

Another key distinction of the SUM framework is its ability to provide real-time feedback. Based on the high spatial and temporal resolution and coupled with a real-time calculation engine, this feedback can be provided through HCI-driven interfaces such dashboards, smartphone apps, Sankey diagrams, and augmented reality (Paper I; Paper III) and through simpler solutions such as automated summary reports. Given the different nature of these, real-time feedback in no way replaces the more reflective traditional reports, but may provide decision makers with relevant feedback relating to day-to-day decisions.

I: Exploration of Causalities in Urban Areas

A welcome "by-product" of rich, integrated, structured, real-time data storage is big data that enable analytics of sub-systems. These in-depth studies are very much in line with the data exploration nature of the fourth research paradigm (Lynch, 2009). Thus, it is more explorative in nature and does not always begin with clear and specific questions, but rather a clear aim and solid subject matter expertise surrounding a local sustainability challenge such as energy efficiency (Paper IV) or efficient waste collection (Paper V). This "exploration of big urban data" could entail mapping, identifying previously unknown patterns, clustering, and correlation analyses from which insights may be derived. These insights are useful if they lead to a better understanding of the causalities that govern systems in cities. In turn, this understanding is aimed at arriving at new sustainability intervention measures.

Summary of the Benefits of the Smart Urban Metabolism Framework

As this thesis demonstrates, the SUM framework manages to overcome the limitations encountered in conventional urban metabolism. Following the procedures in the framework (Paper I; Paper III) overcomes the problem of data scarcity at the city level (Ngo and Pataki, 2008; Hodson et al., 2012). While the initial resource requirement is high in conventional urban metabolism (Minx et al., 2010) and even higher in SUM, the subsequent analyses in SUM are conducted at very small additional cost and effort (Paper I), a prospect that could make the adaptation of SUM easier. By the same token, SUM overcomes the identified lack of longitudinal studies on changing metabolic flows (Kennedy et al., 2007).

An interesting opportunity that SUM may be able to provide is to overcome the challenge of identifying cause and effect relationships of activities in urban areas. These concerns are raised by Alberti (1999), Minx et al. (2010), and Barles (2010), where Alberti (1999) mentions the static nature of conventional urban metabolism studies as the main barriers towards this understanding. The SUM framework provides real-time urban metabolism Sankey diagrams (Papers I and III), together with a process for big data analytics on high spatio-temporal urban metabolism data (Papers IV and V), which can help uncover many aspects of urban activities and casualties (Pietsch, 2013) that still remain beyond reach.

5.2 Limitations of the SUM Framework (R2)

It could be argued that the SUM framework is simply an expression of a combination of major global trends (sustainable urban development, urban sensing, smart cities, and big data analytics) that will be implemented in the future, whether or not this is explicitly done under the SUM framework. Given the demonstrated value of the framework, it should be in the interest of sustainability scientists, industrial ecologists, and the public alike for the SUM framework or a similar framework to be established. Given this, there may be barriers to widespread adaptation. Just as urban metabolism had its limitations (Holmes and Pincetl, 2012), SUM will provide its practitioners with new challenges (Paper I; Paper II; Paper III). Pioneers that adapt the SUM framework or similar frameworks will need to make a significant and coordinated effort in the form of local triple helix partnerships to collaborate towards a set of common goals and overcome its inherent barriers. In this section, some of the barriers that have already been identified are presented, but are not ranked in order of importance.

5.2.1 Limitation 1: Data Access and Trust

The literature review (Paper I; Paper III) pointed to a lack of data at the city scale (Hodson et al., 2012; Ngo and Pataki, 2008). This thesis, along with studies in the smart city domain (Naphade, 2011; Ratti and Townsend, 2011), demonstrate that there is actually a wealth of data at the city scale. What is problematic is that the data are siloed and owned by a multitude of stakeholders. Moreover, there are still no conventions on how to approach this sharing of data without exposing business-sensitive information or infringing on privacy. This is especially true for business-driven data owners, who are key enabling stakeholders. Therefore, incentives, trust, and legal agreements need to be negotiated for similar future initiatives. Making business data available to joint R&D projects, no matter how strong the agreements and security measures put in place, requires a significant amount of trust among the partners, along with strong data security measures. The experience from this thesis is that this trust can be built by galvanizing partners towards a common vision and working with the partners to identify their roles towards meeting this vision.

