THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Quantifying the Metabolism of Individual Households

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"Earth provides enough to
satisfy every man's need,
but not every man's greed."

Mahatma Gandhi

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Abstract

The magnitude of the flows of matter and energy resulting from human activities is influenced by human needs and demands as well as the practices and technologies applied to fulfil them. The aim of this study was to explore differences in resource use and waste generation between individual households through the simultaneous quantification of physical flows entering and leaving the households. A pilot study was initiated where infrastructure-mediated sensing was combined with manual data collection approaches for fine-grained monitoring of resource use and waste generation at the level of individual households. A further aim was to relate resource and waste flows to specific household activities. This thesis presents the main findings from the pilot study, embeds the concept of household metabolism within the research field of socio-economic metabolism, and outlines which other research fields contribute to, or benefit from the quantification of household metabolism. The main scientific contribution of this thesis is the development and evaluation of two approaches for the collection of highly disaggregated data on goods consumption and related waste generation. In conclusion, comprehensive data collection at the level of detail envisaged in this study is challenging. Data collection can potentially be significantly simplified once easy to install single-point sensors for sensing disaggregated consumption data become commercially available, and data on goods consumption can be more readily obtained from retailers. Based on the work on household metabolism presented in this thesis, two meaningful possible directions for future research emerge. First, quantification of household metabolism can be embedded in living lab facilities in order to assess the impact of innovations on resource consumption and waste generation. Second, researchers and household members could co-develop a way to comprehensively track and evaluate resource consumption and waste generation of individual households. This could include seeking cooperation with supermarkets and retailers to provide consumption data to households.

List of Papers

At first, this thesis was meant to cover phosphorus management, urban metabolism, and urban water systems. This initial focus resulted in significant contributions to a paper on pathways and management of phosphorus in urban areas (Paper II). Later, the emphasis shifted towards the metabolism of individual households, which led to a paper on the quantification of goods purchases and waste generation at the level of individual households (Paper I). Only Paper I is appended to this thesis as both the conceptual framework and the reflections presented in this thesis relate to the metabolism of individual households.

Paper I

Towards quantification of goods purchases and waste generation at the level of individual households.

Harder, Robin, Kalmykova, Yuliya, Morrison, Greg, Feng, Fen, Mangold, Mikael, Dahlén, Lisa.
Manuscript under revision.

Paper II

Pathways and management of phosphorus in urban areas.

Kalmykova, Yuliya, Harder, Robin, Borgestedt, Helena, Svanäng, Ingela.
Journal of Industrial Ecology, 16(6), p.928-939.

Acknowledgements

The work presented in this thesis needs to be seen in the context of a research group focusing on urban metabolism that was launched just before this thesis project was initiated, and is still in the process of being established. This implies the challenge of contributing to the advancement of a research field, whilst at the same time finding a way into and exploring it.

First of all, I would like to thank Yuliya Kalmykova for taking me on as a doctoral student and for her supervision efforts. I would also like to thank Gregory Morrison for his diligence in handling some of the challenges that arose throughout the past two years, for going through this thesis several times and providing valuable feedback that helped me to continuously improve my work, and for supporting me in and advising me on revising the manuscript appended to this thesis.

I would also like to thank my colleagues at the division of Water Environment Technology for many entertaining coffee breaks and lunches, and my colleagues at the division of Building Technology for providing a new social environment for me during the past months. Special thanks go to all the fellow doctoral students who have made life as doctoral student much more pleasant by sharing experiences, lunch breaks, and after work. In particular, Mikael Mangold, who started his doctoral studies at Water Environmental Technology on the same day as me, has helped me through the worst frustrations by his support and many creative talks.

I am also grateful to Fen Feng, who dedicated her master thesis project to one aspect of this thesis, namely the first stage of the quantification of goods purchases and related waste generation; and to Aubin Gonzalez and Sara Prochasson, who are currently working on extending the FoodWatch application through including footprint data.

My warmest appreciation also goes to Lisa Dahlén at Luleå University of Technology, for several inspiring talks as well as reading and commenting various versions of the manuscript appended to this thesis. Special appreciation also goes to Christine Räisänen and Árni Halldórsson, both at Chalmers University of Technology, for offering excellent doctoral courses. You have all contributed to my development as researcher.

Special thanks also go to those who were not individually acknowledged, but helped with planning and implementing the sensor network or inspired me otherwise, as well as the area of advance Built Environment at Chalmers University of Technology, the SusLab NWE project (INTERREG IVB North-West Europe), and Kretsloppskontoret (City of Gothenburg) for providing financial support for this work.

Last, but certainly not least, I would like to sincerely thank my family and friends for always being there for me with a listening ear, for continuously supporting me and believing in me, for sharing the joyful moments and putting up with me during less joyful ones, and for giving me the strength and reflection required to continue with a rewarding, though sometimes bumpy journey.

Göteborg, March 2013
Robin Harder

Contents

Chapter 1

Introduction

During the past decades, resource use and generation of residuals have multiplied as a result of population growth and increased consumption levels (Giljum *et al.*, 2009; Kitzes *et al.*, 2008; Turner, 2008), and the related global environmental problems and resource issues are becoming ever more apparent. Reducing resource use and waste generation requires action and choices on various levels, including changes in technological settings, institutional arrangements, societal values, and consumption patterns.

All economic activities ultimately serve final consumption, and individual private households drive resource consumption, waste generation and environmental impacts. The aim of the research underlying this thesis was to investigate the magnitude of differences in the metabolism (i.e. resource consumption and waste generation) of different individual households to reveal factors determining the metabolism of a household.

This thesis is structured as follows. Chapter 2 introduces the field of socio-economic metabolic research and positions household metabolism within this field. Chapter 3 summarises methods and tools for the acquisition of disaggregated environmental data, and outlines which other research fields contribute to, or benefit from the quantification of household metabolism. Chapter 4 describes the case study underlying this thesis. Chapter 5 presents a critical discussion on the application of household metabolism in general. Chapter 6 concludes this thesis and briefly presents three meaningful ways to continue the research presented in this thesis.

Chapter 2

Framing Socio-Economic Metabolism

The scope of this chapter is to provide an introduction to socio-economic metabolism research, the context in which the concept of household metabolism is embedded. Hence this chapter introduces various metabolism notions, outlines the conceptual model of socio-economic metabolism applied in this thesis, highlights different levels of spatial and functional disaggregation of socio-economic metabolism, and provides a classification framework for socio-economic metabolism research. There are a number of other research fields that are relevant for, related to, or contribute to the quantification of household metabolism or selected aspects thereof. These research fields will be discussed more in detail in chapter 3.

2.1 Introducing Socio-Economic Metabolism

Planet Earth, home to humans and millions of other species, is subject to constant change through flows of matter, energy, and information between the different entities of our planet[1]. These flows, as well as the related stocks and stock changes, are often referred to using the notion metabolism:

> "The notion *metabolism* is used to comprehend all physical flows and stocks of energy and matter within and between the entities of the system Earth." (Baccini and Brunner, 2012, p.16)

Baccini and Brunner (1991) were the first to combine this notion with the term anthroposphere, thereby introducing the expression metabolism of the anthroposphere:

[1] Note that information is mentioned as a third flow besides matter and energy in, e.g. Baccini and Brunner (2012), though not consistently. Other authors do not mention information as a separate flow.

> "Mankind's sphere of life, a complex technical system of energy, material, and information flows, is called the anthroposphere. It is part of planet Earth's biosphere. We think of the anthroposphere as a living organism with its own history. In analogy to the physiological processes in plants, animals, lakes and forests, the metabolism of the anthroposphere includes the uptake, transport and storage of all substances, the total chemical transformation within the sphere, and the quantity and quality of all refuse." (Baccini and Brunner, 2012, p.1)

Baccini and Brunner (2012) further point out that the notion metabolism is also widely used in connection with adjectives; some examples are industrial metabolism, urban metabolism, household metabolism, social metabolism, societal metabolism, and socio-economic metabolism (the latter three are synonymous). The concepts of metabolism of the anthroposphere and socio-economic metabolism are closely related, yet one difference is particularly noteworthy. The concept of metabolism of the anthroposphere as framed by Baccini and Brunner (1991, 2012) is characterised by a strong emphasis on the anthroposphere as a complex technical system. In contrast, the concept of socio-economic metabolism highlights the role of social organisation, and socio-economic production and consumption systems:

> "Socio-economic systems depend on a continuous throughput of materials and energy for their reproduction and maintenance. This dependency can be seen as a functional equivalent of biological metabolism, the organism's dependency on material and energy flows. We therefore address the concept of a 'social metabolism'. Contrary to the biological notion, however, this socio-ecological concept links materials and energy flows to social organisation, recognising that the quantity of economic resource use, the material composition and the sources and sinks of the output flows are a function of socio-economic production and consumption systems that are highly variable across time and space." (Institute of Social Ecology, 2009)

The concept of socio-economic metabolism implies that resource use, generation of residuals, and related environmental impacts are ultimately connected to what we do and how we do it. Socio-economic metabolism is a result of the activities, routines and practices we apply in order to satisfy our needs and desires. This implies room for choice—choice regarding type and extent of needs and desires, choice regarding preferred activities, routines and practices, and ultimately choice regarding characteristics and magnitude of the socio-economic metabolism.

The core aim of socio-economic metabolism research is the description and analysis of socio-metabolic patterns at different scales and the identification of possible interventions for guiding current patterns into a more sustainable direction (Institute of Social Ecology, 2009). It is likely that a reduction of socio-economic metabolism will require action and choices on all levels, including technological, organisational, socio-cultural, and individual change and innovation (Doyle and Davies, 2013; Weinstein *et al.*, 2013). Studies approaching socio-economic metabolism from a macro perspective often consider overall patterns, aggregated numbers, and generalised phenomena (e.g. Giljum *et al.*, 2009; Liu *et al.*, 2008; Ott and Rechberger, 2012); the corresponding units of analysis are nations or regions, and observations are based on aggregated statistical data.

Ultimately, all economic and regulatory activities serve final consumption, and therefore other studies have chosen the sum of private households as the unit of analysis and attribute all resource use and environmental impacts to private consumption. Bin and Dowlatabadi (2005) estimated that more than 80% of the energy used and the carbon dioxide emitted in the US are a consequence of consumer demands and the economic activities to support these demands; Hertwich (2011) found that on the global level 72% of greenhouse gas emissions are related to household consumption.

Bearing in mind that individual private households ultimately drive resource consumption, waste generation and environmental impacts, a further set of questions arises regarding the spatial and temporal variations between different households and household types. Accordingly, research is increasingly being directed towards the individual private household as the unit of analysis. This focus raises a number of practical challenges. First and foremost, as pointed out by Hutter (2001), a clear system delimitation is of paramount importance on such a low level of aggregation. On the one hand, the household could be defined as a socio-economic entity consisting of individuals who live together occupying all or part of a dwelling. On the other hand, the household could be seen as a physical entity consisting of humans, domestic animals and artifacts. The implications are that flows will be either calculated in terms of people and their activities (independent of where they induce the flows) or related to the physical household (independent of which people induce the flows). Furthermore, the introduction of a clear system delimitation inevitably raises questions as how to deal with flows and impacts that are outside the system delimitation and yet related to the system.

2.2 Conceptual Model of Socio-Economic Metabolism

All flows of matter, energy and information are related to one or several natural or anthropogenic processes. An anthropogenic process is understood as a series of routines or practices that transform inputs into outputs and lead to a particular result. All anthropogenic processes are conducted on either the household, corporate, or community level. The interplay between different entities and levels, as well as the natural environment, is illustrated in Figure 2.1.

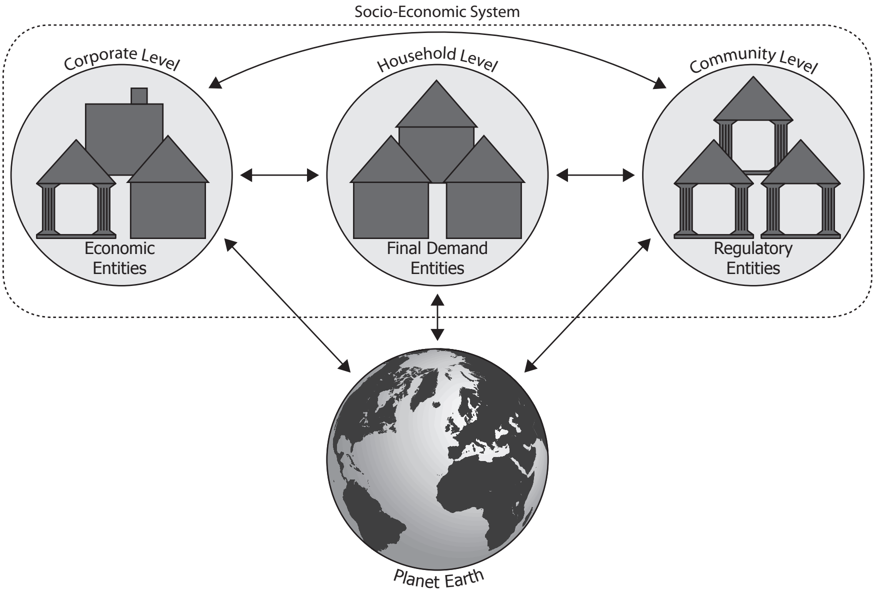

Figure 2.1: The socio-economic system consists of three levels. The household level consists of final demand entities (i.e., private households in the role of customers). The corporate level consists of economic entities (i.e., private households, private corporations, and public agencies in the role of suppliers). The community level consists of regulatory entities (i.e., public administrative bodies). Socio-economic entities exchange material, energy, information, and services with each other but also with planet Earth (indicated by the arrows). This exchange is referred to as socio-economic metabolism.

The household level consists of private households, which are described as key entities of the anthroposphere by Baccini and Bader (1996):

> "In a society based on a free market economy, the sum of all private households is the process on which all other processes depend or which all other processes serve directly or indirectly."[2]

[2] Translated from German: "In einem marktwirtschaftlich organisierten Gesellschaftssystem ist die Summe aller Privathaushalte jener Prozeß, auf den (direkt oder indirekt) alle anderen Prozesse ausgerichtet sind oder von dem alle anderen abhängen."

Accordingly, the household level is the level where final demand is located and which the two other levels serve. The corporate level represents the level where supply of goods, energy, services and infrastructure as well as discharge of residuals are taken care of. The community level represents an institutional level that provides a framework within which individuals, private households, private corporations and public agencies can operate.

Private households are defined as socio-economic entities consisting of individuals who live together occupying all or part of a dwelling. Private corporations are defined as privately owned socio-economic entities established in order to manufacture goods and/or provide services. Public agencies are defined as socio-economic entities that form the executive bodies of the administration and provide certain services to the general public. Public administrative bodies refer to the judiciary and legislative bodies of the administration that provide a framework for all human activities and ensure that this framework is adhered to.

Whereas private corporations are clearly situated on the corporate level, private households have an ambiguous role and can be situated on the household level and the corporate level simultaneously. Private households in the sense of entities that demand resources and services in order to satisfy needs and desires are located on the household level, whilst households as suppliers of goods or services are located on the corporate level. Public administrative bodies are located on the community level whilst public agencies are located on the corporate level, as they are providers of services and infrastructure. Private households in the former role as customers will be referred to as final demand entities. Private households in the latter role as suppliers, as well as private corporations and public agencies, will be referred to as economic entities. Public administrative bodies will be referred to as regulatory entities.

Within any kind of entity, several activities take place. An activity is understood as a single process or a combination of processes that serves a specific purpose and entails flows of matter, energy, and information (Figure 2.2). These flows can enter and leave different entities along various pathways, and are composed of several products and layers (Figure 2.3). The type and magnitude of flows relating to entities on different levels is determined by the type and extent of needs and desires, and the characteristics of the processes performed on various levels by various entities.

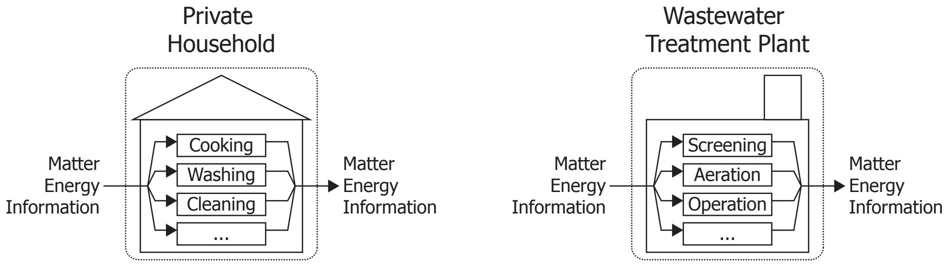

Figure 2.2: Activities take place within different entities (e.g., private household or wastewater treatment plant) and entail flows of matter, information and energy. The types of flows depend on the processes applied to perform certain activities. The sum of all activities taking place in a given entity and the processes applied determine the types and magnitudes of flows into and out of this entity. *Left:* Typical processes in private households are cooking, washing, cleaning, etc. *Right:* Typical processes in wastewater treatment plants are screening, aeration, operation, etc.

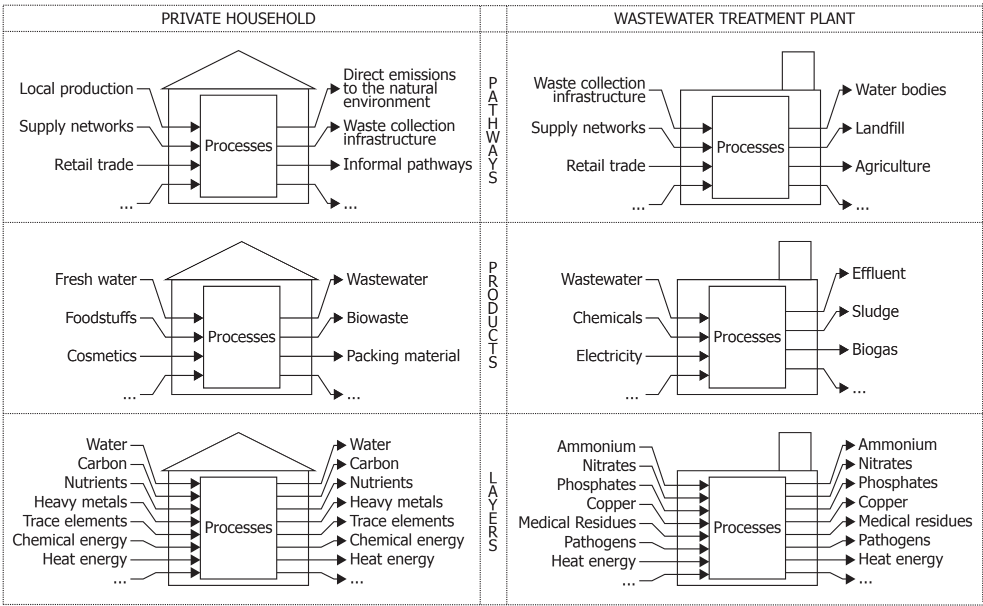

Figure 2.3: Matter, energy and information is normally carried by physical flows. These physical flows can enter and leave socio-economic entities through different pathways. Furthermore, different products can be distinguished, which again can consist of several layers representing various constituents. The term layer refers to a certain constituent of interest (e.g., phosphorus) that can be present in several flows. Constituents of interest might be elements, compounds, certain forms of energy, or organisms (e.g., bacteria, viruses). Different layers are often intrinsically related to each other through a specific product (e.g., heat energy and nutrients embodied in wastewater). Note that the lists of pathways, products, and layers provided in this illustration are not exhaustive.