5.2.2 Limitation 2: Steep Learning Curves

A strong vision would also help in overcoming the second barrier, which is the potentially steep learning curves that could be experienced by each partner when implementing the SUM framework. This entails an understanding of the benefits of SUM, developing skills to collaborate across organizations, and implementing procedures for safe management of data. This is important so that partner representatives can communicate and explain the project internally in their organizations. This is another reason why the up-front resource requirements of SUM are even higher than those of conventional urban metabolism studies (Minx et al., 2010).

5.2.3 Limitation 3: Unclear Business Opportunities

The third barrier is that of creating market value, in particular for urban data owners. Business strategists have an obligation to their businesses to question how taking a risk (in time, effort, and, in some cases, data exposure) might affect their business.

Experiences from the case study in this thesis, after in-depth investigation, indicated that there are numerous potential business opportunities for partners, but it is not always clear how and when a profit can be made. All of the sustainability benefits related to SUM can in one way be described as efficiencies (except the social sustainability benefits), by allowing better and more informed decisions to be made by people or machines. Although perhaps overly simplified, wherever there is an efficiency to be gained, there could also be a related business opportunity for one or a few of the stakeholders in that value chain.

For instance, if there is a water leakage which leads to € 1M losses a year, a sensor solution to identify where these leaks occur and sends notification to fix them is in theory worth something and could be commercialized, but realizing such benefits in practice is more complex. Therefore, Smart City SRS has invested substantial efforts in understanding the value chains (Webb et al., 2011) and business models associated with these types of smart city solutions. An underlying business model, Smart City Marketplace, has been designed, in which stakeholders can buy and sell, give and take, services and data on a platform, based on micro-transactions. That could, at least in theory, allow data owners to profit if their data lead to socio-economic benefits for society. This will be tested and evaluated in the near future.

5.2.4 Limitation 4: Privacy

The massive amounts of data in the SUM framework may raise questions about privacy and personal integrity. However, this should not discourage professionals and researchers from pursuing SUM with the intention of achieving sustainability outcomes. Privacy and personal data integrity might be one of the greatest challenges of the 21st century, regardless of whether the SUM framework is adapted or not (Spiekermann, 2012). In short, the privacy challenge goes far beyond the scope of this study, but future SUM studies should actively seek to manage sensitive data with the best practices and privacy-enhancing principles and technologies (Ma et al., 2012; Speiser and Harth, 2012).

5.3 Feedback Interfaces (R3)

The real-time feedback interfaces developed specifically for the case of SRS were developed either as responses to explicit requirements or as experiments based on identified needs of stakeholders, within the limited budget constraints available to the project (Paper III). The real-time Sankey diagrams were developed primarily for an academic audience and could become an important tool in understanding the changes in urban metabolism at the varying urban scales and in visually identifying patterns in the dynamically shifting flows. They could also be used for education purposes when explaining factors such as weather, local events, and the interrelations between the various city sectors.

The building monitoring app was built as a Master's project to meet the city's requirement on monitoring and identifying what buildings fail to meet their energy targets of 55 or 45 kWh/m^2. The smARt Viz solution for household waste might have limited value for citizens, since the feedback is not set in a local context, whereas the smARt Viz solution for comparative building performance may have a good audience among city planners, architects, realtors, and building owners. It is also a way of creating recognition for high performing buildings and creating exposure for their sub-contractors for Heating, Ventilation, and Air-Conditioning (HVAC), architects, and building material suppliers such as window or insulation suppliers. In this regard, the smARt Viz solution may have interesting market potential.

The dashboard was built in response to the feedback from citizens, who did not want smart energy meters or sustainability indicators covering the walls of their relatively expensive homes. A key question put to them was: "If we were going to put something on your wall that included our sustainability indicators, how would you like to receive that information?" The response was quite informative; the citizens explained that if we could put our sustainability indicators in the context of the other decisions they need to make during their day, they would probably sometimes also review their sustainability metrics. This raised a deeper question about HCI and behavioral sciences. With regard to environmental awareness, recent studies (Hargreaves et al., 2013) have found that smart energy meter dashboards in homes tend to become "backgrounded", with limited efficacy in increasing awareness over time. Another related issue is that some citizens might feel alienated by top-down interests wanting to affect their choices (Verbong et al., 2013). The dashboard was designed as an attempt to begin with the daily lives of the members of the household, their information and communication needs and, as an integral and limited part of that, their environmental performance. Given the feedback and the current state of research, the hypothesis is that such a design approach may lead to more engaged and empowered citizens.

5.4 New Sustainability Intervention Measures Identified through High Spatio-temporal Urban Metabolism Data (R4)

The resulting big data from Stockholm, coupled with in-depth sub-sector analytics, confirmed one of the framework's promises, namely the ability of high spatio-temporal urban metabolism to uncover previously hidden or unknown insights about city functions that enable new sustainability intervention measures. The big data alone were not necessarily useful, nor was the ability of data science to analyze large amounts of data.

However, when coupled with subject matter expertise, in this case on sustainable urban development and the operations of the city, an array of interesting findings were uncovered. A few of these were of particular value, since they actually led to the identification of new sustainability intervention measures that could not have been understood previously. Big data analytics is relatively resource-intensive, as simply curating the data and mapping require resources. Due to restricted funding, the analytics provided in this thesis only scratched the surface of the large number of studies that the data enable. From a short-term sustainability perspective, these studies could make the greatest contribution to the local sustainable development process. Integrating high spatio-temporal urban metabolism data from different sectors may lead to a better understanding of causalities that govern cities (Pietsch, 2013).

5.5 Implications of SUM for the Field of Industrial Ecology

Since urban metabolism is one of the main tools in the industrial ecology toolbox (Ferrao and Fernandez, 2013) and also acts as an integrating tool between the other industrial ecology tools, methodology development merits a discussion about what this could imply for the field of industrial ecology. Robert Socolow (1994, p. 9) summarized the aim of industrial ecology thus:

> The task of comparing present and potential levels of human activity to thresholds, absorptive capacities, and other quantitative measures of stress on the natural environment is one of the frontiers of industrial ecology.

The better the causalities that govern our cities can be understood, the better the field of industrial ecology can serve this aim. The shift from aggregated statistics to disaggregated real-time data is not trivial in this regard. It uncovers new potential to understand how our cities function, such as building performance degradation, increased heavy transport on roads, and how that is related to increased waste generation. More importantly, it enables industrial ecologists to identify the appropriate points of system interventions that will improve the urban metabolism. Finally, managing such data over time allows decision-makers and industrial ecologists to monitor the outcomes of the interventions in real time. This monitoring provides an understanding of the efficacy of the intervention measures and helps inform decisions for additional or future intervention measures.

However, it should be pointed out that in SUM, nothing fundamental has changed; the methods and tools available to industrial ecologists are still largely the same. New urban data should lead to an advanced understanding of the field, not naïvely replacing what has been known with what is new. Townsend (2013, p.314) succinctly describes this risk:

> If this new urban science dismisses what has come before it, it fails to ground itself in what has already been discovered, it runs the risk of being at best wrong, and at worst […] deeply misleading.

Therefore SUM could be considered to be a bridge that leads industrial ecology into the fourth paradigm of research, in a similar sense as described by Lehning et al. (2009). In addition to the existing methods and tools, this paradigm requires newer tools to augment the industrial ecology toolbox, including statistics (big data analytics), data management, and computer science, i.e., the skillsets of data scientists (Cleveland, 2001). In the hands of industrial ecologists and sustainability scientists, these tools can advance the next generation of sustainable urban development practices. Data science proficiency requires substantial training that is not part of the traditional industrial ecology training (Graedel, 1994).

In light of methodological advances such as SUM and the increasing adaptation of ICT-enabled efficiencies in cities (Farnworth and Castilla-Rubio, 2010), there is an emerging need for a new type of data scientist among industrial ecologists, the "industrial ecology data scientist". This new type of industrial ecologist could significantly advance the field and their skills will most likely be in high demand in the near future. Furthermore, the complexity involved in providing relevant feedback to citizens and decision makers is a challenge that demands contributions from multiple key disciplines. While industrial ecologists can develop sustainability KPIs, behavioral scientists need to provide information about what feedback should be made, when, and how often, and to whom (which groups), and HCI designers need to design interfaces that provide the industrial ecologists with KPIs according to the instructions of the behavioral scientists, through a design that is intuitive and appealing to intended demographics. This implies that the field of industrial ecology will need to build more bridges to the aforementioned and related disciplines.