2.3 Disaggregation of Socio-Economic Metabolism

Socio-economic metabolism can be analysed on different levels of aggregation (see also Baccini and Brunner, 2012). Often, the comparison of different types of households, neighbourhoods, cities, regions, countries, or societies is of particular interest in order to understand which factors cause metabolic differences. In this context, a number of terms are commonly used: industrial metabolism (metabolism of industrialised societies), urban metabolism (metabolism of urban areas), metabolism of neighbourhoods, and household metabolism (metabolism of private households). Disaggregation of socio-economic metabolism is illustrated in Figure 2.4.

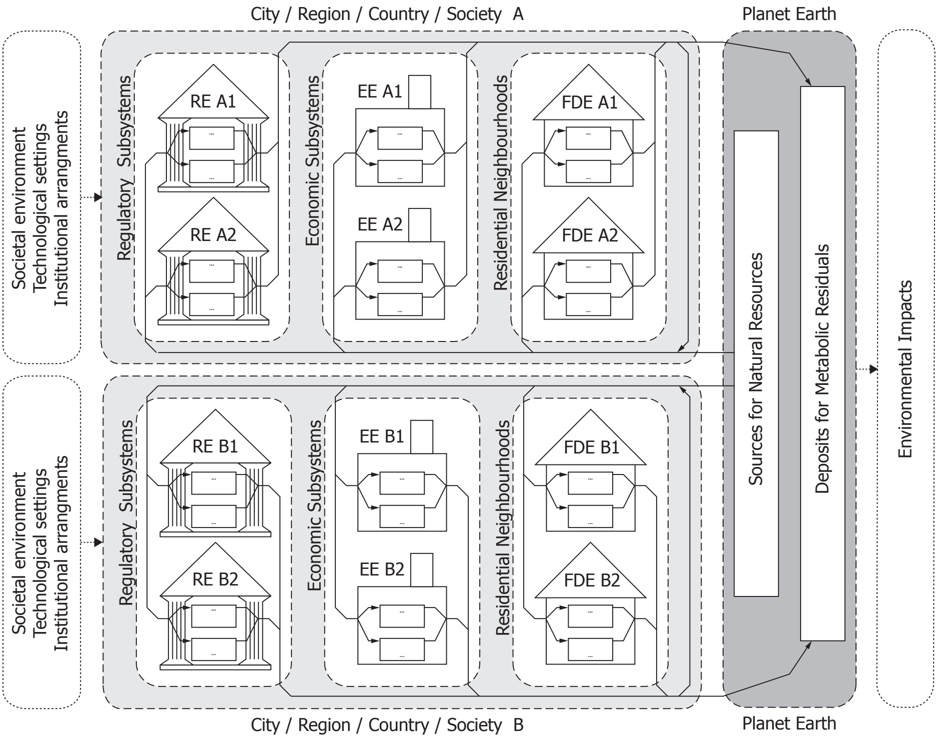

Figure 2.4: There is a constant exchange of matter, energy, information, and services within and between different entities of the socio-economic system. Note the internal recycling and reuse loop that enables the flow of matter and energy from one entity to another entity. Socio-economic metabolism can be analysed and compared on different levels of aggregation, e.g. societies, countries, regions, or cities. Furthermore, specific final demand entities (FDE), economic entities (EE), regulatory entities (RE), or the sum of specific entities (e.g., private households, industrial sectors) can be considered. Besides the magnitude of the flows between the entity under consideration, other entities as well as planet Earth, also factors of influence and environmental impacts can be analysed and compared.

Several industrial sectors participate in the pathway from resource abstraction towards final consumption, and material (or monetary) flows can also be disaggregated into component flows among different sectors and between sectors and final consumption, thereby also accounting for import and export. Sectoral disaggregation is often analysed in input-output tables, which represent monetary flows (economic input-output tables) or material flows (physical input-output tables) between sectors, and usually in a matrix form (see Table 2.1).

Table 2.1: Typical structure of an input-output table. Rows and columns represent single sectors. The intersection of a row and column identifies the economic value or physical quantity of output from the row sector that is used as input to the column sector.

	Sector 1 · · Sector n	Exports 1 · · Exports n	Final Use 1 · · Final Use n
Abstraction 1 · · Abstraction n			
Sector 1 · · Sector n			
Imports 1 · · Imports n			

In the case of material flows, different levels of detail are conceivable. At one end of the spectrum, physical input-output tables could represent the gross weight of products. At the other end of the spectrum, only one specific layer (e.g., phosphorus) could be considered. Input-output tables normally represent economies of a single nation. Most nations create economic input-output tables of their economies to varying degrees of specificity and frequency. In Europe, sectors are normally classified in accordance with NACE, Statistical Classification of Economic Activities in the European Community (Eurostat, n.d.), and final consumption in accordance with COICOP, Classification of Individual Consumption According to Purpose (United Nations Statistics Division, n.d.).

Spatial and functional disaggregation inevitably requires choices regarding system boundaries. These choices might be between the inclusion of direct and/or indirect flows. In order to get a truly comprehensive picture of resource use, waste generation and environmental impacts caused by a specific socio-economic entity, all physical flows related to this socio-economic entity, even if located outside its physical system boundary, should be included in the analysis. The internalisation of virtual flows is illustrated in Figure 2.5 using the example of an individual private household.

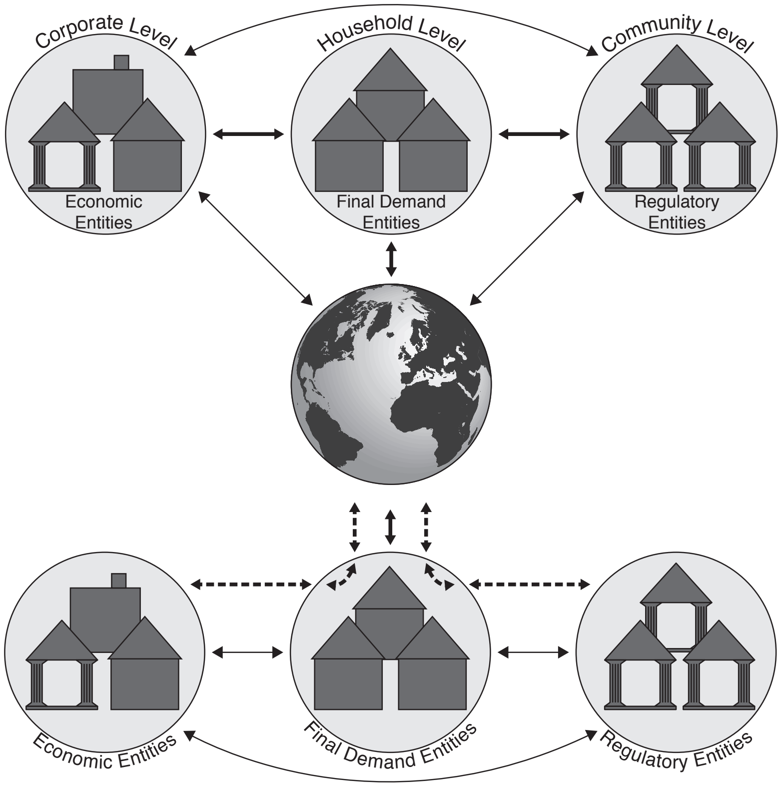

Figure 2.5: Attributing resource use and environmental impacts to private consumption. The top half of the illustration shows the actual physical flows constituting the socio-economic metabolism. The bottom half of the illustration shows how the flows between corporate level, community level and the environment are attributed to private consumption or the consumption of a particular individual final demand entity. The physical flows are still the same, yet all exchange with the environment is conceptually re-routed through the 'lens' of the sum of private households or a specific individual household (dashed lines).

Physical flows entering and leaving a socio-economic entity as well as services provided to the entity sustain a number of activities and practices. Treating the individual socio-economic entity as a black box by only quantifying the flows entering and leaving the physical system boundary thus hides information on which activity actually accounts for which share of the flows. This suggests further disaggregation within the socio-economic entity in order to disclose information on resource consumption and waste generation by individual activities, or through practices and appliances. Finally, it is important to note that there is no superior or optimal level of disaggregation. Whichever level of disaggregation or unit of analysis is most appropriate depends on the specific context and research questions.

2.4 Classification of Socio-Economic Metabolism Research

Research on socio-economic metabolism varies widely in terms of the motivation to perform the study (research scope), what aspect of socio-economic metabolism is focused on (analytical lens), how the system is delimited in time and space (system boundaries), and what the context and purpose of the study is (research typology).

2.4.1 Research Scopes

The motivations for performing a study in the field of socio-economic metabolism research can be manifold, although four broad research scopes can be identified and are described in Table 2.2. Note that, for any given research scope, factors and patterns considered cover both technological and behavioural aspects of socio-economic metabolism.

Table 2.2: Four research scopes for socio-economic metabolism studies. Note that the research scope for a given study is often not well defined but can feature elements of two or more of the research scopes identified in this table. The examples provided hence are examples where the main research scope belongs to the respective category.

Type	Description	References
Exploratory	Revealing present and past patterns and magnitudes of socio-economic metabolism.	(Antikainen *et al.*, 2005; Bin and Dowlatabadi, 2005; Neset *et al.*, 2008; Ott and Rechberger, 2012; Røpke, 2001; Tukker and Jansen, 2006)
Explanatory	Understanding factors influencing patterns and magnitudes of socio-economic metabolism.	(Faist *et al.*, 2001; Isenhour, 2010; Lenzen *et al.*, 2012; Moll *et al.*, 2005; Sundramoorthy *et al.*, 2011)
Indicative	Modelling present and possible future patterns and magnitudes of socio-economic metabolism.	(Baker *et al.*, 2007; Kirkeby *et al.*, 2006; Stamminger, 2011; Wirsenius *et al.*, 2010)
Persuasive	Attempting to influence patterns and magnitudes of socio-economic metabolism.	(Crosbie and Baker, 2009; Hunter *et al.*, 2006; Lawrence and McManus, 2008; Reid *et al.*, 2011)

2.4.2 Analytical Lens

Socio-economic metabolism research can be distinguished by the analytical lens through which a given study is narrowed down to a selected aspect of socio-economic metabolism. The analytical lens can also be seen as a functional system delimitation: the range spans from tracking the flows of single or several substances (e.g. Antikainen *et al.*, 2005; Neset *et al.*, 2008; Ott and Rechberger, 2012) to assessing the life-cycle impacts or footprints of products and services (e.g. Faist *et al.*, 2001; Holden and Høyer, 2005; Tukker and Jansen, 2006), household consumption (e.g. Holden, 2004; Hunter *et al.*, 2006; Moll *et al.*, 2005; Røpke, 2001; Tukker *et al.*, 2010), or systems and strategies (e.g. Kirkeby *et al.*, 2006; Wirsenius *et al.*, 2010). In general, three analytical lenses can be identified: material flow analysis, life-cycle assessment, and footprinting.

2.4.2.1 Material Flow Analysis

Studies approaching socio-economic metabolism through the lens of material flow analysis (MFA)[3] aim at providing a systematic assessment of the flows exchanged between and within the natural environment and the anthroposphere as well as the related material stocks and changes therein (e.g. Antikainen *et al.*, 2005; Björklund, 2010; Kalmykova *et al.*, 2012; Matsubae-Yokoyama *et al.*, 2009; Neset *et al.*, 2006, 2008; Ott and Rechberger, 2012; Palm and Jonsson, 2003; Villalba *et al.*, 2008).

MFA connects the sources, the pathways, and the intermediate and final sinks of a material. The mathematical core of MFA is the mass-balance principle, which needs to hold for every process and every material considered in an MFA: the mass of all inputs into a process must equal the mass of all outputs of this process plus a storage term that considers the accumulation or depletion of materials in the process (Brunner and Rechberger, 2004). The results of an MFA are often visualised as a network of processes (nodes) and flows (edges) as exemplified in Figure 2.6.

Theoretically, MFA delivers a complete and consistent set of information about all flows and stocks of a particular material within a system, although in practice completeness and consistency can often not be achieved due to system complexity and lack of data. A more comprehensive treatment of MFA can be found in Brunner and Rechberger (2004).

[3] Note that the term material can refer to individual substance, specific material, or bulk material flows (Brunner and Rechberger, 2004)

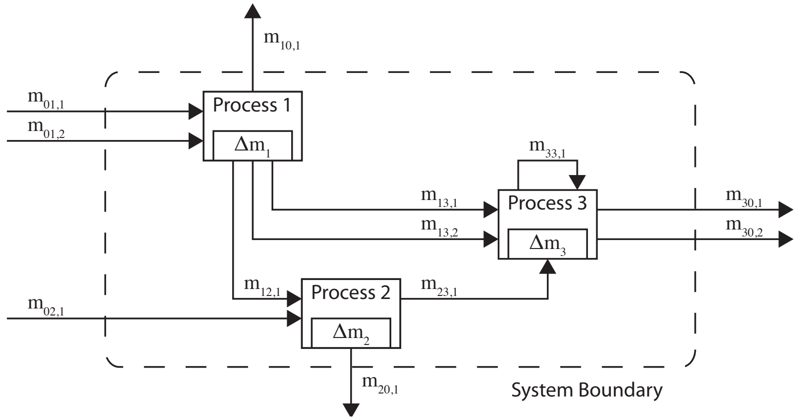

Figure 2.6: Connections between processes through flows as investigated in an MFA. The notation $m_{xy,z}$ indicates a mass flow: *x* indicates the source node (process *x*), *y* the target node (process *y*), and *z* the flow number (flow *z* from process *x* to process *y*). Note that process 0 stands for any process outside the system boundary.

2.4.2.2 Life-cycle Assessment

Studies approaching socio-economic metabolism through the lens of life-cycle assessment (LCA)[4] aim at providing a complete picture of the environmental impacts associated with a material, product, process, or service throughout its whole life span. LCA can also be used to assess different production and supply systems (e.g. Faist *et al.*, 2001), waste management systems (e.g. Kirkeby *et al.*, 2007), or final consumption (e.g. Hertwich, 2011), and can also be integrated in Environmental Impact Assessment (EIA) or Strategic Environmental Assessment (SEA) (e.g. Björklund, 2012; Manuilova *et al.*, 2009).

Early LCAs used a process-based approach: each input (materials and energy resources) and output (emissions and wastes to the environment) is itemised for every step in the production, use and disposal of a product or service. This approach is similar to MFA, but the focus lies on the various material demands and subsequent impacts for a single product, rather than on a single material in many different products. The process-based LCA method may require the inclusion of an overwhelming number of inputs and outputs. Defining a clear boundary for the analysis is therefore crucial when it comes to creating a manageable LCA project. Excluding and ignoring some inputs and outputs, however, creates an underestimate of the true life-cycle impacts, the so-called cutoff error.

[4] The content of this section is inspired by and partly adapted from an introduction to LCA provided by the Green Design Institute at Carnegie Mellon University (http://www.eiolca.net/index.html, retrieved 31 October 2012)

The issue of boundary definition of process-based LCA can be alleviated by combining LCA with input-output analysis. This approach is referred to as economic input-output life cycle assessment (EIO-LCA) and is based on economic input-output tables that are appended with information on resource use and emissions to the environment. Often, imports are implicitly assumed to have the same production characteristics as comparable products made in the country of interest, which is not always the case. Furthermore, aggregation of different products with similar characteristics is problematic: as highlighted by Hertwich (2005), differences implied by consumption choices are often not properly taken into account by analysis of averages.

2.4.2.3 Footprints

Studies approaching socio-economic metabolism through the lens of footprints are concerned with ecological accounting; footprints are the metric describing human pressure on the planet. Three common footprint indicators are the Ecological Footprint, Carbon Footprint, and Water Footprint, which have recently been grouped under a single conceptual framework named the Footprint Family (Galli *et al.*, 2011).

The Ecological Footprint concept was introduced by Mathis Wackernagel and William Rees (Rees, 1992; Wackernagel, 1994). Although the Ecological Footprint measures resource flows, the respective flows are expressed in terms of how much land and water area a human population uses to maintain its socio-economic metabolism (Galli *et al.*, 2011). This includes the areas for producing the resources consumed, the space required for buildings and roads, and the ecosystems for absorbing wastes and emissions. The concept of Ecological Footprint goes beyond accounting in that it compares human demand against nature's supply of biocapacity. The Ecological Footprint can be applied at different scales, ranging from single products, to cities and regions, to countries and the world as a whole (Galli *et al.*, 2011). The Carbon Footprint refers to the total amount of greenhouse gas (GHG) being emitted by an activity, a product, an organisation, a region, or a nation (Galli *et al.*, 2011). The Water Footprint was introduced by Arjen Hoekstra (Hoekstra, 2003). The Water Footprint is an indicator of water use that includes both direct and indirect water use of a consumer or producer. The water footprint of an individual, community or business is defined as the total volume of freshwater that is used to produce the goods and services consumed by an individual or a community, or produced by a business (Hoekstra *et al.*, 2011).

Other footprints are emerging, such as for example extinction footprints (Lenzen *et al.*, 2012). Another related concept is Material Input per Service Unit (MIPS), which calculates the material input required for a product or service in terms of five input categories: abiotic materials, biotic materials, water, air, and earth movement in agriculture and silviculture (Ritthoff *et al.*, 2002).

2.4.3 System Delimitation

In addition to the analytical lens as functional system delimitation, there are two more dimensions to system delimitation: temporal and spatial system boundaries. Common spatial boundaries are specific countries (e.g. Bin and Dowlatabadi, 2005; Ott and Rechberger, 2012), regions (e.g. Baccini and Bader, 1996; Faist *et al.*, 2001), cities, neighbourhoods (e.g. Codoban and Kennedy, 2008), industrial sectors (e.g. Antikainen *et al.*, 2005; Kirkeby *et al.*, 2006), or private households (e.g. Hertwich, 2011; Tukker *et al.*, 2010); studies can either be an inventory of one specific system (e.g. Faist *et al.*, 2001; Røpke, 2001) or they can point out differences between different systems by means of a cross-sectional study (e.g. Moll *et al.*, 2005). The temporal focus of a study can be on the past (e.g. Neset *et al.*, 2008), the present (e.g. Sundramoorthy *et al.*, 2011), or on the future (e.g. Wirsenius *et al.*, 2010); studies can either be a snap-shot of a given moment in time (e.g. Kalmykova *et al.*, 2012; Ott and Rechberger, 2012) or they can point out the evolution of a system by means of a longitudinal study (e.g. Neset *et al.*, 2008; Røpke, 2001).