5.6 Vision, Future Research, and Development Agenda

Given the complexities associated with sustainable urban development and the added layer of complexity when coupled with the SUM framework, it might be appropriate to share a more tangible vision of how SUM could be successfully implemented in SRS. Parts of this vision are already implementable today and, as the field matures, more wireless sensor networks are deployed, HCI feedback solutions are integrated into the fabric of urban life, and more data continue to be made accessible, the vision might become common practice. The vision (partially outlined in Paper III) is that anyone in the city, based on the SUM framework, is able (and has the right) to receive real-time feedback on the system consequences of their choices, allowing each decision maker the liberty of making their own informed choices. These consequences include local and global environmental impacts, as well as economic and social consequences.

The vision can be extended in in the context of the SRS, hinting at a data-driven, sustainable urban development process with emphasis on the empowered citizens. Along with improved decision-making processes by citizens (bottom-up), infrastructures (top-down) also become more efficient (Paper III; Paper IV; Paper V). By sensing the amount of waste and water content of the waste generated in the city today, the district heating utility can better plan its combustion process. The 30 waste management companies in Stockholm can optimize their waste collection route planning based on real-time road conditions and, with sensed waste bins, they could further optimize their waste collection by only traveling to empty bins that are at least half full. Food waste and sludge from the households are converted to biogas, by sensing organic waste generation on building or household level, allowing households to become recognized and awarded as energy producers by better recycling of organic waste. By sensing the actual water consumption throughout the different zones of the city, the water utility can better optimize its water pumping and distribution. Urban stakeholders, including citizens, building owners, and city officials are always able receive relevant feedback on their decisions. Towards this vision, and to overcome the previous challenges described, a future research and development agenda is proposed.

5.6.1 Developing New Case Studies

This thesis focused on methodology development and enabled some sustainability intervention measures in SRS. To advance this research, the SUM framework needs to be implemented in more urban districts, with the dual aims of supporting local sustainability practices and advancing the research and the body of knowledge around causalities in cities. As more districts implement the framework, the resulting data should be explored in collaboration with other disciplines (Hey et al., 2009b). In the long-term, this could also enable some generalizations with regard to SUM studies.

5.6.2 Developing In-Depth Big Data Analytics of Metabolic Flows

The implementation of SUM in SRS has yielded rich big data sets on energy use (Paper IV), waste generation (Paper V), waste collection (Paper V), vehicle registrations, public transportation delays, and Twitter moods in the city (Paper III). Only a small amount of these data has yet been explored in the spirit of the fourth research paradigm, but this has already resulted in several new R&D applications (e.g., on novel citizen feedback and engagement mechanisms). With more adaptations of SUM in other urban areas, there will be a growing opportunity for research within specific sectors, but also uncovering correlations between these, with the aim of identifying new intervention measures. This research area could serve as platform to develop the "industrial ecology data scientists".

5.6.3 Feedback of System Consequences

Little work has been done to provide intuitive feedback in terms of local and global consequences and comparative metrics. This research lies at the intersection of behavioral sciences and HCI design, and is an effort that could have a significant impact on the adaptation of SUM and on decision-making processes. In parallel, the SUM data and KPIs on citizen level should be further developed (as proposed in Paper I) to become even more relevant in decision-making processes.

5.6.4 Integration with Social LCA

Providing feedback on global consequences of local decisions overcomes a significant problem of identified "distancing" (Princen, 2002). Beyond providing feedback on environmental consequences, social consequences could play an increasingly important role in this feedback. While the field of social LCA (SLCA) is still in its early phases (Benoît Norris, 2013), a coordinated research effort could still incorporate social impacts as feedback on decisions. The feedback would initially be quite general, but given its potential role in affecting decision-making processes, it could serve as a "good enough" starting point to understand how decisions impact on social hotspots around the world.