2.4.4 Research Typologies

Socio-economic metabolism research encompasses both natural and social sciences, as both technology and lifestyle are important determinants of resource consumption and waste generation. Previous studies span a wide variety of different research scopes, analytical lenses, and system delimitations. Studies on the metabolism of distinct socio-economic entities (e.g. countries, neighbourhoods, individual households) are often designed to analyse and compare different entities in order to identify salient features that determine resource use, waste generation, and/or environmental footprints. Such studies focus on spatial and temporal patterns of, and variations among and within different entities and types of entities. For a truly complete accounting of the resource consumption and waste generation of an individual entity, hidden flows related to the provision of services and the supply and discharge of goods should be quantified and attributed to the respective entity. These hidden flows are often attributed to a good or service as virtual flows.

Socio-economic metabolism studies can also be designed to support policy and decision making by evaluating the environmental impacts of different policy options or scenarios. For instance, Kirkeby *et al.* (2006) investigated the environmental impacts of different solid waste systems and technology, and Wirsenius *et al.* (2010) calculated land-use requirements for global food production under different scenarios.

Household metabolism as specific type of socio-economic metabolism research is concerned with private households and private consumption. A number of studies have for instance calculated environmental impacts of private consumption (Benders *et al.*, 2012; Bin and Dowlatabadi, 2005; Hertwich, 2011; Tukker and Jansen, 2006; Tukker *et al.*, 2010), or the spatial impact of city dwellers on their resource hinterland (Lenzen and Peters, 2009). These studies normally build on national statistics and aim at determining the relative importance of different final demand categories and consumption areas—such as food, shelter, clothing, mobility, and leisure—for generating environmental and resource impacts (Hertwich, 2011).

Other studies have compared the metabolism of the sum of private households in different neighbourhoods (Codoban and Kennedy, 2008), or have focused on quantifying and characterising household waste generated in different neighbourhoods or municipalities (Dahlén and Lagerkvist, 2008; Dahlén *et al.*, 2007; Lebersorger and Beigl, 2011; Sterner and Bartelings, 1999). The former studies aim at evaluating resource consumption and waste generation patterns, the latter ones the performance of different municipal waste collection systems. Either type of study is generally designed in such a way as to obtain a representative sample of a given neighbourhood (e.g., villa area, area with apartment blocks, area with property close collection system, area with drop-off collection system). This means stratified sampling, and the samples need to be large enough to even out spatial and (short-term) temporal variations on the level of individual households. Comparing household metabolism at the neighbourhood or city scale certainly reveals differences between different household types, neighbourhoods, or municipalities, but does not reveal differences between individual households.

Ultimately, individual private households drive resource consumption, waste generation and environmental impacts. Rather than evening out spatial and temporal variations through aggregation to larger spatial scales, it is exactly these variations that are of interest. Various studies analysed and compared resource use and environmental impacts of individual households (Baker *et al.*, 2007; Carlsson-Kanyama *et al.*, 2002; Holden, 2004; Hunter *et al.*, 2006; Kotakorpi *et al.*, 2008; Moll *et al.*, 2005; Stamminger, 2011). Studies focusing on individual households normally aim at revealing the differences in resource use and waste generation between different individual households or household types. Holden (2004) compared the ecological footprints of homes defined as either green or ordinary based on four indicators: energy use for heating and operating housing, material consumption for housing, distance travelled in a private car, distance travelled through private air travel. Hunter *et al.* (2006) applied a diary-based data acquisition methodology to estimate and compare the ecological footprint of different individual households for goods purchases, transport, and waste generation. Moll *et al.* (2005) compared average household energy requirements for four countries (the Netherlands, the United Kingdom, Norway, Sweden) and several consumption categories. Studies on waste generation of individual households (e.g., Abu Qdais *et al.*, 1997; Bandara *et al.*, 2007) are sparse.

Other research directions focus on household activities and practices, and include the investigation of behavioral aspects of consumption and consumption choices (Evans, 2011; Gilg *et al.*, 2005; Holden and Linnerud, 2010; Isenhour, 2010; Reid *et al.*, 2011), close examinations of household practices (Gram-Hanssen, 2010; Kuijer and de Jong, 2012), or co-management of household practices (Bulkeley and Askins, 2009; Bulkeley and Gregson, 2009; Strengers, 2011a). For example, Isenhour (2010) investigated difficulties and barriers consumers faced in their attempts to reduce their environmental and social impacts.

Chapter 3

Framing Household Metabolism

Household metabolism was presented in chapter 2 as a specific type of socio-economic research, where the system boundary is represented by either the sum of private households, or individual households. This chapter on the one hand describes additional research fields that are related to, or to which quantification of the metabolism of individual households can be applied. On the other hand, methods and tools for the acquisition of disaggregated environmental data are summarised.

3.1 Contextualising the Quantification of Household Metabolism

Substantial contributions in terms of sensor development for the quantification of household metabolism have been made by the human computer interaction (HCI) research community, in particular through studies on eco-feedback (e.g Froehlich *et al.*, 2012; Staake *et al.*, 2011; Sundramoorthy *et al.*, 2011), smart homes (e.g Demiris and Hensel, 2008; Kientz *et al.*, 2008), and ambient assisted living (e.g Chiriac *et al.*, 2011; Cook *et al.*, 2009). On the application side, quantification of household metabolism can be meaningfully integrated in user-centred research and in evaluating the impact of innovations on resource flows and waste generation.

3.1.1 Eco-Feedback

Eco-feedback is based on the assumption that most people lack awareness and understanding about how their everyday behaviours, such as driving to work or showering, affect the environment; eco-feedback is in most cases designed to provide information on resource consumption and/or environmental impacts related to everyday activities in order to promote environmental behaviour and facilitate informed decision-making at the individual and household level (Froehlich, 2011). The reduction of resource consumption through visualisation was investigated for personal tranportation activities (e.g. Froehlich *et al.*, 2009), water consumption for showering (e.g. Staake *et al.*, 2011), and household energy consumption (e.g. Sundramoorthy *et al.*, 2011).

3.1.2 Smart Homes and Ambient Assisted Living

Smart homes are residences equipped with technology that observes the residents and provides proactive services (Ding *et al.*, 2011). In order to be able to observe the residents, sensors are required. Infrastructure-mediated systems are one type of sensor technology applied in smart homes. A more comprehensive overview on sensor technology for smart homes is provided in Ding *et al.* (2011). An example of a smart home is reported in Kientz *et al.* (2008).

Ambient assisted living refers to approaches to support elderly people who live on their own. This is often facilitated by activity monitoring and assessment. Sensing human activity in the physical world can be achieved by mobile and wearable sensing, distributed direct environmental sensing, and infrastructure-mediated environmental sensing (Froehlich, 2011). The approach of distributed direct environmental sensing was for example applied by Chiriac *et al.* (2011), who used humidity, motion, contact and temperature sensors for activity recognition. Infrastructure-mediated sensing on the other hand was investigated by Noury *et al.* (2009), who monitored electrical activities on the residential power line to remotely follow up the health state for elderly people living on their own.

3.1.3 User-centred Research

Studies that aim at understanding and influencing household practices (e.g. Gram-Hanssen, 2010; Kuijer and de Jong, 2012), or studies on co-management of household resource use (e.g. Strengers, 2011a) are related to household metabolism in two ways. On the one hand, these studies have a direct impact on the magnitude of specific resource streams and thus a subset of household metabolism. On the other hand, quantification of household metabolism is a valuable tool to examine the effects of changed practices in terms of the resulting changes in resource use and waste generation patterns.

3.1.4 Living Laboratories

A recent trend in user-centred research are living laboratories, which are usually referred to as living labs. The term living lab is used to refer to both an innovation methodology and the arena or facilities created for its practice (Almirall *et al.*, 2012; Ståhlbröst, 2012). From the methodological perspective, living labs are networks composed of heterogeneous actors, resources, and activities that integrate user-centred research and open innovation (Leminen *et al.*, 2012). From the infrastructure perspective, living labs are facilities that enable experimentation and co-creation with users in real-life environments (Sundramoorthy *et al.*, 2011).

3.1.4.1 Living Lab Methodology

Almirall *et al.* (2012) formulated three propositions (which are listed in their original form below) to describe the living lab methodology:

> **Proposition 1.** Living lab methodologies engage a selected group of users in the innovation process to capture market and domain-based knowledge and involve them iteratively through a co-creation process.
>
> **Proposition 2.** Living labs elicit new understandings and meanings, and capture tacit and domain-based knowledge by situating and evolving innovation projects in real-life contexts and taking the opportunity to involve the whole ecosystem.
>
> **Proposition 3.** Living labs take advantage of public-private partnerships for generating an initial demand and often involve other actors such as small and medium-sized entreprises to lower barriers of entry in complex multi-stakeholder or highly regulated environments.

3.1.4.2 Living Lab Categories

Leminen *et al.* (2012) studied 26 living labs and identified four living lab categories: utiliser-driven, enabler-driven, provider-driven, and user-driven. Utilisers are companies that are interested in new knowledge for product and business development; enablers are public-sector actors and non-governmental organisations that seek societal improvement and development towards a certain preferred direction; providers are educational institutes or consultants that aim at augmenting knowledge creation; users are individuals or communities that seek to solve everyday-life problems (Leminen *et al.*, 2012).

3.1.4.3 Key Principles of Living Labs

Ståhlbröst (2012) proposed five key principles that should permeate all living lab operations: value, sustainability, influence, realism, and openness. Living labs should create value for all stakeholders, particularly for customers and users; living labs should take responsibility for their ecological, social, and economic effects; users should be allowed to influence innovation processes in the role of competent partners and domain experts; innovation activities should be carried out in realistic, natural, real-life and use settings and situations; and the innovation processes should be open to allow for a variety of perspectives (Ståhlbröst, 2012).

3.1.4.4 Examples of Studies Using the Living Lab Methodology

Studies that used the living lab methodology are diverse and fields of application include management education (Bourgault, 2012), knowledge management in universities (Tikhomirova *et al.*, 2012) or university hospitals (Sampedro *et al.*, 2012), optimisation of energy costs in office buildings (Georgievski *et al.*, 2012), building e-participation strategies (Cleland *et al.*, 2012), home care (Vuorimaa *et al.*, 2012), eco-feedback (Jakobi and Schwartz, 2012; Ståhlbröst, 2012; Sundramoorthy *et al.*, 2011), manufacturing automation (Wadhwa, 2012), fostering everyday life innovation (Tang and Hämäläinen, 2012), and bathing practices (Scott *et al.*, 2012).

3.1.4.5 Living Labs and Sustainability

A specific type of living lab seeks to create innovation for sustainability. Liedtke *et al.* (2012) elaborate five research lines for sustainable living labs: design, construction and maintenance of sustainable homes; integrated approaches to home energy management; the connected home; resource-efficient lifestyles and social networks; as well as new product and service development.

3.1.4.6 Living Labs and Household Metabolism

Clearly, the research on home energy management, resource-efficient lifestyles and social networks, and new product and service development are related to household metabolism. On the one hand, living lab studies aim at making resource and waste flows visible and hence reduce them (e.g. eco-feedback). On the other hand, quantification of household metabolism is valuable to examine the effects of innovations on resource use and waste generation patterns.

3.2 Methods and Tools for the Collection of Disaggregated Data

Quantification of selected aspects of household metabolism first and foremost requires data, that is to say, factual information as the basis for reasoning, discussion, calculation or inference. In recent years, research on the metabolism of individual households has gained popularity. This implies the need for disaggregated data rather than aggregated average figures. Such factual information is often obtained as information output by a sensing device or organ. Physical sensing devices are referred to as sensors; they transform an input signal which is considered unknown and inaccessible into an output signal, the measurement or observation (Harder, 2010). Alternatively, data can also be obtained by questionnaires or diaries (where individuals become surrogate sensors), or as the output of a mathematical model.

3.2.1 Direct Sensing

Physical flows enter and leave individual households through various pathways[5]. In industrialised countries, the public mains supply of potable water and energy is often nationwide. Energy is mostly supplied in the form of electrical energy (national grid), chemical energy (gas supply) or heat energy (district heating). Once water and energy carriers supplied by public mains have reached individual households, they are normally distributed through in-house supply networks to different appliances for end-use.

Supply channels other than public mains supply include retailers or direct acquisition (e.g., home-grown food). The range of goods acquired through these latter channels is much more varied than for goods supplied in public mains and mainly includes durable goods (e.g., household appliances, furniture) and consumer goods (e.g., detergents, food). The composition of these goods is much less homogeneous than for goods supplied in public mains.

Used products as well as packaging are disposed of by households through several formal or informal pathways. In industrialised countries, used water is normally discharged via public sewer systems whereas solid waste is collected through solid waste collection schemes with extensive source separation.

[5] It is worthwhile pointing out that, at least in industrialised countries, a large portion of physical flows and services provided are accompanied by a monetary flow, often in the opposite direction. Substituting monetary flows for physical flows is tempting and indeed done in expenditure surveys used to estimate for instance the environmental impacts or energy intensity of household consumption, but is not further discussed in this thesis.

Physical flows can be measured at different levels of disaggregation, for example at the level of an individual household or at the level of fixtures/appliances or fixture/appliance groups. For water, fixtures and appliances include washing machines, dishwashers, toilets, showers, and taps. For electricity, appliances include personal electronics and other household appliances such as the stove, fridge, washing machine or dishwasher, but also electric radiators and lighting. Gas is normally used for heating purposes (boilers for hot water and space heating) or for cooking. Heat distributed through district heating networks is normally used solely for heating purposes (hot water, space heating). Waste flows can be grouped into recyclables, biowaste, bulky waste, hazardous waste, and residual waste. Recyclables, for instance, could be further disaggregated into used products and packaging material, which in turn could be divided into paper packaging, metal packaging, plastic packaging and so forth.

The supply of goods through public mains is normally quantified using meters or sensors. Sensing in general requires that there is a physical quantity that can be measured and that there is a known relation between the quantity measured and the quantity to be estimated, in this case consumption of water or energy. For quantification of flows at the level of an individual household, at least one meter per flow is required. In a case where disaggregated consumption data per fixture/appliance is required, two approaches are possible. The first approach is straightforward, at least in theory, and consists of placing one meter on every fixture/appliance of interest (e.g. Cho *et al.*, 2009; Ibarz *et al.*, 2008; Kim *et al.*, 2008). In practice, however, this approach requires a substantial number of meters and may be hampered by costs and cumbersome installation. The second approach builds on using pattern recognition techniques and algorithms (e.g. Chen *et al.*, 2011; Cohn *et al.*, 2010; Froehlich *et al.*, 2011a; Gupta *et al.*, 2010; Kim *et al.*, 2009; Larson *et al.*, 2012). Pattern recognition allows for a considerable reduction of the number of sensors to be deployed, often to as little as one single sensor per flow to be quantified; the downside is that not all events may be correctly classified and assigned to a given fixture/appliance.

Quantifying purchases of goods and related waste generation at the level of individual households is more difficult than the installation of meters for water or electricity supplied in public mains, mainly due to batch-wise supply and discharge through several pathways as well as the heterogeneous composition of the related physical flows. As a result of the variety of pathways, quantification of the respective physical flows cannot be achieved by means of a single sensor, but requires an approach that is likely to feature elements that already exist in warehouse or supermarket management systems for maintaining stock.

3.2.1.1 Water

As soon as water is used at a given fixture/appliance, the water that is abstracted needs to be replaced from the supply network, resulting in physical displacement of water in the piping system, which is normally accompanied by vibration and sound. In addition, the beginning and end of a use event triggers a pressure wave that propagates through the piping. Quantification of water use can be based on sensing any of these physical properties. Among the sensing and disaggregation approaches tested by the research community are sound-based distributed sensing (Fogarty *et al.*, 2006; Ibarz *et al.*, 2008), vibration-based distributed sensing (Kim *et al.*, 2008), pressure-based single-point sensing (Froehlich *et al.*, 2011b; Larson *et al.*, 2012), and disaggregation based on low sample rate smart meters (Chen *et al.*, 2011) or high sample rate smart meters (Kim *et al.*, 2009). A comprehensive overview of sensing water consumption is presented in Froehlich (2011).

3.2.1.2 Electricity

Each time an electrical appliance uses electricity, the electrons moving in the wiring do work. Furthermore, switching an appliance on or off leads to a specific high-frequency noise or interference pattern. These quantities can be measured using appropriate sensors. Among the sensing and disaggregation approaches tested by the research community are distributed sensing on the breaker board level (Lin *et al.*, 2010), single-point sensing and disaggregation based on high frequency electromagnetic interference patterns (Gupta *et al.*, 2010), and disaggregation based on high sample rate flow meters and additional side information (Kim *et al.*, 2009). A comprehensive overview is presented in Froehlich *et al.* (2011a) and Zeifman and Roth (2011).

3.2.1.3 Gas

Use of gas relates to the movement of gas molecules in the supply pipe, which is often accompanied by a characteristic noise. This displacement or noise can be sensed and translated into the volume of gas used. For example, Cohn *et al.* (2010) tested a sound-based single-point sensing and disaggregation approach.

3.2.1.4 Heat

Heat is different from water and gas as it is not the actual substance that is of interest but rather its embodied heat. Hence, the quantity of interest is the transfer of heat from one medium to another rather than the use of a substance. In the case of district heating, quantification of the heat supplied requires both an estimation of the mass flow and the temperature difference between feed and return flow. In other contexts, heat transfer can also be estimated indirectly, for example by measuring surface and ambient temperature and calculating heat transfer based on a heat transfer model.

3.2.1.5 Consumer Goods and Durable Goods

Quantification of goods supplied other than through the public mains is more difficult due to batch-wise supply and discharge through several pathways as well as the inhomogeneous composition of the related physical flows. Essentially, there are two approaches. First, weight and product characteristics for every product purchased, or acquired otherwise, can be recorded manually, which may require substantial efforts. Second, data on product weight and characteristics could be obtained directly from retailers, which limits data collection to purchased goods.

3.2.1.6 Disposal of Residuals

With the exception of wastewater, quantifying the disposal of residuals is subject to the same difficulties as quantifying goods supplied through channels other than public mains. Accordingly, there is also a direct approach that manually analyses and records relevant information on disposed residuals. The indirect approach estimates waste generation based on material composition and throughput of products through households.

3.2.1.7 Mobility

Mobility in a narrow sense is an activity or service rather than a physical flow. However, depending on the definition of the household (i.e., household as a socio-economic entity or household as a physical entity), physical flows caused by mobility can account for a considerable part of the overall physical flows related to a household. For example, Froehlich *et al.* (2009) developed a mobile tool for sensing and providing feedback about personal transportation habits and choices.

3.2.1.8 Quantifying Activities within the Household

For the sensing of specific activities within a household, there are two main paradigms. The first paradigm focuses on the recognition of actual activities rather than assignment of flows to activities. The second paradigm focuses on flow disaggregation and assigning consumption of a certain good to a specific activity. For example, sound-based activity recognition for water tap use was investigated by Vu *et al.* (2011), and recognition of the use-mode of kitchen appliances was investigated by Bauer *et al.* (2009). Cho *et al.* (2009) used programmable logic devices in order to detect the use of different appliances and their location, whereas Stamminger (2011) modelled resource consumption for laundry and dish treatment.