5.6.5 Real-Time Ethics

Citizens are faced with a myriad of daily decisions that relate to sustainability goals. These include questions such as whether and how to travel to work, what to buy, what food to prepare, saving energy, recycling, and reducing waste. Smart cities that are designed to be citizen-centric as described by Towsend (2013) are based on the assumption that transparent data and feedback can empower citizens to become more informed, aware, and influential in the sustainable urban development process.

Sustainability studies have raised the importance of shifting some of the responsibility for sustainability targets to citizens (Law, 2008). Citizens play a more important role in the smart city and have been referred to as self-decisive, independent, and aware citizens (Giffinger et al., 2007). As an opposing force, it has been concluded that there is a large industry designed to influence decisions of citizens by appealing to their irrational side (Tye, 1996). As appropriately described by Kibert et al. (2006, p. 139), the real threat to global sustainability is not the visible and excessive use of resources by a growing population in developing countries, but instead the increasing demands of nonlocal consumers, primarily in the developed countries. Kibert et al. (2006, p. 139) concluded that “Providing these consumers with useable information about the products they buy is crucial to the development of a sustainable global marketplace.”

Thus if SUM can make available real-time feedback on the social, economic, and environmental consequences that people’s choices have locally and globally, it may perhaps support decisions that are more aligned with each citizen’s personal ethical principles. Furthermore, it is imortant to explore the negative consequences of citizen empowerment. As more responsibility is moved to citizens, they will face more ethical choices than ever before. Future research must determine what this paradigm of “real-time ethics” (Shahrokni and Solacolu, 2015) means for citizens and how technology can support it towards desired outcomes.

6 Conclusions

This thesis explored the potential for an ICT-enabled urban metabolism framework to improve resource efficiency by supporting urban development decision-making processes. This was done by addressing the three main objectives set for the work. The first objective was to identify how ICT-aided urban metabolism could support decision-making processes, the second was to design and develop SUM as a concept, framework, and tool, and the third was to highlight how high spatial and temporal urban metabolism data could lead to efficiency improvements. The results of the research suggested the following answers to the questions raised in relation to the three objectives:

1) Smart urban metabolism can overcome some of the limitations that conventional urban metabolism has been facing.

2) For the purposes of studying metabolic flows, most necessary real-time data are already being collected in urban areas.

3) It is possible to overcome organizational, legal, and structural barriers to integrating existing siloed real-time data.

4) Providing individualized and relevant feedback could support urban decision-making processes, with contextually appropriate HCI.

5) The Smart Urban Metabolism framework can uncover previously hidden sustainability intervention measures by introducing high spatio-temporal resulting from the metabolic flows.

With regard to the first objective, it was shown that SUM could aid the decision-making processes of different types of urban stakeholders (as exemplified in Papers I, III, IV, and V), with real-time feedback and feedback in terms of historical insights. The most significant difference of the SUM framework to conventional urban metabolism is that it collects, integrates, analyzes, and feeds back high spatial and temporal resolution urban metabolism data, as opposed to statistical data for long time horizons.

With regard to the second objective, SUM was developed, tested, and implemented in SRS. There were two key case-specific factors that facilitated SUM implementation in Stockholm. First, that city has set out a sustainability program with targets for 2030 that involve key infrastructure stakeholders. Second, the city owns the land and is therefore allowed to set its own requirements on building performance and project design features such as measurement and verification systems. The implementation of the SUM framework resulted in real-time feedback and in-depth big data analytics feedback on sub-systems. The implementation of the SUM framework led to identification of its key limitations. These include access to business-sensitive urban data and trust, steep learning curves for members of the consortia, and unclear business opportunities for industrial partners and urban data owners. The fourth limitation is privacy, which should be managed in future SUM implementations using a set of privacy-enhancing principles and technologies. From an operational perspective, the technical obstacles that delayed implementation in the test cases were failed integrations, data gaps, and incomplete datasets.

With regard to the third objective, SUM yielded several new inights about urban patterns in Stockholm, which led to the identification of two sustainability intervention measures on energy and waste. The findings confirm that there are hidden patterns in the city that only become apparent on analyzing structured big data on the city. Some of those patterns may lead to the identification of appropriate intervention measures for sustainable urban development.