3.2.2 Questionnaires and Diaries

Questionnaires and diaries are data collection approaches where humans indirectly act as sensors. Whereas direct sensing is limited to physical flows and household activities, questionnaires and diaries go beyond collecting household environmental data and can also disclose information on personal attitudes, values and motivations leading to a given behaviour. Reid *et al.* (2011) used household diaries beyond mere data collection to bring about behavioural change through reflection.

Chapter 4

Quantifying the Metabolism of Individual Households: a Case Study

Within the framework of this thesis, an attempt was made to simultaneously quantify water use, electricity use, heat use, mobility, goods consumption and waste generation for individual households. In particular, the ambition of the study was to reveal the factors causing metabolic differences between different household types, but also among households belonging to the same household type. This implies the need to go beyond merely comparing explanatory variables such as building type, socio-economic status, or family size; data on household activities need to be collected as well. This chapter describes the motivation for, the reasoning behind, the implementation of, the findings from, and the lessons learnt from this investigation.

4.1 Scope and Motivation

The choice of the individual household as the unit of analysis and individual activities as the unit of observation was motivated by the hypothesis that this level of disaggregation holds relevant information that is otherwise lost by aggregation; the consideration of multiple flows was motivated by the hypothesis that there is a gain from measuring and comparing multiple flows simultaneously rather than investigating only one flow at a time. When this case-study was conceived, to our knowledge, no study had addressed this question. Later, we discovered a study that investigated natural resource consumption of 27 Finnish households by considering seven components: housing, mobility, tourism, leisure activities, food, packaging and wastes, and household goods and appliances (Kotakorpi *et al.*, 2008).

The initial scope of this study was to acquire a comprehensive dataset on consumption and waste generation patterns of a representative number of households in Gothenburg, Sweden. The extent of data collection required to meet the scope of this study necessitates a sufficient number of households to ensure that the dataset is representative, and a sufficient level of detail so that the dataset is meaningful. Collecting highly disaggregated data for a large number of households requires substantial effort and may not be practically feasible with a limited amount of resources at hand. Therefore, this study also aimed at finding a viable trade-off between depth and breadth of data collection.

4.2 Overall Study Design

The study was conceived in three stages with decreasing degree of detail and increasing degree of representativeness from stage to stage. Table 4.1 summarises the characteristics of the three stages.

Table 4.1: Envisaged project stages.

Project Stage	Scale	Description
1	Pilot	Detailed investigation of two selected households: first experiences with the data collection methods pointing to potential shortcomings and pitfalls; first division of the data collected into essential data and optional data.
2	Bench	Less detailed investigation of about a dozen households: validating whether the data collection methods are applicable for a larger, less controllable sample and whether the reduced level of detail still produces a meaningful data set.
3	Full	The actual data collection study on a representative set of households (in the order of tens).

The system household was defined as a physical entity with the physical household as system boundary. This physical household comprises all humans, domestic animals and artifacts belonging to a specific household in the sense of a socio-economic entity. As a first approximation, the quantification of flows was limited to direct physical flows of matter and energy; neither services nor flows outside of the system boundary of the household would be considered. The main physical flows to be covered were determined to be supply of water, energy carriers, heat, consumer goods, durable goods, and disposal of different types of solid waste (see Figure 4.1).

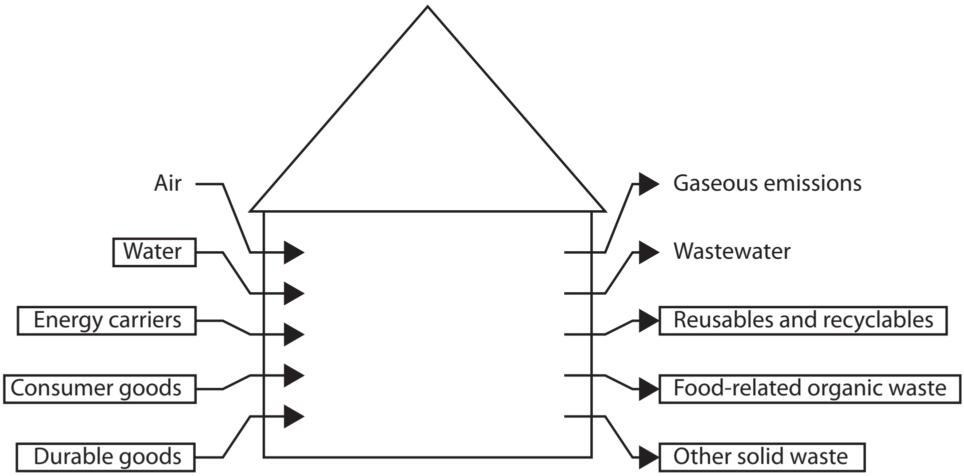

Figure 4.1: The flows considered in this study are marked by squares. The other flows could be of potential interest but were not considered.

For the detection of household activities, the level of detail was restricted to knowing which appliances/fixtures or appliance/fixture groups cause a given physical flow; the reason behind why certain appliances/fixtures were used in practice was not investigated further. Activity detection was conceived to be entirely based on infrastructure-mediated sensing; time-diaries or log-books were not considered in this study.

Data collection at the high level of detail envisaged for the pilot study requires substantial instrumentation and produces large amounts of data. The pilot study required several tasks to be completed in parallel. With regard to quantifying goods supplied by public mains, the tasks included the following: specification of suitable instrumentation; installation of sensors and data loggers; setup of a database structure to handle the large amount of data; programming suitable algorithms for data validation and visualisation; programming suitable algorithms for event detection and representation; programming suitable algorithms for data analysis. With regard to goods not supplied by the public mains and the related waste generation, a data collection approach for manual data collection needed to be developed as no standard tools and routines were available at the time the pilot study was started. Completing all these tasks was so time consuming that, so far, the study has not progressed beyond the pilot stage (Table 4.1).

4.3 Implementation of the Pilot Study

For the pilot study, two households of the researchers involved in the project were chosen as test households in order to ensure full control and feedback on the process of data collection as well as to directly experience the extent to which the data collection may impact daily life. Given that the focus of this study was on method development and evaluation rather than on data comparison, these two advantages outweigh the bias introduced by selective sampling. Some key characteristics of the two pilot households are summarised in Table 4.2.

Table 4.2: Key characteristics of the two test households.

Household Characteristic	Pilot Household A	B
Building Type:	Detached House	Apartment
Floor Space:	300 m^2	70 m^2
Adults/Children:	2/7	1/0
Pets:	1 dog, 1 cat	none
Cars:	2	0 (car sharing)

Concurrent data collection by means of both infrastructure-mediated sensing and manual data collection was meant to take place during Spring 2012. However, due to the various challenges met during setting up the sensor network and developing the data collection approach for consumption of goods and related waste generation, not all of the flows initially envisaged were quantified during the pilot study, and the different elements of data collection were not entirely synchronised. Figure 4.2 summarises the sampling periods for the different elements of data collection considered.

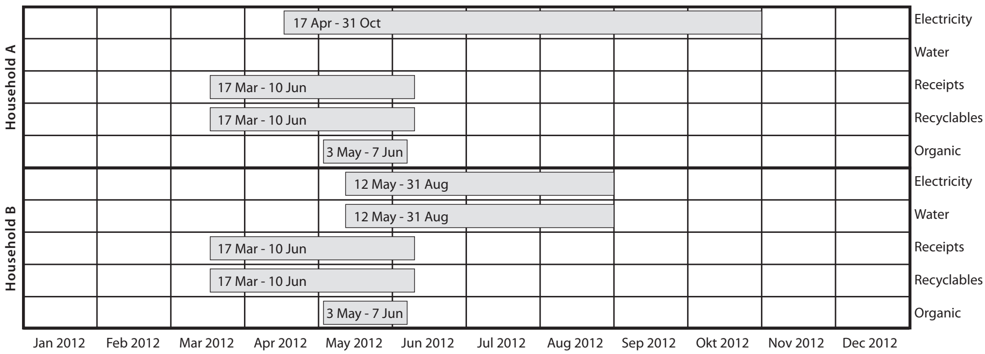

Figure 4.2: Pilot study sampling periods for different flows. Note that stages two and three of the manual data collection are not included in the graph.

4.3.1 Sensor Network Deployment

Infrastructure-mediated sensing covered the quantification of the use of electricity and water at different appliances/fixtures or appliance/fixture groups, respectively. Quantification of heat flows connected to space heating was not accomplished. Deployment and operation of sensor networks requires a number of choices. First, the sensor network can be deployed and operated directly by the researchers, or a commercial company can be commissioned to do this job. The sensor network used in the pilot study was designed and operated directly by the researchers and deployed in cooperation with local electricians and plumbers. This provided full control and full flexibility, but getting the data into a useful format required substantial efforts. Second, there are countless possibilities for setting up a sensor network. Choices pertain to: sensor types, number of sensors, location of sensors, type of data loggers, type of communication (wired or wireless), communication protocols, sampling frequency, and database management. The sensor network components and typology were chosen to enable self-administration. This meant sensors with a simple communication protocol (S0 impulse); data loggers that can be easily configured by the user and remotely accessed via the local internet connection; and wired communication between sensors and data loggers. Table 4.3 summarises the characteristics of the sensor network components deployed in this study.

Table 4.3: Sensor network components deployed in this study.

Component	Model	Range	Impulse Valency
Electricity Meter:	Eltako WSZ12DE-32A	0.02 - 32 A	2 000 Imp./kWh
Water Meter:	Biotech FCH-C-Ms	0.5 - 30 L/min	480 Imp./L
Impulse Logger:	EMU LS920000	0 - 166 Imp./sec	user defined

Electricity meters were installed on the breaker board on the level of individual circuits. At household A, one additional electricity meter was placed at the television. At household B, one additional electricity meter was placed at the plug connector serving personal electronic devices. Furthermore, separate electricity meters for the data loggers were installed at both households. Water meters were installed on the level of individual fixtures and only at household B[6]. At household A, 22 electricity meters were connected to 4 data loggers. At household B, 11 electricity meters and 6 water meters were connected to 2 data loggers. The sampling frequency was 0.1 Hz. The sensor network topology is summarised in Figure 4.3 and Table 4.4.

[6] The water meters were ordered at the beginning of February 2012 and should have been delivered by the end of February 2012. At the end of March 2012, only 6 water meters could be delivered due to a supply bottleneck; just enough for household B. The remaining 22 water meters arrived only by the beginning of June 2012. Swedish summer holidays further delayed installation up to the point where it was decided not to install them at all.

Table 4.4: Pilot study sensor network topology. At household A, 23 electricity meters were installed; at household B, 12 electricity meters and 6 water meters were installed.

Household	Sensor	Data Logger	Type	Description
A	EL-T01	LOG-A01	Electricity	Oven
A	EL-T02	LOG-A01	Electricity	Stove (Phase 1)
A	EL-T03	LOG-A01	Electricity	Stove (Phase 2)
A	EL-T04	LOG-A01	Electricity	Various Appliances
A	EL-T05	LOG-A02	Electricity	Various Appliances
A	EL-T06	LOG-A02	Electricity	Fridge/Freezer
A	EL-T07	LOG-A02	Electricity	Dishwasher
A	EL-T08	LOG-A02	Electricity	Various Appliances
A	EL-T09	LOG-A02	Electricity	Data Logger
A	EL-T10	LOG-A02	Electricity	Data Logger
A	EL-I01	LOG-A02	Electricity	TV
A	EL-L06	LOG-A03	Electricity	Various Appliances
A	EL-M01	LOG-A04	Electricity	Various Appliances
A	EL-M05	LOG-A04	Electricity	Various Appliances
A	EL-M06	LOG-A03	Electricity	Various Appliances
A	EL-M07	LOG-A04	Electricity	Various Appliances
A	EL-M11	LOG-A03	Electricity	Various Appliances
A	EL-M13	LOG-A03	Electricity	Fridge/Freezer
A	EL-R04	LOG-A03	Electricity	Various Appliances
A	EL-R05	LOG-A03	Electricity	Various Appliances
A	EL-R07	LOG-A03	Electricity	Washing Machine
A	EL-R08	LOG-A03	Electricity	Washing Machine
A	EL-R10	LOG-A04	Electricity	Various Appliances
B	EL01	LOG-B01	Electricity	Stove / Oven (Phase 1)
B	EL02	LOG-B01	Electricity	Stove / Oven (Phase 2)
B	EL03	LOG-B01	Electricity	Stove (Phase 3)
B	EL04	LOG-B01	Electricity	Fridge
B	EL05	LOG-B01	Electricity	Freezer
B	EL06	LOG-B02	Electricity	Various Appliances
B	EL07	LOG-B02	Electricity	Various Appliances
B	EL08	LOG-B02	Electricity	Various Appliances
B	EL09	LOG-B01	Electricity	Water Kettle
B	EL10	LOG-B01	Electricity	Data Logger
B	EL11	LOG-B02	Electricity	HiFi and PC Equipment
B	EL12	LOG-B02	Electricity	Other Personal Electronics
B	WA01	LOG-B01	Water	Kitchen tap (warm)
B	WA02	LOG-B01	Water	Kitchen tap (cold)
B	WA03	LOG-B02	Water	Shower (mixed)
B	WA04	LOG-B02	Water	Toilet (cold)
B	WA05	LOG-B02	Water	Bathroom tap (warm)
B	WA06	LOG-B02	Water	Bathroom tap (cold)

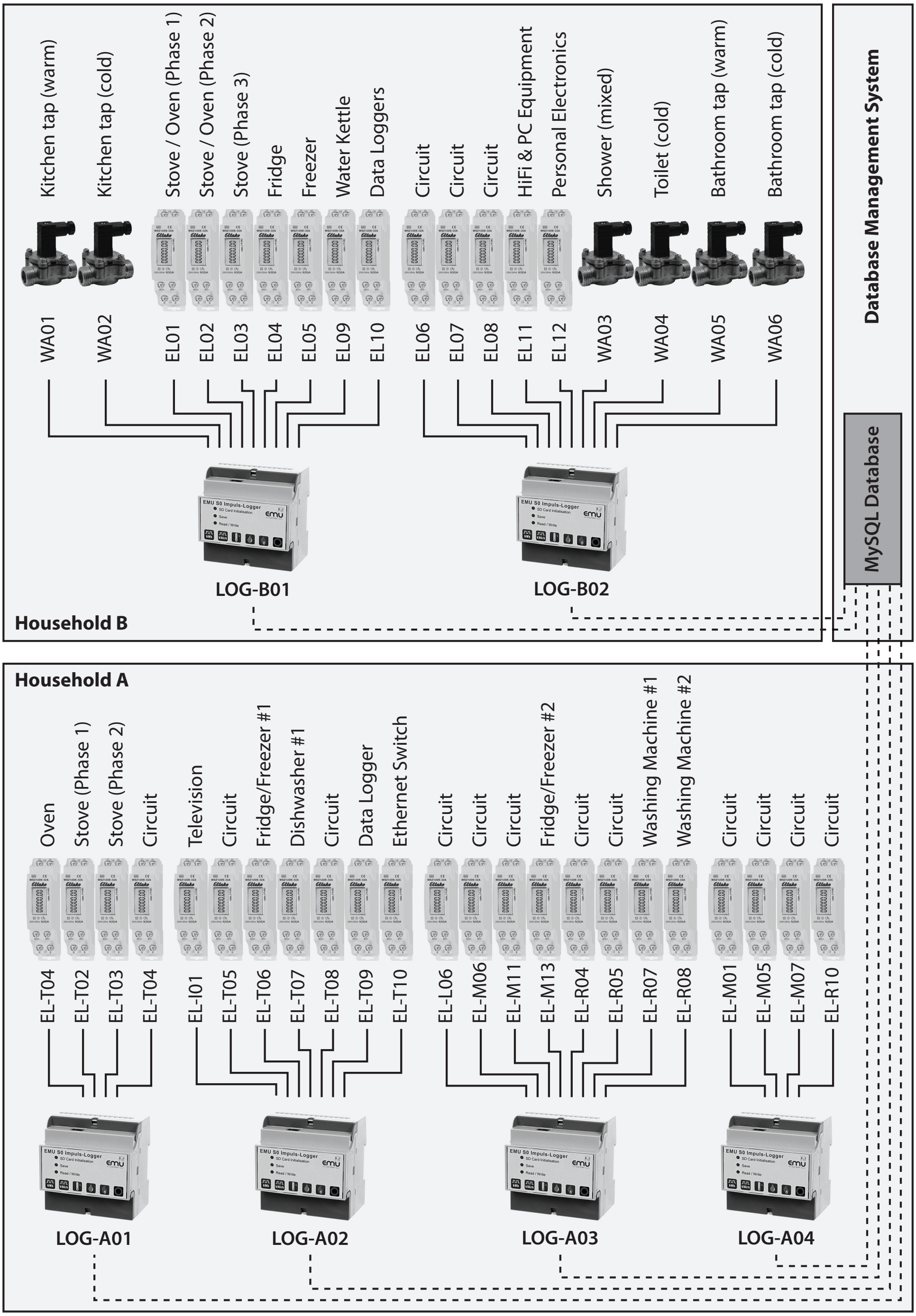

Figure 4.3: Pilot study sensor network topology. Note that sensor codes (e.g., EL-T05) have no specific meaning but just indicate the type of sensor (EL = electricity, W = water) and the location on the breaker board (e.g., T = "top floor").

4.3.1.1 Limitations of the Chosen Sensor Network Topology

The chosen sensor network topology implies that, for electricity meters, disaggregation to a single appliance or appliance group was not always possible. Particularly at household A, it was difficult to get separate consumption estimates for appliance groups other than washing machines, dish washers, stove, oven or combined fridge/freezer. At household B though, given the relatively small number of electrical appliances, it was possible to also obtain separate consumption estimates for the kettle, personal electronic devices, and lamps. The partial delivery of water meters meant that one water meter was lacking at household B, whereas installation at household A was not possible at all. Due to anticipated installation difficulties at the shower valve at household B, only one water meter was installed. Disaggregation into cold and warm water usage was hence not possible.

4.3.1.2 Limitations of the Chosen Sensor Network Components

The chosen sensor network components imply three limitations. First, the electricity meters have a lower detection limit of 4.6 W instantaneous power (at a voltage of 230V). Second, a mismatch of data logger sampling interval and electricity sensor impulse valency that was not discovered during planning complicated the data processing required to ensure usability of the dataset obtained: that power consumption per 10 second interval can only be resolved to steps of 180W[7]. Third, water flow rates above 20 L/min are cut off[8].

4.3.1.3 Problems Revealed by Data Validation

Each of the sensors installed produced 8640 measurements per day. Almost 17.5 million measurements were collected during the sampling period for household A and just under 40 million measurements for household B. This huge amount of data required storage in a database management system and the development of tailor-made validation and visualisation algorithms. Data validation in particular is important in order to assess data quality and completeness.

[7] For instance, a constant load of 90W leads to one impulse count every other 10 second interval. This problem can be explained by the electricity meter impulse valency of 2000 Imp./kWh combined with the data logger sampling interval of 10 seconds. Electricity sensors with 10 000 Imp./kWh are available on the market and would improve the resolution to 36W steps, but are considerably more expensive. Finally, sensors with different protocols enable recording instantaneous power rather than impulses, but are more complex to install.