Looking ahead, the main implication of the SUM framework for industrial ecology could be the emergence of a new type of researcher, the "data scientist industrial ecologist". Furthermore, the explicit focus of the SUM framework on citizens brings a need for interdisciplinary collaboration with HCI designers and behavioral psychologists. Proposed future research includes new SUM case studies to reach a better understanding of urban causalities, big data analytics of metabolic flows within sub-sectors of urban areas and across sectors, and research on feedback mechanisms.

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Summary of Appended Papers

Paper I

Title: Shahrokni, H., Lazarevic, D., & Brandt, N. (2014). Smart Urban Metabolism: Toward a real-time understanding of the energy and material flows of the city and its citizens. Urban Technology 22, 65–86. doi:10.1080/10630732.2014.954899

This paper identifies the limitations of the conventional urban metabolism framework and proposes an adaptation in the emerging context of smart cities. The resulting framework is called smart urban metabolism and is illustrated by a study of metabolic flows with high resolution spatio-temporal data. The proposed framework can overcome the identified limitations of conventional urban metabolism, while introducing a few new limitations.

Aim: Developing the framework of Smart Urban Metabolism in the context of smart cities towards sustainable urban development goals

Objectives: 1 Literature review on urban metabolism to identify its current limitations. 2 Designing the smart urban metabolism concept. 3 Discussing the smart urban metabolism concept's benefits and limitations

Methods: Literature review, design and development, urban metabolism, case study

Results: Uses and limitations of the conventional urban metabolism concept were identified: 1 Lack of data at city scale; 2 High data and resource requirements of urban metabolism studies; 3 Difficult to analyze the evolution of a city's urban metabolism; 4 Difficulties in identifying cause and effect relationships

Key features of the proposed smart urban metabolism concept are: 1 It is based on the integration of high-quality, siloed, heterogeneous data streams in urban environments; 2 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; 3 It continuously informs these flows to city officials, organizations, and citizens through feedback tailored to each stakeholder level

Benefits and limitations of Smart Urban Metabolism were discussed

Conclusions: Some of the limitations of conventional urban metabolism can be overcome through smart urban metabolism

Paper II

Title: Shahrokni, H. & Brandt, N. (2013). Making sense of smart city sensors. In C. Ellul, S. Zlatanova, M. Rumor, & R. Laurini (Eds.), Urban and Regional Data Management, UDMS Annual 2013 (pp. 117–127). London: Taylor & Francis Group.

This paper describes the key system design decisions that need to be made when developing a calculation engine for smart urban metabolism. The system design decisions range from dealing with data gaps and drawing system boundaries to developing data structures and ontologies that allow for comparability among smart cities. Most of these decisions are currently being made on an ad hoc basis by system architects, while the need for comparability and transparency necessitates standardization.

Aim: Describing and collating the initial findings and challenges in developing a metabolic flow calculation engine for a smart city.

Objectives: 1 Identify key design decisions for developing a calculation engine for the carbon metabolism of a city; 2 Propose strategies for addressing the design decisions

Methods: Design and development, urban metabolism, case study

Results: 1 Necessary data components (open data, public data, and sensor data) were identified; 2 Design decisions for dealing with real-time emission factors were identified; 3 Design decisions for data modeling were identified; 4 Design decisions when multiple sensors track the same flow were identified; 5 Design decisions for addressing data gaps and delayed data were identified

Discussion: 1 Design decisions for calculation engines are summarized; 2 Strategies for addressing these are discussed

Paper III

Title: Shahrokni, H., Årman, L., Lazarevic, D., Nilsson, A., & Brandt, N. (2015). Implementing Smart Urban Metabolism in Stockholm Royal Seaport: Smart City SRS. J. Ind. Ecol. 00, n/a–n/a. doi:10.1111/jiec.12308

This article presents the first implementation of SUM in the Smart City Stockholm Royal Seaport R&D project. It analyzes barriers and discusses the potential long-term implications of this study. Four key performance indicators were generated in real-time based on the integration of heterogeneous, real-time data sources.