[8] This problem can be explained by a misinterpretation of the specifications of the data logger, which state that the maximum sampling rate equals 333 gradients per second. Gradients were wrongly interpreted as peaks and it was not taken into account that one peak has two gradients. The maximum data logger sampling rate of 166 Imp./sec combined with the water meter impulse valency of 480 Imp./L hence limits the maximum flow rate to 20 L/min.

For each sensor, two tests were performed in order to reveal sensor and logger related problems: (1) number of recorded measurements per day, and (2) cumulative amount of impulses recorded per day. The two simple tests applied during data validation revealed a number of problems and the results are visualised in Figure 4.4.

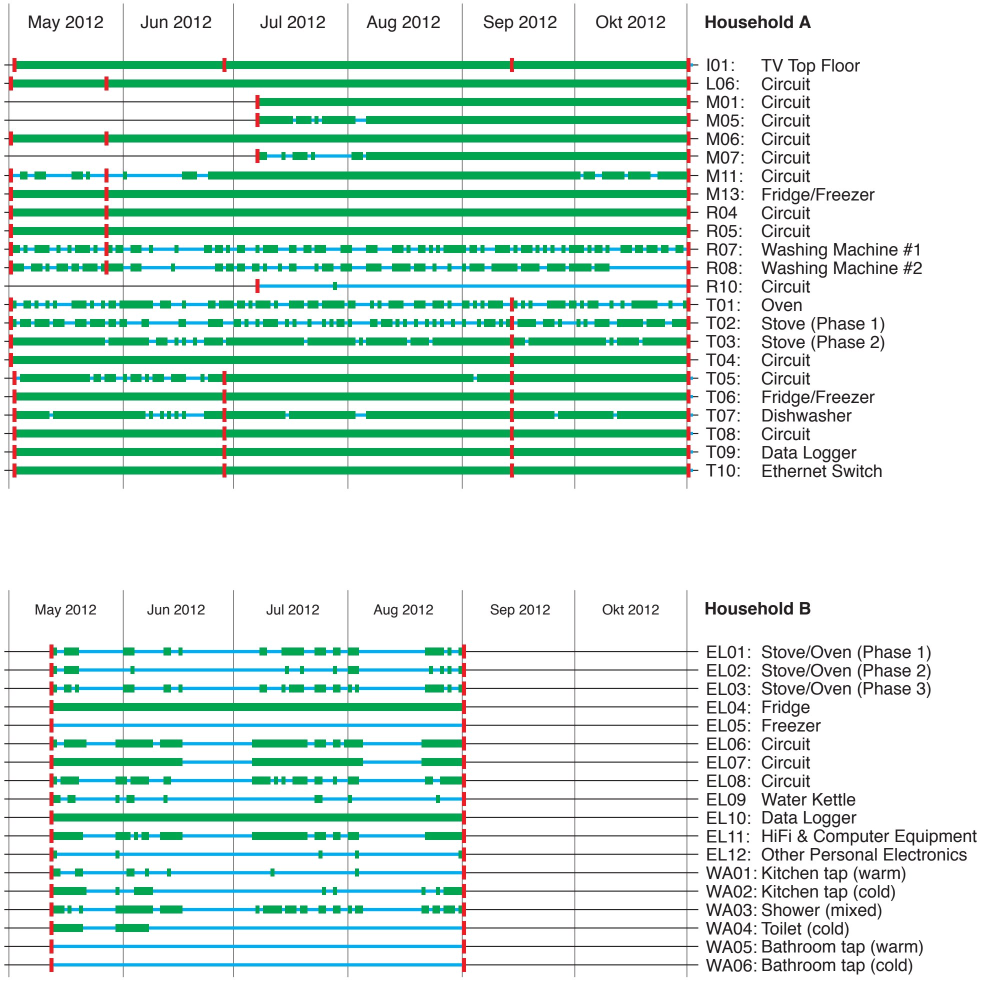

Figure 4.4: Data quality and completeness for infrastructure-mediated sensing for household a (above) and household B (below). Red dots represent days where less or more than 8640 measurements were recorded for a given sensor. The light blue lines represents days where 8640 measurements were recorded for a given sensor; a green dot in addition means that the logger recorded at least one impulse on a given day, whereas absence of a green dot means that no impulse was recorded on a given day.

Problems Encountered at Household A

At household A, it is salient that for the sensors connected to data logger A04 (EL-M01,EL-M05, EL-M07, EL-R10) no data are available until mid-July. The reason is that logger A04 was wrongly configured, which only emerged after data were collected for the first time. Furthermore, all sensors connected to loggers A02 and A03 (Table 4.4 and Figure 4.3) recorded more or less than 8640 measurements at the end of May or the end of June, respectively (red dots in Figure 4.4). The reason is that the data loggers occasionally synchronise their internal time with an external time. The internal time is only adjusted if the time differences are larger than 30 seconds, leading to too many or too few measurements on the day synchronisation takes place. However, impulse counting remains unaffected by synchronisation and no impulses were lost or double counted during synchronisation.

Problems Encountered at Household B

At household B, no impulses were registered for the water meters at the bathroom tap (WA05, WA06) during the whole sampling period (lack of green dots in Figure 4.4); this indicates that a connection problem between meters and logger occurred shortly after installation and testing of the sensors. No impulses were registered for the water meter at the toilet (WA04) from 8th of June onwards; this points to a connection problem between meter and logger occurring about four weeks after installation. For the water meters at the kitchen tap (WA01, WA02), impulses were registered every once in a while but far less often than the use of the stove would suggest; most likely the water flow was below the detection limit of the water meter most of the time[9]. No further problems are visible for the remaining sensors (EL01-EL12, WA03). Note that, for these sensors, extended periods where no impulses were recorded (lack of green dots in Figure 4.4) coincide with periods where nobody was present at household B.

4.3.1.4 Summary Sensor Network Deployment

Sensor network deployment was successful only for the electricity meters; installation of the water meters was problematic and provided very fragmentary data. Furthermore, the different limitations related to sensor network components and topology complicated data processing and data analysis.

[9] When choosing water meters, flow rates for every fixture were estimated and compared with the lower detection limit of the water meter. However, it was not taken into account that flow rates for hot or cold water can be significantly lower if both streams are used concurrently at the same fixture.

4.3.2 Manual Data Collection Approaches

Quantifying purchases of goods and related waste generation at the level of individual households is more difficult than metering water or electricity supplied in public mains, mainly due to batch-wise supply and discharge through several pathways as well as the heterogeneous composition of the related physical flows. Ideally—at least from the perspective of a researcher—for every good moving through a household, all information regarding its detailed composition would be available, what it was used for, and when and on which pathway(s) (see Figure 4.5) its constituents left the household.

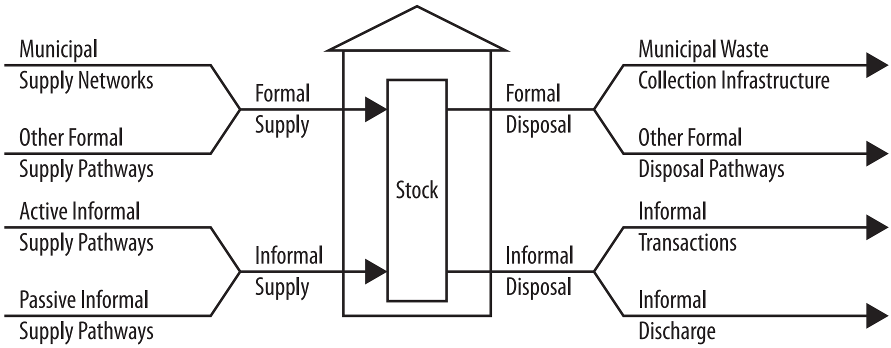

Figure 4.5: Pathways of goods through individual households. Supply pathways are municipal supply networks (water, electricity and gas mains), other formal pathways (flows that are accompanied by formal monetary transactions such as purchases in stores), active informal supply pathways (such as self-supply through gardening, hunting and collection), and passive informal supply pathways (supply that cannot be controlled, such as presents and advertisements). Disposal pathways are the municipal waste collection infrastructure (sewer systems and solid waste collection infrastructure), other formal disposal pathways (for example selling through second-hand schemes), informal transactions (giving away something for free), and informal discharge (disposal of waste to the natural environment).

The main challenge regarding data collection is to reach a sufficient level of detail whilst using a data collection approach that is practical and feasible. Three data collection approaches were developed and evaluated in this study. The first data collection approach aimed at minimising involvement of, and disturbance to test households. In particular, households should not be required to write log-books, and data collection should be possible without obtaining data from producers or retailers. Given this design space, two main data sources came into consideration: shopping receipts and waste component analysis by manual sorting. The second and third approach were responses to the shortcomings of the first approach.

4.3.2.1 Stage 1

For the first stage of data collection, both households were asked to collect (1) shopping receipts relevant to purchases of goods, (2) selected recyclables (i.e., glass, metal, paper, cardboard, plastic) in a separate container on a daily basis, and (3) food-related organic waste in four different fractions per day (i.e., vegetable waste and peelings, fruit waste and peelings, wasted food, other food-related organic waste). Shopping receipts and collected waste was subsequently analysed manually. Shopping receipts and recyclables were collected between 17th of March and 10th of June 2012, organic waste between 3rd of May and 7th of June 2012.

Analysis of Shopping Receipts

The overall structure of shopping receipts is very similar. Header and footer include shop details, payment details, purchase date and total price of the purchases, whereas the receipt body lists the individual articles purchased (Figure 4.6). The type of information provided for the individual articles purchased, however, varies considerably from shop to shop. Ideally, article number (e.g., EAN-13), article description, quantity and price are printed on the receipt. However, article numbers are provided only by few shops and information on quantities is often incomplete as weight indications are only stated for products bought by weight rather than by package. All shopping receipts were digitised and stored in a database.

Analysis of Collected Waste

Organic waste samples were weighed, dried in the oven at 120 °C to constant weight and weighed again (Feng, 2012). Wet weight, dry weight, fraction and generation date of the respective sample were stored in the database. Recyclables were first grouped into two categories: standardised packaging items (i.e., packaging material from articles that can be identified by the product barcode) and remaining recyclables. For standardised packaging items, product barcode, amount and date of disposal were recorded in the database. Furthermore product name, manufacturer, manufacturing country as well as the weight of different fractions of the packaging (glass, metal, paper, cardboard, plastic) was determined and stored in the database along with the respective product barcode in case the product did not exist in our database. The remaining recyclables were grouped into ten types (newspaper, magazine, commercials, envelope, unspecified paper, unspecified cardboard, unspecified plastic, unspecified metal, unspecified glass, unspecified wood) and the weight of each type was registered along with the generation date.

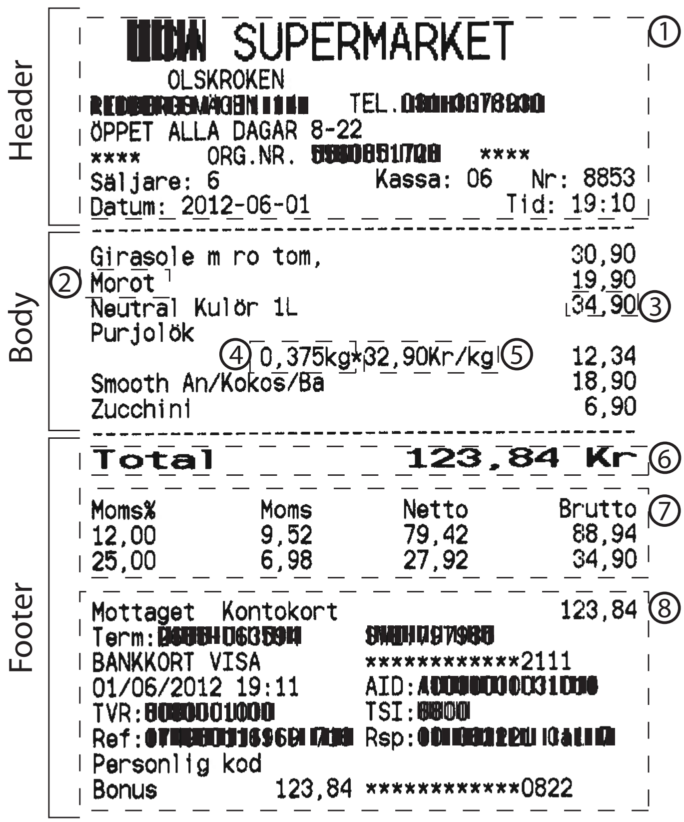

Figure 4.6: Typical shopping receipt holding information on (1) shop, (2) articles purchased, (3) price per article, (4) quantity per article, (5) unit price per article, (6) total price, (7) VAT, and (8) payment.

Complementarity of Data Sources

Throughout the first stage of data collection, 776 distinct articles were identified on shopping receipts and 715 distinct standardised products were recorded during analysis of collected waste. A total of 1650 articles were purchased and a total of 1282 standardised packaging items were disposed of. Data obtained from shopping receipts and waste component analysis in principle are complementary. In order to relate product and waste flows, the two sources were triangulated (see Figure 4.7). It was often difficult, however, to relate a certain shopping receipt item to a certain package item. This is because the names of items on shopping receipts are often not identical with the names on the product packaging. Furthermore, different supermarkets use different names on the shopping receipt to refer to one and the same product. Finally, purchased products can be put on stock and products used can come from the stock. In both cases no matching item combination can be found either. All in all, we were able to relate 94 packaging items to a specific purchase and a further 289 standardised packaging items could be related to a specific shopping receipt item.

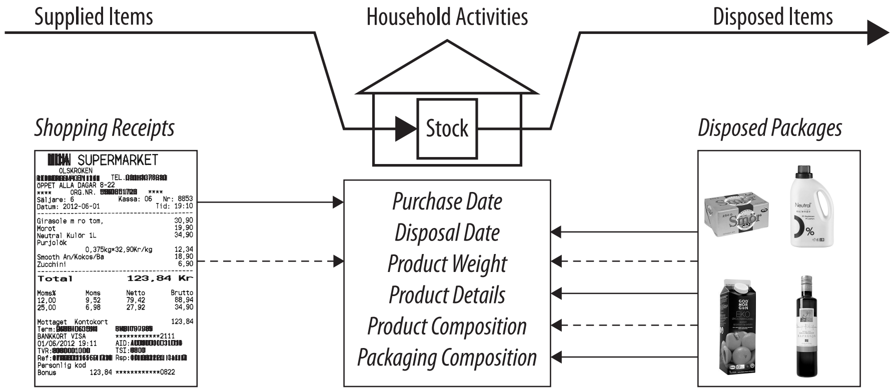

Figure 4.7: Data collection relies on two data sources: shopping receipts and disposed packages. Solid lines indicate that the respective information is available for every distinct article flowing through the household; dashed lines indicate that the respective information is only available for some of the articles.

Shortcomings of the First Stage

The main methodological shortcomings emerging from the first stage of data collection are related to the estimation of overall product flows. Broadly speaking, three cases can be distinguished: (1) food products with a short shelf-life, (2) food products with a long shelf-life, and (3) non-food products. For products with a short shelf-life (e.g., vegetables, fruits, dairy products), changes in stock can be neglected and the product flow can be estimated based on a combination of input data (shopping receipt analysis) and output data (waste component analysis). However, care needs to be taken to avoid double counting for products bought by weight. On the one hand, such products often have no packaging or just a small plastic bag with no further information provided on it, whilst information on the weight is provided on the shopping receipt. On the other hand, pre-packed similar products often have no weight indication on the shopping receipt but the package holds this information instead. Sometimes, weight information is provided both on the shopping receipt and the packaging (e.g., vacuum-packed meat products). In other cases, neither shopping receipt nor packaging hold information on the weight (e.g. fresh bread). Products with a long shelf-life (e.g., alcoholic beverages, canned food) are often subject to a considerable time-lag between purchase and consumption. For these products, data obtained from the analysis of collected waste give a better reflection of the actual consumption in a given period than data obtained from shopping receipts. Non-food products often do not indicate a product weight, in which case an estimation of the product flows in terms of weight is not possible based on the two data sources considered in the first stage of this study. Finally, the restriction to shopping receipts and waste component analysis by manual sorting implies that only formal supply and disposal pathways were considered.

4.3.2.2 Stage 2

In order to solve some of the problems encountered during the first stage of data collection (i.e., difficulties in relating packaging items to shopping receipt items, systematic lack of weight indications for certain product groups), a different method of data collection was tested at household B from 18th of July to 29th of August 2012. This second approach required considerable involvement of the households and, given the substantially larger throughput of goods at household A, would not have been practical at household A.

The main difference in this second stage of data collection was that each good entering the household was furnished with a sticker holding a unique barcode, subsequently to be referred to as a sequence barcode. Subsequently, shopping receipts were digitised, and the sequence barcode and product barcode (if available) were scanned and stored along with the other elements on the shopping receipts as described in the first stage of data collection. Furthermore, purchased goods where information on the weight was provided on neither shopping receipt nor packaging were weighed manually and the information stored in the database. Finally, the sequence barcode was scanned again upon disposal of the packaging, thereby ensuring proper traceability from input to output. In addition, any packaging item (whether or not the item featured a product barcode) was assigned one out of twelve different packaging types (i.e., cardboard box, glass bottle, glass jar, metal can, metal collapsible tube, paper bag, paper wrapping, plastic bag, plastic bottle, plastic box, plastic wrapping, tetra pak). By this means an overlap of packaging material without product barcode and used products inherent to some of the ten types of recyclables specified during the first stage of data collection was prevented. Food-related organic waste was manually weighed at irregular intervals determined by waste generation and the data was stored in a database.

Evaluation of the Second Stage

The introduction of a sequence barcode enabled proper tracking of a good from purchase to disposal, very much in analogy to a warehouse management system. Yet the involvement of the household was substantial as it included both digitising of shopping receipts and scanning product and sequence barcodes. Overall, this produced a consistent dataset, although data collection is not practical for a normal household.

4.3.2.3 Stage 3

The third stage of data collection aimed at simplifying the data collection approach tested during the second stage. To this end, a mobile application was developed that facilitates keeping a log-book of purchases and consumption of food products. Using this application, a dataset was collected at household B from 1st of January until 16th of January 2013.

The mobile application developed was conceived to track purchase, consumption, and disposal of food products in particular. The application will henceforth be referred to as FoodWatch. The home screen and the different functions of the application are shown in Figure 4.8

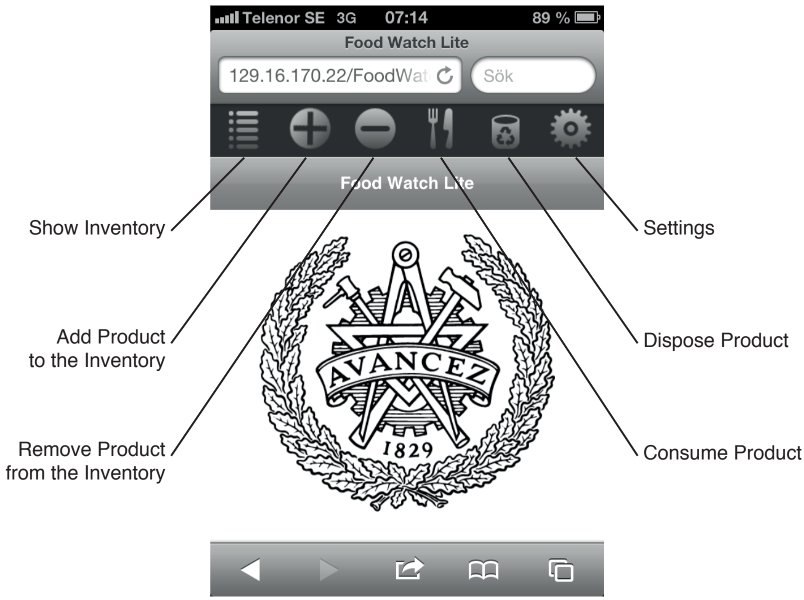

Figure 4.8: FoodWatch home screen.

In essence, the FoodWatch application facilitates keeping track of the inventory of food products. When food products are bought, householders add them to the inventory (see Figure 4.9) by scanning the product barcode, or choosing a product group in case no product barcode is available. Optionally, a sequence barcode can be attached to every single product bought and scanned as well. Products can then be taken outside of the physical boundary of the home (see Figure 4.10), be consumed (see Figure 4.11), or be disposed of (see Figure 4.12). In either case they are removed from the inventory by scanning the sequence barcode, the product barcode, or choosing a product group in case no product or sequence barcode is available.

Finally, the application also provides an overview of the inventory in real time (Figure 4.13), or an overview of purchases, consumption, and disposal of food products (Figure 4.14). Further functionalities are currently under development. On the one hand, it is possible to provide a history of purchase, consumption, and disposal of food products. On the other hand, it is possible to integrate footprints such as the carbon footprint or the water footprint.

Evaluation of the Third Stage

The FoodWatch application considerably simplifies data collection in comparison to the data collection approach tested during the second stage. In particular, it is no longer necessary to digitise shopping receipts. However, there are still some limitations; each time a product without a barcode is added to the inventory, or any product is consumed or disposed, the respective amount needs to be weighed manually and the weight noted in the application upon submitting the barcode or product group. This could be further simplified by having an automatic connection between the scale and the FoodWatch application. Note that packaging material is not considered at this stage.

Recording purchases with FoodWatch is relatively simple and straightforward. In addition, FoodWatch also allows tracking of the consumption and disposal of food products. This latter functionality is more cumbersome and requires discipline and time from householders. If FoodWatch is restricted to recording purchases, however, the routines are much less demanding and can be sustained over a longer time period. In this latter case, sequential barcodes are no longer required.

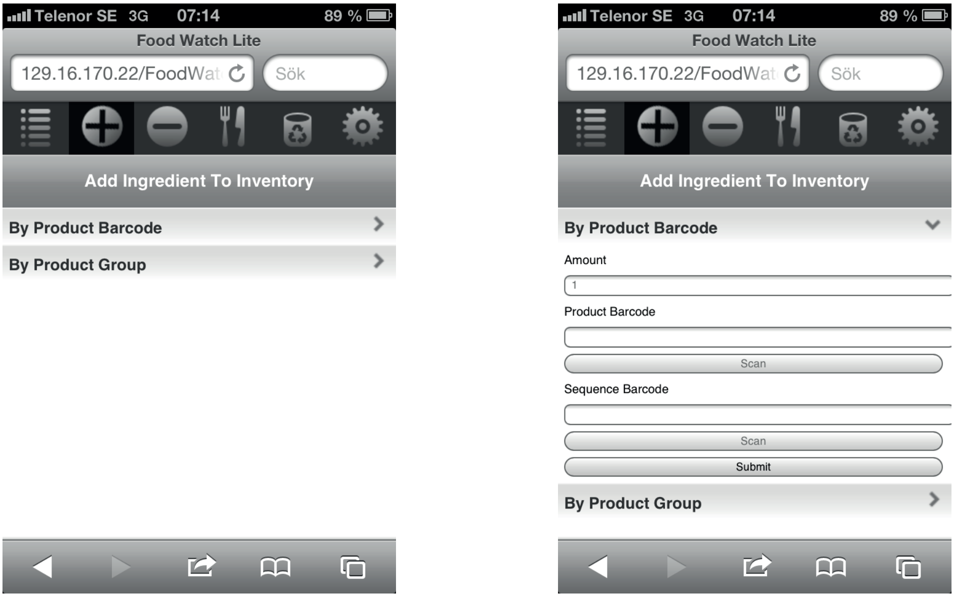

Figure 4.9: FoodWatch functionality to add a product to the inventory. *Left:* Products can be added using the product barcode, or the product group in case a product barcode is missing. *Right:* Adding a product by using the product barcode.

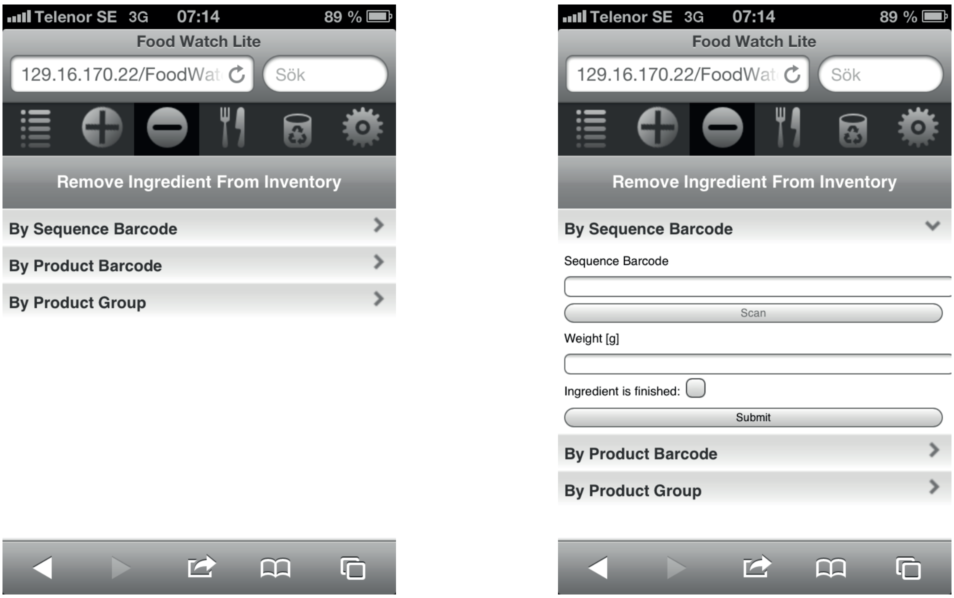

Figure 4.10: FoodWatch functionality to remove a product from the inventory. *Left:* Products can be removed using the sequence barcode, the product barcode, or the product group in case a product or sequence barcode is missing. *Right:* Removing a product using the sequence barcode.

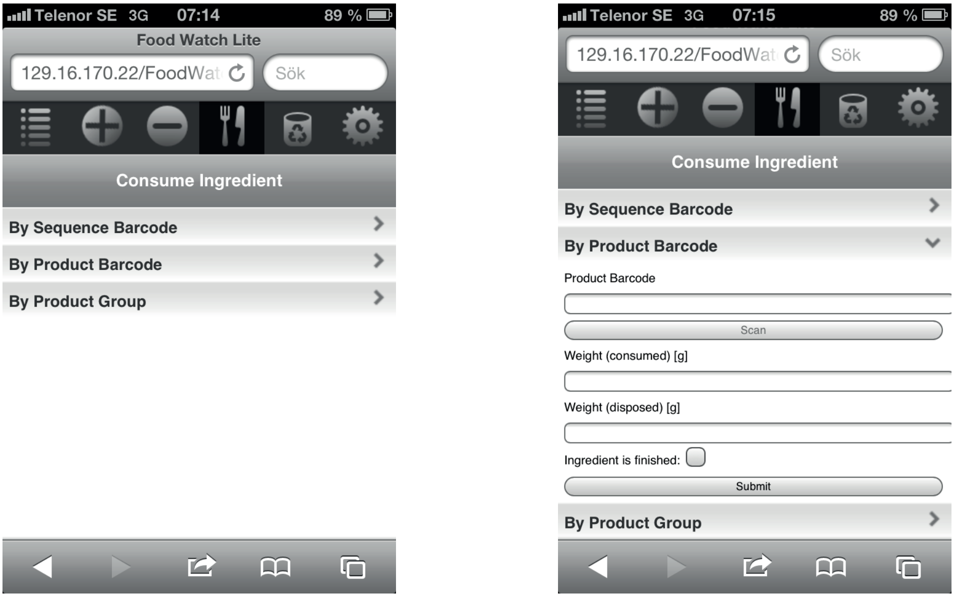

Figure 4.11: FoodWatch functionality for recording consumption of a product. *Left:* Products can be recorded using the sequence barcode, the product barcode, or the product group in case a product or sequence barcode is missing. *Right:* Removing a product using the product barcode.

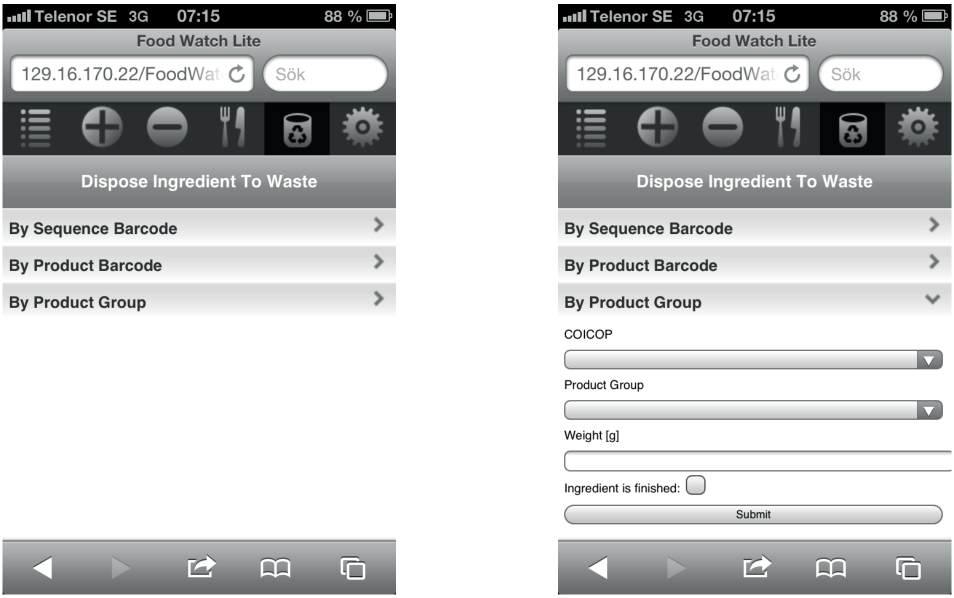

Figure 4.12: FoodWatch functionality for recording disposal of a product. *Left:* Products can be removed using the sequence barcode, the product barcode, or the product group in case a product or sequence barcode is missing. *Right:* Removing a product using the product group.

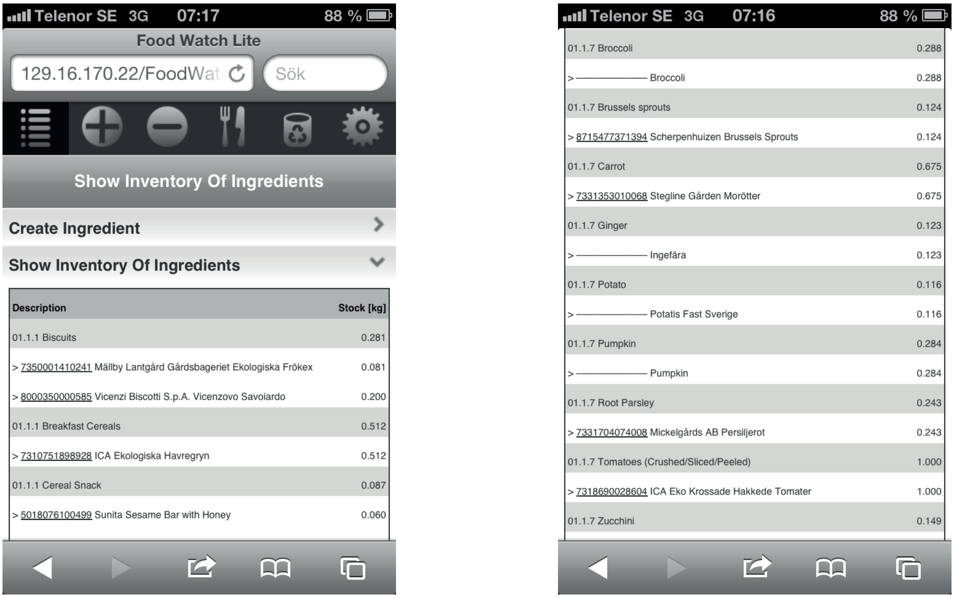

Figure 4.13: FoodWatch functionality providing the inventory of products currently available in the household.

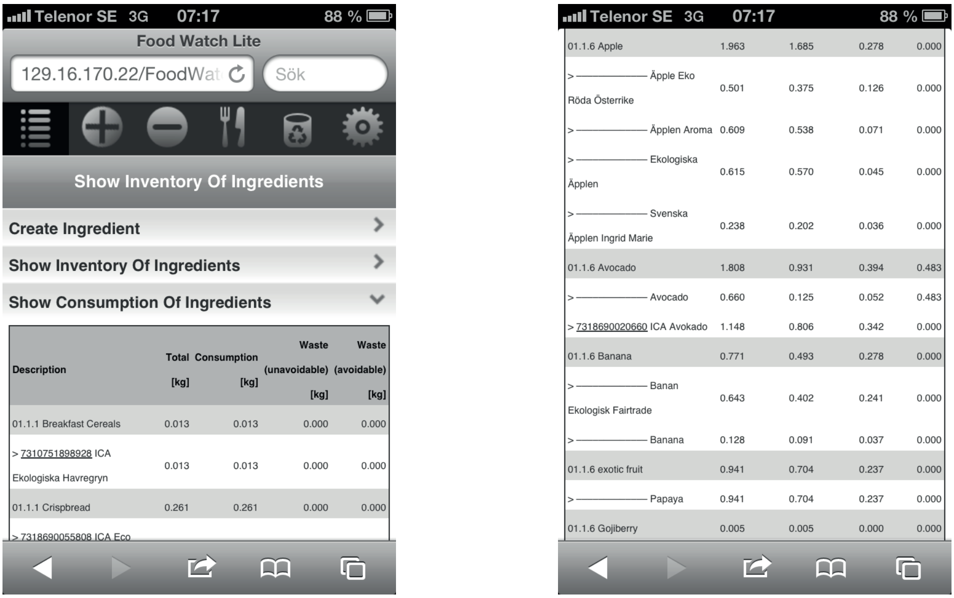

Figure 4.14: FoodWatch functionality providing an overview of purchases, consumption, and disposal of products.

4.4 Making Sense out of the Data

4.4.1 Analysis of Single Events

Infrastructure-mediated sensing enables the analysis of resource use and duration of single events, as exemplified in Figure 4.15 for showering and in Figure 4.16 for TV use, respectively. Based on individual events, the distribution of resource use per event type can be analysed, as exemplified in Figure 4.17 for showering and cooking.

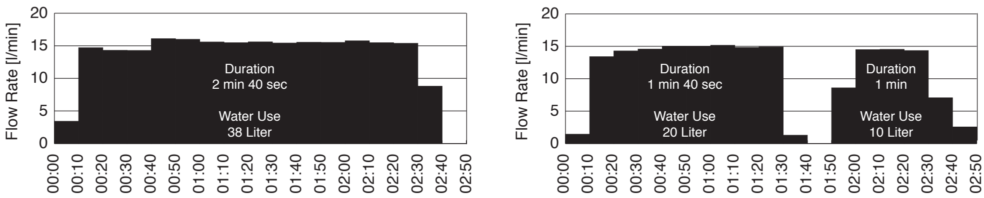

Figure 4.15: Typical shower events at household B. *Left:* typical continuous shower event. *Right*: typical discontinuous shower event—the shower is turned off while applying soap products. Note that the total shower duration for the two shower event types is roughly equal. The maximum water flow rate of 15 l/min indicates a conventional shower head.

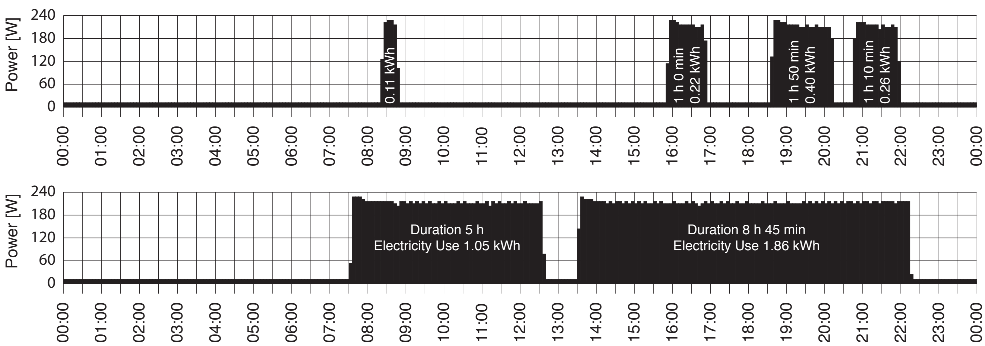

Figure 4.16: Typical TV usage events at household A. *Top:* Typical TV usage on weekdays. *Bottom:* Typical TV usage on weekends. Note the standby power of 11.5 W.

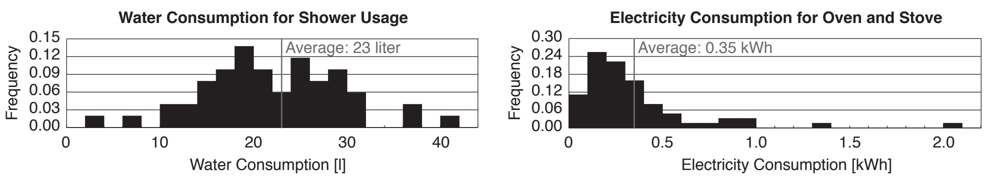

Figure 4.17: Frequency distribution of resource consumption per event type at household B. *Left:* water consumption for shower usage. *Right:* electricity consumption for operation of oven and stove.

4.4.2 Analysis of Temporal Patterns and Correlations

Consideration of the sequence or co-occurrence of events reveals temporal patterns and correlations. Analysis of temporal patterns for single appliances is exemplified in Figure 4.18 for showering, in Figure 4.19 for TV usage, and in Figure 4.20 for separated waste generation, respectively.