Some of these data sources are electricity, district heat, water, and household waste. The resulting KPIs were kWh/m^2, CO2e/capita, kWh primary energy/capita, and share of renewables (%), fed back on three levels (household, building, and district) on four interfaces, aimed at different audiences.

Aim: Implementing and evaluating Smart Urban Metabolism in Stockholm Royal Seaport to identify benefits. Discussing the framework's short-term and long-term implications.

Objectives: 1 Evaluate implementation of the Smart Urban Metabolism framework; 2 Identify barriers and limitations; 3 Identify short-term and long-term implications

Methods: 1 Design and development research; 2 Urban metabolism research; 3 Case study research

Results: 1 The Smart Urban Metabolism framework, with approximately 25 real-time data sources, is successfully implemented in a neighborhood in Stockholm Royal Seaport; 2 Data collection, integration, calculations, and feedback mechanisms are evaluated; 3 The accuracy of the calculation engine is verified; 4 Barriers and limitations are identified; 5 Short-term and long-term implications and needed future research are identified

Conclusions: 1 The Smart Urban Metabolism framework was demonstrated to work; 2 Key barriers identified were data integration from stakeholders, specifically with regard to their incentives for data sharing.

Paper IV

Title: Shahrokni, H., Levihn, F., & Brandt, N. (2014). Big meter data analysis of the energy efficiency potential in Stockholm's building stock. Energy and Buildings, 78, 153–164. doi:10.1016/j.enbuild.2014.04.017

This study evaluates the energy efficiency potential in the city of Stockholm drawing on big data from district heating meters, leading to a new understanding of energy use in the city. Analysis of the energy efficiency potential of different building vintages revealed that the retrofitting potential of the building stock to current building codes would reduce heating energy use by one-third. In terms of market segmentation, the greatest reduction potential in total energy is for buildings constructed between 1946 and 1975.

Aim: Using big data generated from the SUM framework to identify new sustainability intervention measures and efficiency potential in the City of Stockholm's building stock

Objectives: 1 Quantify district heating production hourly emissions; 2 Quantify buildings' hourly consumption; 3 Identify efficiency potential of the buildings of the City of Stockholm

Methods: Urban metabolism, big data analytics, case study research

Results: 1 A model of the hourly district heating production and consumption side is developed based on metered data; 2 A theoretical energy efficiency potential of 35% is identified, corresponding to a 20% decrease in GHG emissions; 3 Contrary to commonly held beliefs, the worst performing buildings are those constructed between 1926 and 1945

Conclusions: The building stock of the City of Stockholm can be theoretically retrofitted to reduce energy use by 35% and GHG emissions by 20%, where the focus should first be on buildings constructed between 1946-1975, and then on buildings constructed between 1926 and 1945.

Paper V

Title: Shahrokni, H., van der Heijde, B., Lazarevic, D., Brandt, N., 2014. Big Data GIS Analytics towards Efficient Waste Management in Stockholm, in: Proceedings of the 2014 Conference ICT for Sustainability. Atlantis Press, Stockholm, pp. 140–147. doi:10.2991/ict4s-14.2014.17

This paper presents preliminary findings from big data analysis and GIS to identify the efficiency of waste management and transportation in the City of Stockholm. Based on a large dataset consisting of roughly half a million entries on waste fractions, weights, and locations, a series of new waste generation maps is developed. The paper identifies inefficiencies in waste collection routes in the City of Stockholm and suggests potential improvements.

Aim: Using big data generated from the SUM framework to identify new sustainability intervention measures for the City of Stockholm's waste collection process

Objectives: 1 Quantify the spatio-temporal patterns of waste generation in the City of Stockholm; 2 Analyze potential inefficiencies in waste collection processes

Methods: Urban metabolism, big data analytics, case study research

Results: 1 A bulky waste map of Stockholm presenting patterns of bulky waste generation was created; High inefficiency of waste collection was shown when analyzing collection truck routes; these inefficiencies are due to the free market conditions of waste companies; 3 A map of overlapping waste collection trucks was generated

Conclusions: The waste collection process in the City of Stockholm is extremely inefficient today, since there are approximately 30 publicly procured waste management companies that operate in free market conditions, with customers scattered across the city. New R&D projects are being designed to quantify the inefficiencies of the current system, to inform the next round of procurement.