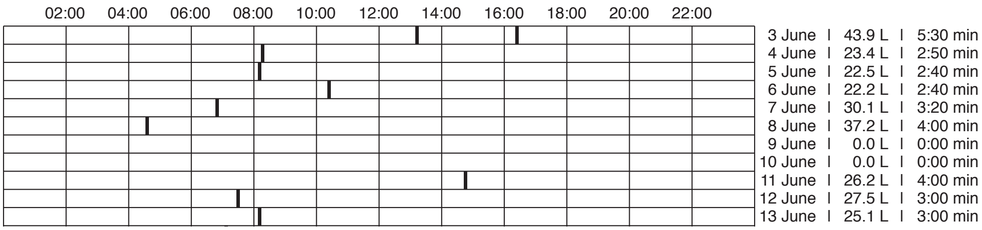

Figure 4.18: Temporal shower usage patterns at household B. Rows represent days, columns indicate the time of the day. Note that the figures to the right of the graph provide total water usage for showering and total duration of all shower events per day.

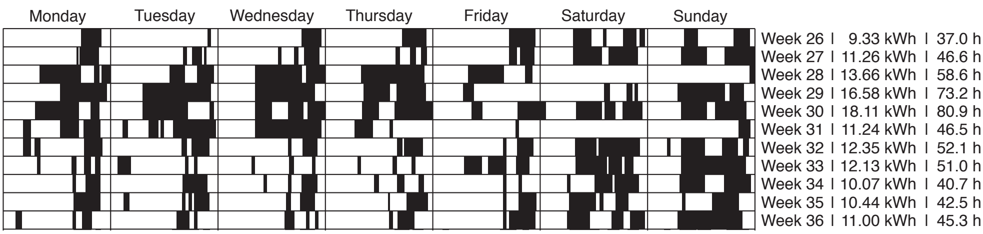

Figure 4.19: Temporal TV usage patterns at household A. Rows represent weeks, columns indicate the day of week and time of day. Note that the figures to the right of the graph provide total electricity usage for TV operation and total duration of TV usage per week. From week 28 until week 31 weekend usage patterns prevail on weekdays as well due to summer vacation.

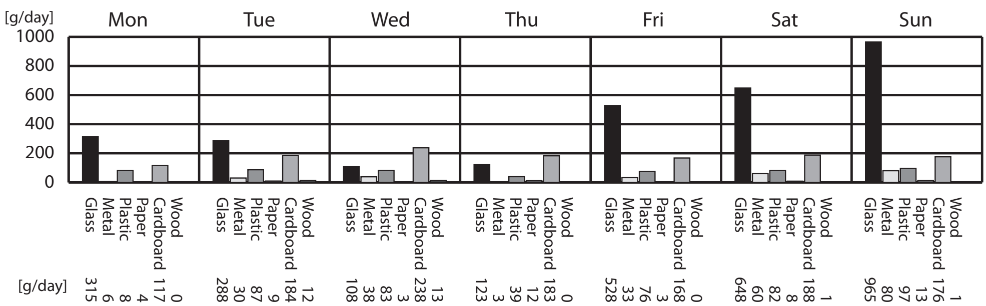

Figure 4.20: Disposal of packaging from standardised products by day of week for household A. Note the peaks for glass during the weekend.

Temporal patterns can also be visualised and analysed for several appliances and resource flows together. This is exemplified in Figure 4.21. This representation is similar to the activity patterns and activity-based load curves as presented by Ellegård and Palm (2011).

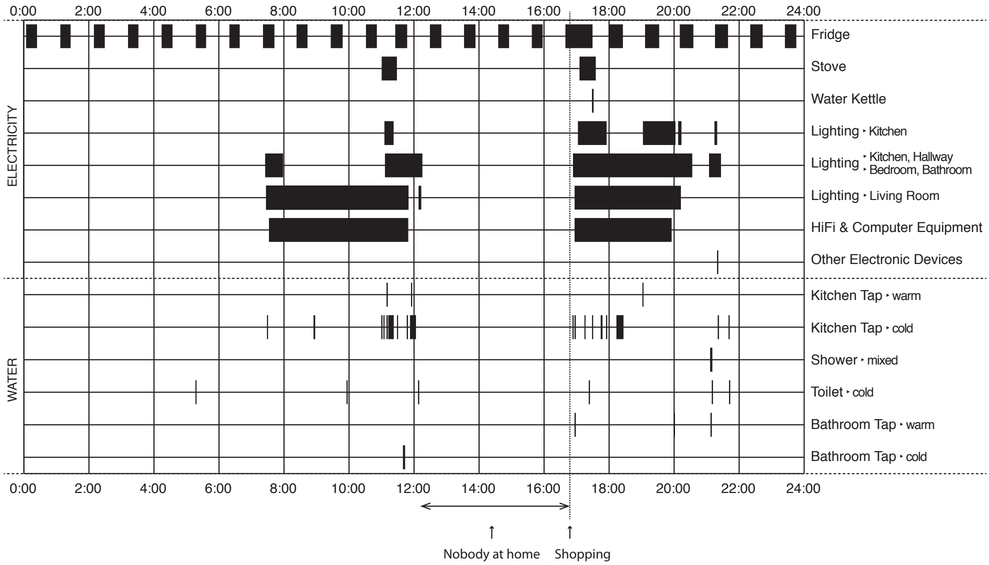

Figure 4.21: Water and electricity usage for household B on 13th of May 2012. The graph suggests that nobody was at home between shortly after 12:00 and shortly before 17:00. In fact, there was a shopping event just before returning home which explains the irregularity in the electricity usage pattern of the fridge: new products were added to the fridge implying a long door opening and the addition of products with a temperature higher than the internal temperature of the fridge. Note that household B does not operate a freezer. It can also be seen from the electricity usage that, at least on this specific day, most of the time the living room is illuminated, also HiFi and computer equipment is being used. It also appears logical that the light is on while taking a shower, as the bathroom has no windows. The coinciding electricity usage for other electronic devices stems from using the hairdryer. Finally, note that the water meters did not provide reliable results and, particularly for the two water meters in the bathroom as well as the warm water meter in the kitchen, the majority of the events is missing due to flows below the detection limit.

Whereas Figure 4.21 detailed one single day, it is also possible to consider longer time periods with a reduced level of detail. The daily use of electricity for different appliances as well as the disposal of various separated fractions of recyclables and organic waste over a period of 35 days is visualised in Figure 4.22. For these longer time series it is also possible to compute the dependence between different time series by means of cross correlation coefficients.

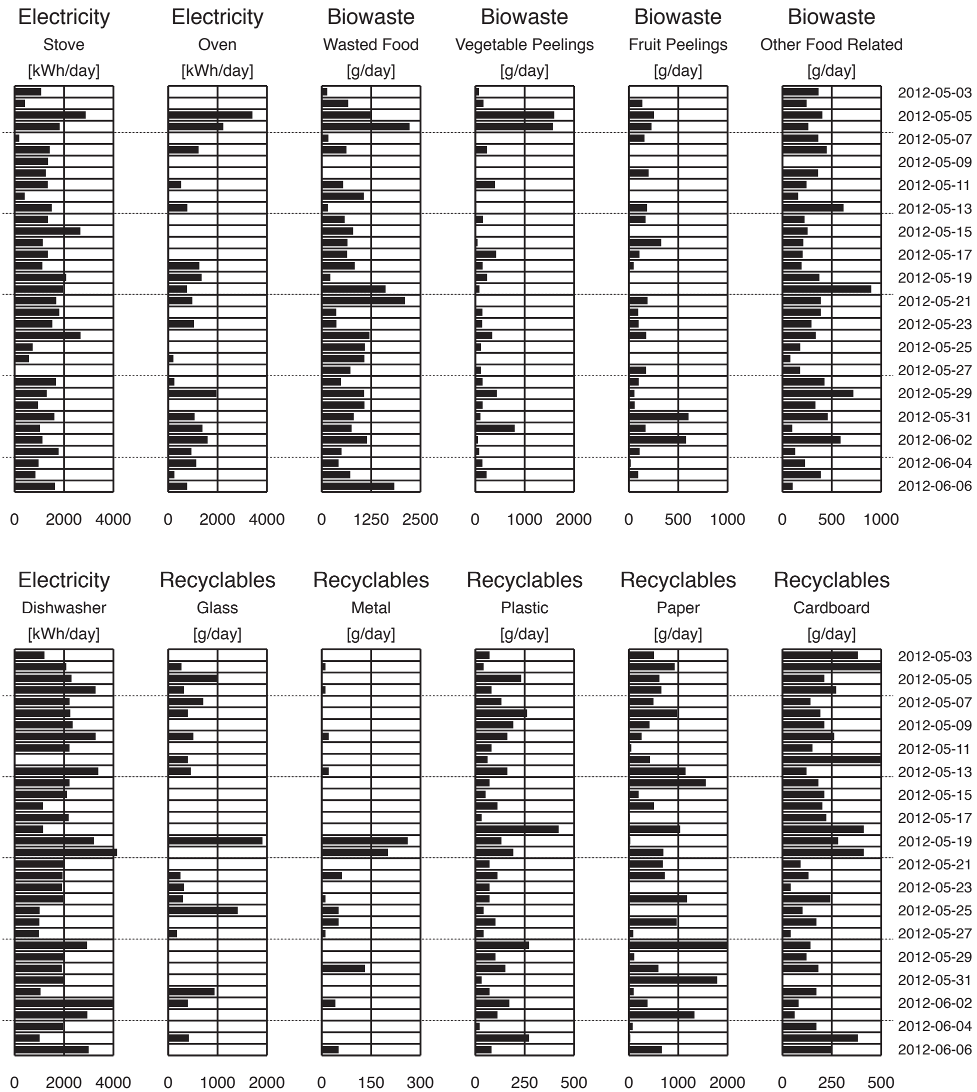

Figure 4.22: Daily electricity usage of selected appliances and disposal of various fractions of recyclables and organic waste at household A over a period of five weeks. To improve readability, different scales were used for different graphs. On the weekend of the 19th of May 2012, there is a distinct peak for both disposal of glass and metal coinciding with a relatively high disposal of other packaging material, a peak in dishwasher usage, and a peak in disposed biowaste. Overall, the most significant correlations for household A were found between electricity use for cooking (stove plus oven) and dishwashing (normalised cross-correlation function estimate at zero lag of 0.88) and between electricity use for cooking and wasted food (normalised cross-correlation function estimate at zero lag of 0.82).

4.4.3 Analysis of Aggregated Consumption Figures

For infrastructure-mediated sensing, consumption data can be aggregated according to appliance (group) or fixture (group). This is exemplified for electricity consumption in Table 4.5, and for water consumption in Table 4.6.

Table 4.5: Electricity consumption at households A and B aggregated per appliance group.

Appliance Group	Average Daily Consumption [kWh]	Average Power [W]	Percentage
Household A			
Oven+Stove	1.78	74.1	6.3
Fridges+Freezers	3.93	163.7	14.0
Dishwasher	1.58	65.9	5.6
Washing Machines	1.11	46.4	4.0
Television Equipment	1.67	69.4	5.9
Remaining	17.99	749.5	64.1
TOTAL	28.06	1169.1	100.0
Household B			
Oven+Stove	0.21	8.6	14.5
Fridge	0.55	23.0	38.9
Lights	0.54	22.7	38.4
Personal Electronics	0.12	4.8	8.2
TOTAL	1.42	59.1	100.0

Table 4.6: Water consumption at household B aggregated per fixture group. Note that, whilst the consumption estimates for toilet and shower are accurate, the consumption estimates for the taps are very conservative due to issues with flows below the detection limit.

Fixture Group	Average Daily Consumption [L]	Percentage
Household B		
Toilet	27.2	52.6
Shower	15.0	29.0
Kitchen Tap	8.8	17.0
Bathroom Tap	0.7	1.4
TOTAL	51.7	100.0

The average electricity consumption of household A is almost 20 times higher than household B. There is a factor of 7 for fridge and freezers, which gives approximately the same per capita electricity consumption for both households. For stove and oven, the difference amounts to a factor of 8.5, but it needs to be pointed out that household B only cooked at home on a third of the days during the sampling period, whereas at household A cooking activities took place on 95% of the days. When making direct comparisons, it is therefore crucial to be clear on what is actually compared.

Based on manual data collection (stage one), product flows can be quantified, as exemplified in Table 4.7 and Figure 4.23. Furthermore, waste generation can be analysed as exemplified in Figure 4.24 for the disposal of food-related organic waste, and in Figure 4.25 for the disposal of recyclable material.

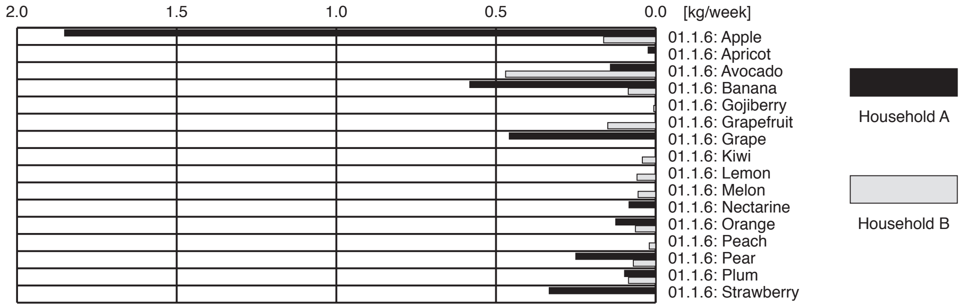

Figure 4.23: Product flows for COICOP class 01.1.6: fruits. Data was collected during the first stage, 17th of March until 10th of June 2012. Note that this type of data might also be directly obtained from retailers for purchases registered with customer fidelity schemes.

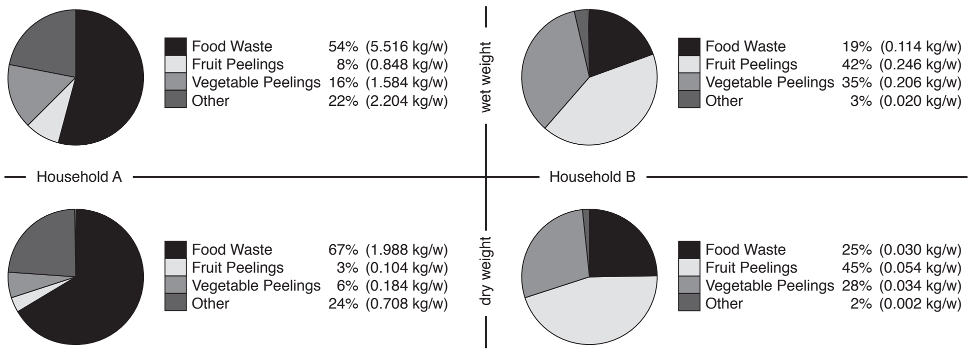

Figure 4.24: Disposal of food-related organic waste. Data was collected during the first stage, 3rd of May until 7th of June 2012. The graph represents both wet weight (top) and dry weight (bottom) for household A (left) and household B (right). Both the percentage and the absolute weight of the respective four fractions are indicated in the graph.

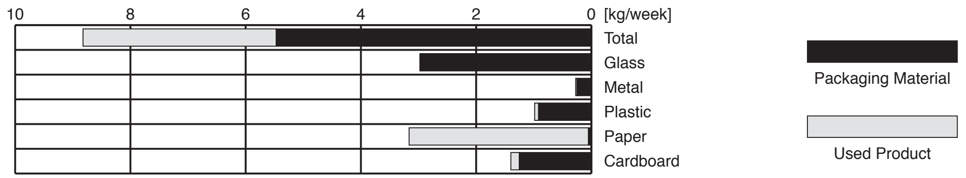

Figure 4.25: Disposal of recyclables at household A. Most recyclables are packaging, except for paper.

Table 4.7: Product flows at households A and B estimated based on manual data collection (stage one). Estimates for food products with a short shelf-life are based on both data sources (columns (6)-(9) highlighted). Estimates for food products with a long shelf-life are based on disposed packaging only (fields (7) and (9) highlighted). For non-food products, weight indications are often lacking altogether (no column highlighted). COICOP class 05.6.1 contains mostly detergents; COICOP class 12.3.1 contains mostly personal care products.

COICOP Class		Household A Number of items (12 weeks)					Mass (kg per week)			
		purchased (total)	purchased (with weight indication)	disposed (total)	disposed (with weight indication)	overlap between data sources	of products based on receipts (extrapolation)	of products based on disposed packaging	overlap between data sources	estimated overall product flows
Code	Description	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
01.1.1	Bread and cereals (ND)	183	66	156	156	6	0.92	6.98	0.59	7.31
01.1.2	Meat (ND)	120	110	119	119	31	2.80	5.55	2.00	6.35
01.1.3	Fish and seafood (ND)	18	10	8	8	1	0.41	0.34	0.03	0.71
01.1.4	Milk, cheese and eggs (ND)	190	28	206	195	8	0.56	16.58	0.42	16.72
01.1.5	Oils and fats (ND)	29	0	19	19	0	0.00	1.05	0.00	1.05
01.1.6	Fruit (ND)	95	40	44	44	13	2.71	3.10	1.41	4.39
01.1.7	Vegetables (ND)	255	173	183	183	44	5.70	7.60	2.21	11.09
01.1.8	Sugar, jam, honey, chocolate and confectionery (ND)	10	0	6	6	0	0.00	0.46	0.00	0.46
01.1.9	Food products n.e.c. (ND)	76	27	68	64	4	0.28	2.13	0.09	2.32
01.2.1	Coffee, tea and cocoa (ND)	11	0	11	11	0	0.00	0.48	0.00	0.48
01.2.2	Mineral waters, soft drinks, fruit and vegetable juices (ND)	76	55	83	83	0	0.22	9.42	0.00	9.42
02.1.1	Spirits (ND)	1	1	1	1	0	0.03	0.08	0.00	0.11
02.1.2	Wine (ND)	34	34	42	42	26	3.25	3.81	2.58	4.48
02.1.3	Beer (ND)	26	26	38	38	26	1.02	1.47	1.02	1.47
03.1.2	Garments (SD)	2	0	0	0	0	0.00	0.00	0.00	0.00
04.5.4	Solid fuels (ND)	3	0	1	1	0	0.00	0.17	0.00	0.17
05.2.0	Household textiles (SD)	2	0	0	0	0	0.00	0.00	0.00	0.00
05.4.0	Glassware, tableware and household utensils (SD)	5	0	3	0	0	0.00	0.00	0.00	0.00
05.6.1	Non-durable household goods (ND)	142	0	29	26	0	0.00	5.39	0.00	5.39
06.1.1	Pharmaceutical products (ND)	1	0	5	0	0	0.00	0.00	0.00	0.00
09.1.3	Information processing equipment (D)	1	0	1	0	0	0.00	0.00	0.00	0.00
09.2.1	Major durables for outdoor recreation (D)	1	0	0	0	0	0.00	0.00	0.00	0.00
09.3.3	Gardens, plants and flowers (ND)	16	0	0	0	0	0.00	0.00	0.00	0.00
09.3.4	Pets and related products (ND)	4	0	4	4	0	0.00	0.77	0.00	0.77
09.5.1	Books (SD)	1	0	0	0	0	0.00	0.00	0.00	0.00
09.5.2	Newspapers and periodicals (ND)	2	0	0	0	0	0.00	0.00	0.00	0.00
09.5.4	Stationery and drawing materials (ND)	2	0	0	0	0	0.00	0.00	0.00	0.00
12.1.3	Other appliances, articles and products for personal care (ND)	28	0	45	45	0	0.00	1.08	0.00	1.08
	TOTAL	1334	570	1072	1045	159	17.89	66.47	10.35	74.01

COICOP Class		Household B Number of Items (12 weeks)					Mass (kg per week)			
		purchased (total)	purchased (with weight indication)	disposed (total)	disposed (with weight indication)	overlap between data sources	of products based on receipts (extrapolation)	of products based on disposed packaging	overlap between data sources	estimated overal product flows
Code	Description	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
01.1.1	Bread and cereals (ND)	52	22	18	18	0	0.01	0.52	0.00	0.53
01.1.2	Meat (ND)	23	12	16	16	4	0.17	0.29	0.13	0.33
01.1.3	Fish and seafood (ND)	3	1	0	0	0	0.02	0.00	0.00	0.02
01.1.4	Milk, cheese and eggs (ND)	31	14	20	20	2	0.50	0.56	0.17	0.89
01.1.5	Oils and fats (ND)	2	0	5	5	0	0.00	0.15	0.00	0.15
01.1.6	Fruit (ND)	51	26	10	10	0	0.67	0.45	0.00	1.12
01.1.7	Vegetables (ND)	62	44	36	33	5	1.13	1.12	0.15	2.10
01.1.8	Sugar, jam, honey, chocolate and confectionery (ND)	9	0	8	8	0	0.00	0.13	0.00	0.13
01.1.9	Food products n.e.c. (ND)	9	0	8	8	0	0.00	0.04	0.00	0.04
01.2.1	Coffee, tea and cocoa (ND)	3	3	1	1	0	0.02	0.01	0.00	0.03
01.2.2	Mineral waters, soft drinks, fruit and vegetable juices (ND)	23	0	16	16	0	0.00	0.56	0.00	0.56
02.1.2	Wine (ND)	0	0	3	3	0	0.00	0.09	0.00	0.09
03.1.2	Garments (SD)	0	0	5	0	0	0.00	0.00	0.00	0.00
05.2.0	Household textiles (SD)	1	0	8	0	0	0.00	0.00	0.00	0.00
05.4.0	Glassware, tableware and household utensils (SD)	0	0	4	0	0	0.00	0.00	0.00	0.00
05.6.1	Non-durable household goods (ND)	21	1	7	1	0	0.08	0.08	0.00	0.08
06.1.1	Pharmaceutical products (ND)	0	0	16	0	0	0.00	0.00	0.00	0.00
09.1.3	Information processing equipment (D)	0	0	7	0	0	0.00	0.00	0.00	0.00
09.3.3	Gardens, plants and flowers (ND)	15	0	0	0	0	0.00	0.00	0.00	0.00
09.5.4	Stationery and drawing materials (ND)	3	0	4	0	0	0.00	0.00	0.00	0.00
12.1.3	Other appliances, articles and products for personal care (ND)	7	2	4	3	2	0.01	0.05	0.01	0.05
12.3.2	Other personal effects (SD)	1	0	0	0	0	0.00	0.00	0.00	0.00
	TOTAL	316	125	196	142	13	2.61	4.05	0.46	6.11

Using the FoodWatch application (stage three), food consumption and waste can be quantified as exemplified in Figure 4.26. Note the distinction between food consumption and food waste.

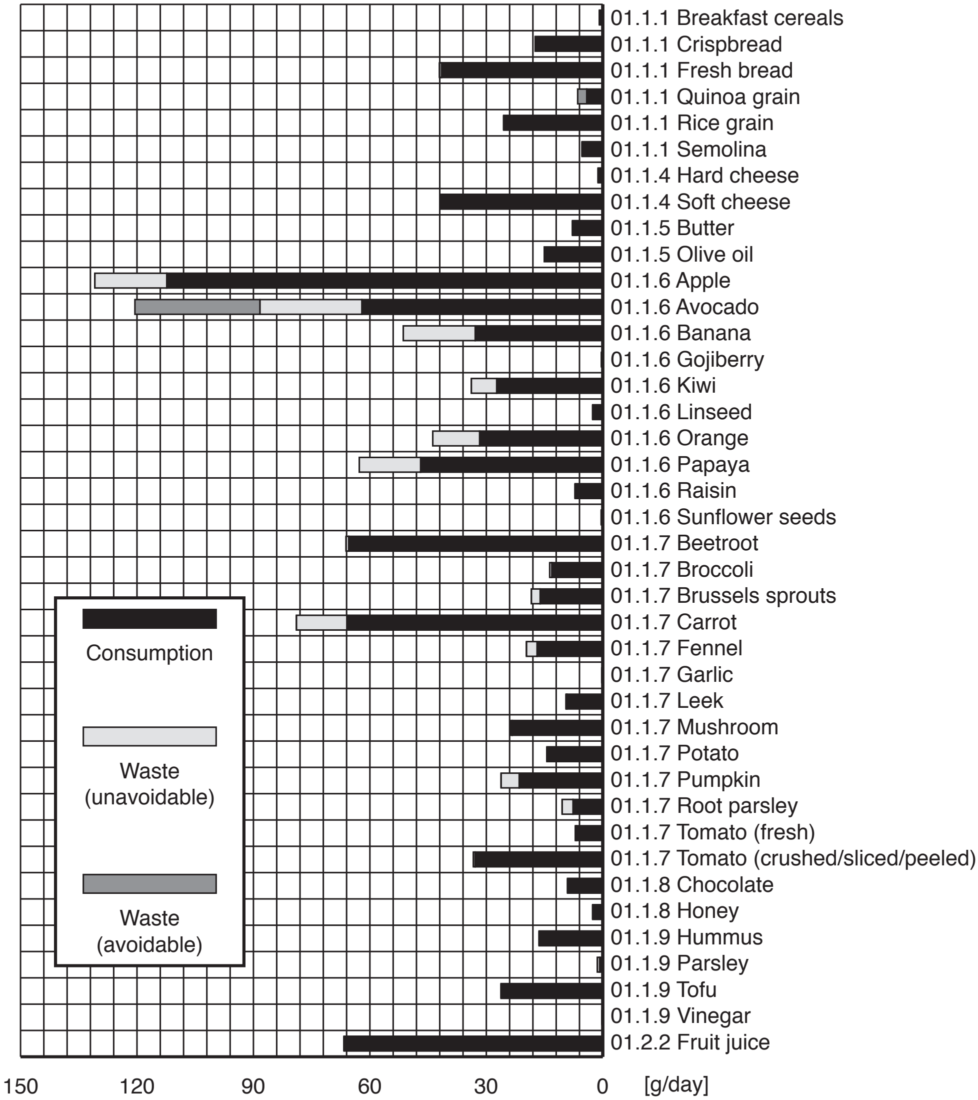

Figure 4.26: Food consumption and waste at household B. Data collected during the third stage, 1st of January until 16th of January 2013. Unavoidable refers to food products that are not normally eaten (e.g., peelings). Avoidable refers to food products that would normally be eaten, but can no longer be eaten because they are spoilt. Note that peelings of spoilt food are included in this latter category as well.

4.5 Evaluation of the Pilot Study

The scope of the pilot study was a detailed investigation of two households in order to: (1) facilitate first experiences with data collection, (2) allow for a division of the data collected into essential and optional data, and (3) point to potential shortcomings and pitfalls. The pilot study showed that comprehensive measurements of the metabolism of individual households at the level of detail envisaged in this study is challenging. Throughout the pilot study, consumption of water, electricity and consumer goods as well as the disposal of recyclables and food-related organic waste was accomplished. Resource use for mobility as well as heat use was not covered by the pilot study. Sensor deployment and data collection required so much effort that data processing and analysis did not go beyond merely indicating what could potentially be done with the data collected.

In this study, households were defined as physical entities with the physical household as system boundary. This physical household is comprised of all humans, domestic animals and artifacts belonging to this specific household in the sense of a socio-economic entity. In other words, ownership of stuff determines whether flows are included or excluded in the study. Hence water and electricity used by the washing machines owned by household A are included, whilst water and electricity used by the washing machines in the shared laundry room used by household B are not included. Similarly, fuel for cars owned by household A would be included in the study, whereas fuel for pool or rental cars driven by members of household B would not. In both cases, use of artifacts not owned by the household is considered a service and thus outside the scope of data collection as defined in this study. This clearly is problematic and introduces considerable bias when comparing households.

In summary, before embarking on a larger scale study, it is of paramount importance to have very clear goals and research questions so that the right combination of data collection approaches and the right level of detail is chosen given the research context. In this regard it is uncertain whether supermarkets would be willing to collaborate in collecting data on goods purchases. Finally, questions remain regarding personal integrity and households' willingness to participate in a study that scrutinises consumption and waste generation and hence lifestyles so comprehensively. This final aspect needs to be carefully considered when collecting this type of data for a larger number of households.

Chapter 5

Discussion and Reflections

Household metabolism is both a concept and a tool. This thesis started by considering the concept of household metabolism as a subset of socio-economic metabolism (chapter 2), and then continued to outline research fields that contribute to, or benefit from the quantification of household metabolism as a tool (chapter 3). Subsequently, the implementation and findings of a household metabolism case study were presented (chapter 4).

Quantification of household metabolism can be an element of socio-metabolic studies with any of the four research scopes indicated in Table 2.2 (i.e., exploratory, explanatory, indicative, and persuasive). For example, disaggregated data on household metabolism can provide the input data necessary to take into account consumption choices in a process-based calculation of life-cycle impacts of household consumption; as pointed out by Hertwich (2005), life-cycle calculations based on economic input-output tables do not properly take into account such differences. On the other hand, disaggregated data on household metabolism is highly relevant for user-centred research and living labs in particular, where the type of data collected in this study is required to assess the impact of innovations and interventions in the domestic environment on household metabolism or selected aspects thereof.

Household metabolism studies can be conceived at different levels of detail. The most aggregated level is the sum of private households in a given city, region, or country. The most disaggregated level are the individuals, activities, practices, or appliances that cause physical flows in individual households. In between lie the total flows for individual households, irrespective of end-use.

The scope of this chapter is twofold. First, to discuss which level of detail appears sensible and feasible given a number of selected research questions and research contexts. Second, to consider several notions of sustainability and sustainable and to discuss whether household metabolism research is compatible with these notions. For this second part, it is assumed that disaggregated data on household metabolism are readily available for a large number of households at any desired level of detail.

5.1 Breadth versus Depth

Four factors influence the efforts needed for the quantification of household metabolism: the number of households, the number of flows, the level of detail, and the length of the period of data collection. The household metabolism study as initially envisaged in this thesis attempted to simultaneously collect disaggregated data on water use, electricity use, heat use, mobility, goods consumption and waste generation for several tens of individual households for a period of several weeks. Hence all four factors determining the efforts required were at the upper end of the scale. In contrast, other studies limited at least one or two of the factors: Kotakorpi *et al.* (2008) considered flows of several resources for 27 households, but only for two weeks and only overall flows irrespective of end-use; Larson *et al.* (2012) considered flows of water only, but for single events and fixtures rather than the household as a whole; and Sundramoorthy *et al.* (2011) limited the quantification to household electricity use but studied 250 households.

Looking back at the challenges experienced throughout the pilot study, and the fact that not all flows initially envisaged were covered, the approach chosen in the pilot study is not viable for a larger number of households. However, if a new facility, such as a living lab, is built, the respective sensors could be put in place right from the beginning. Furthermore, recently developed single-point sensors are a promising way to enable sensing data disaggregated consumption data for water, electricity and gas on the fixture/appliance level with only one sensor that can be easily installed. However, such sensors are not as yet commercial. Finally, changes in legislation on data disclosure (Thaler and Tucker, 2013) could imply a significant boost for data availability on household consumption.

5.2 Household Metabolism and Sustainable Development

Quantifying household metabolism often implicitly or explicitly aims at fostering sustainable development through a reduction of resource use and waste generation. Since the emergence of the concept of sustainable development in the 1980s (United Nations, 1987), the terms sustainability and sustainable development have become commonplace in science, politics, and economy (Kates *et al.*, 2005). Given the lack of general consensus over the societal goals that would count as sustainable development and the inevitable conceptual ambiguity and issue about the true meaning of the term sustainable development (Connelly, 2007), an immediate question is whether household metabolism research implies a specific notion of sustainable development. This issue emerges, amongst others, in the different values and assumptions underlying the principles of weak and strong sustainability, and the two strands of environmental thought identified by Dobson (2000, p.2):

> "*environmentalism* argues for a managerial approach to environmental problems, secure in the belief that they can be solved without fundamental changes in present values or patterns of production and consumption, and, *ecologism* holds that a sustainable and fulfilling existence presupposes radical changes in our relationship with the non-human natural world, and in our mode of social and political life".

Karlsson (2007) argues that these two strands span a whole spectrum of different ontological assumptions, risk assessments, and preferred remedial strategies.

The mainstream discourse on sustainability and sustainable development has, until recently, been characterised by a strong emphasis on economic development in the form of economic growth. The idea of perpetual growth is indeed deeply rooted in present day industrialised societies and economic growth is an axiomatic necessity (Atkinson, 2007; Kallis *et al.*, 2012; Trainer, 2012). Whilst proponents of growth-based sustainable development acknowledge that there are limits to the earth's carrying capacity, there is a strong belief that technology can actually solve all present and upcoming problems, and that economic growth can be decoupled from resource use and waste generation. This strategy is often advocated with terms such as eco-efficiency, better resource management, doing more with less, sustainable economic growth, or green growth. The bottom-line reasoning is that sustainability should not require a sacrifice, but should make life more agreeable and affordable. Household metabolism can fit neatly within this notion of sustainable development if the quantification of flows aims at a more efficient resource use.

Whether the present trajectory of economic growth is sustainable is increasingly being questioned (Duraiappah and Muñoz, 2012). Critics of growth-based sustainable development argue that efficiency and technology are not enough to solve present and upcoming challenges (Huesemann and Huesemann, 2008). Verbruggen (1998) suggested that the conflict between economic growth and environmental improvement can only be overcome if the environment becomes a genuine and adequately priced economic good, which implies that property and use rights should be defined and allocated for all the components of environmental capital. Comprehensive resource management, though compelling in theory, requires full control of all material flows and related environmental impacts across the globe. It is questionable whether comprehensive tracking and allocation of resources is desirable and can be implemented in practice. However, quantification of household metabolism would have a crucial role in such a scenario of comprehensive resource management, as it would enable a comprehensive tracking of flows and impacts back to individual households.

In recent debates on alternatives to economic growth, the concepts of degrowth (Fournier, 2008; Kallis *et al.*, 2012; van den Bergh, 2011) and steady-state economy (Jackson, 2009) have appeared. In a recent criticism of degrowth, van den Bergh (2011) puts forward the idea of a-growth, suggesting agnosticism and indifference about economic growth, based on the perception that GDP is irrelevant and that degrowth should be a consequence of particular societal choices, rather than a goal in itself. Cooper (2005) put forward one such choice, sufficiency, as one of the additional necessary ingredients besides efficiency. Once again, quantification of household metabolism could be a valuable tool to assess to which extent specific individual households contribute to degrowth by increased sufficiency.

So far, the applications of household metabolism have mostly related to resource management and resource tracking. Brynjarsdóttir *et al.* (2012) highlights that eco-feedback and other persuasive technology, rather than tackling the complex problem of sustainability as a whole, reduces sustainability to a limited set of individual consumer behaviours which have a fairly clear and direct impact on sustainability understood as a form of resource management. As a result, these applications are susceptible to be undermined by factors outside of what aims to be measured (Brynjarsdóttir *et al.*, 2012) and outside of what can realistically be measured. Furthermore, Brynjarsdóttir *et al.* (2012) point out that focusing on simple metrics may sidestep more difficult lifestyle choices that may be required to make society more sustainable. Similarly, Strengers (2011b) argues that focusing on simple metrics overlooks the practices householders engage in and take for granted, and that efficiency gains can easily become offset by the adoption of new resource-consuming expectations and desires. To overcome these limitations, Strengers (2011b) and Brynjarsdóttir *et al.* (2012) advocate a shift towards a focus on everyday life and everyday practices, consisting of three central aspects: promoting reflection on what it actually means to be sustainable, negotiating needs and consumption limits, and promoting new practices which challenge taken-for-granted notions of normality. A recent trend in user-centered research are living labs that enable experimentation and co-creation with users in real-life environments (Sundramoorthy *et al.*, 2011). In this last context, quantification of household metabolism could be a valuable tool to assess to which extent specific changes in everyday practices contribute to reduced resource use and waste generation.

The most significant insight from the reflections on sustainability and sustainable development is that sustainability and sustainable development are not absolute terms or concepts, but their interpretation crucially depends on a number of subjective assumptions, values, and interests. Indeed, Benessia *et al.* (2012) state that the assumption that traditional scientific and technological practices are value-free knowledge production is increasingly challenged. Nevertheless, household metabolism can be a useful tool regardless of the assumptions, values, and interests underlying research questions and notions of sustainability.

Chapter 6

Conclusions and Outlook

The case study presented in this thesis suggests that the initial scope was ambitious at the time the study was conceived and performed. In hindsight, it appears as if the basic idea was fine, just that the implementation was some years too early, so that too many elements were lacking. Scaling up the comprehensive quantification of household metabolism on the level of specific appliances or fixtures to a large number of households does not appear viable until easy to install single-point sensors for the collection of disaggregated data become available, and consumption data can be more readily obtained from retailers. These elements are expected to increasingly become available over the coming years.

Although the quantification of household metabolism as such does not solve the problem of overconsumption, it has a clear potential to make a useful contribution on the journey towards sustainability. However, the specific notion of sustainability and sustainable development it fosters is innately connected with the specific context of application. Depending on the underlying notion of sustainability, the quantification of household metabolism can be a tool to monitor the success of drastic changes in behaviour, or a tool to monitor resource management or make resource management more efficient in a system that remains otherwise largely unchanged.

Based on the work on household metabolism presented in this thesis, two meaningful possible directions for future research emerge. First, household metabolism as a sensing exercise could be embedded in living lab facilities in order to assess the impacts innovations have on resource consumption, waste generation, and environmental impacts. Second, the concept of household metabolism could be combined with the living lab methodology: this would mean that researchers and household members co-develop a way to track resource consumption, waste generation, and environmental impacts of individual households. This could include seeking cooperation with supermarkets and retailers to make available consumption data to households.

If household metabolism is to be embedded in a living lab facility, the innovation to be developed or tested essentially determines what needs to be quantified and at which level of detail. The exact extent of quantifying household metabolism hence depends on the research scope of the respective innovation project.

If household metabolism is combined with the living lab methodology, the FoodWatch application could be a valuable starting point. We are currently extending the FoodWatch application in order to include environmental, water, and carbon footprints of food products. Instead of a mobile application, FoodWatch could also be integrated in the personal pages on a retailer webpage. Before continuing research in this direction, it appears advisable to verify whether consumers are interested in such a tool, and whether there are any retailers or grocery stores willing to collaborate in a proof of concept study eventually leading to a showcase that can attract further retailers to participate. Furthermore, it would be sensible to check whether there are already similar applications or databases available that could be utilised.

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