About the Author

Ilse Martine Voskamp was born on January 24th 1990 in Haarlem, The Netherlands. After finishing her Bachelor in Landscape Architecture at Wageningen University, she continued at the same university with a Master in Urban Environmental Management - specializing in Urban Systems Engineering. Driven to gain a better understanding of urban ecosystems and urbanization, she studied cities from a social-ecological-systems perspective at the Stockholm Resilience Centre and Human Geography department at Stockholm University. In 2014, she finished her Masters thesis on a decision support tool for urban planners and designers to retrofit nature-based solutions for urban climate adaptation to extreme weather events (Deltares), and graduated *cum laude*.

Ilse started her academic career at the Landscape Architecture Group at Wageningen University, as a researcher in the Urban Pulse Project - one of the kick-off projects for the Amsterdam Institute for Advanced Metropolitan Solutions (AMS). This was the starting point for her PhD research under the supervision of both Environmental Technology and the Landscape Architecture Group. During her PhD, Ilse combined her research with various educational activities, contributing to the *Master Classes by Adriaan Geuze*, the *Master Studio Landscape Architecture Regional Design: a Systems Approach*, and the course *Planning and Design of Urban Space*. She was also a content coordinator for the Massive Open Online Course *Co-creating Sustainable Cities*, a collaboration between Wageningen and TU Delft for the AMS Institute. Ilse currently works as a researcher at Wageningen Environmental Research. Her research focuses on the implementation of nature-based solutions for urban resilience and on integrated, landscape-based strategies for circularity and climate adaptation on a regional scale.

Ilse is passionate about research that builds bridges between ecological, technological and spatial disciplines on the interface of science and practice.

Resource-conscious urban planning and design

Exploring the potential of urban metabolism assessments

Ilse Martine Voskamp

Propositions

1. Urban metabolism assessments must account for heterogeneity in the urban landscape for use in urban planning and design.
(this thesis)
2. Urban metabolism research requires a social-ecological-technological systems perspective.
(this thesis)
3. Outstanding science necessitates taking distance and detachment.
4. A successful gardener possesses the skills of an excellent researcher.
5. Experiencing a devastated landscape provides more insight in the impacts of our unsustainable consumption patterns than knowing these impacts through facts and figures.
6. Struggles are like sweets: you prefer to keep them for yourself but sharing brings more fulfilment.
7. Science and football have in common that accuracy and speed are negatively correlated.

Propositions belonging to the thesis, entitled

Resource-conscious urban planning and design

Exploring the potential of urban metabolism assessments

Ilse Martine Voskamp

Wageningen, 11 December 2020

Resource-conscious urban planning and design

**Exploring the potential of
urban metabolism assessments**

Ilse Martine Voskamp

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Resource-conscious urban planning and design

Exploring the potential of urban metabolism assessments

Ilse Martine Voskamp

Thesis

submitted in fulfilment of the requirements for the degree of doctor

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Prof. dr A.P.J. Mol,

in the presence of the

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Summary

In view of urbanization, climate change, resource depletion and the impacts associated with resource consumption, it is imperative that cities foster *sustainable resource management*. Given that urban form and function impact urban resource flows and stocks, *urban planners and designers* have an important contribution to make. Moreover, the integrative and strategic problem-solving capacity of design is essential to create plans and develop strategies for the urban environment that guide and effectuate the sustainable management of resources. That said, it is essential to understand how urban areas function with respect to resource flows to make *evidence-based* decisions when formulating such plans and strategic visions. Assessments of the *urban metabolism (UM)* are considered valuable for providing such scientific evidence for planning and design of the urban environment. UM refers to the resource stocks and flows through cities and the affiliated processes that transform raw materials, energy, and water inputs into the built environment, human biomass, and waste. Conventional *UM assessments*, such as a *material flow analysis (MFA)*, consist of a quantification of resource flows to disclose how a particular city functions at a specific moment in time.

Scholars acknowledge the potential of UM assessments generally, and of MFA specifically, to inform *resource-conscious urban planning and design*, but they also point to the shortcomings that hinder the full exploitation of this potential. A significant shortcoming of MFA is its 'black box' approach: it does not give insight in metabolic differences within a city nor in the city's characteristics that shape the city and its UM, such as the type of businesses present, urban form and citizen characteristics. Therefore this research: (I) studies how comprehensiveness and resolution of analysis affect the potential of UM assessments in providing insightful understanding of UM, and (II) investigates the factors and mechanisms that underlie resource flows and stocks, to advance understanding of the systemic characteristics of cities and their metabolism. Energy and water were chosen as main resources of interest.

Given the aim of this thesis to contribute to the evidence base for resource-conscious urban planning and design with methodological advancements and system knowledge, this research can be considered '*research for design*'. This research is of mixed-methods and *transdisciplinary* nature, integrating methods and knowledge from different academic disciplines with knowledge from actors that are active in urban planning and design, and resource management. Stakeholder

input is acquired in a case study of Amsterdam, which is central to this research. Other case-specific parts of this research consist of analyses of empirical data, including a MFA at the municipal level and analyses using more detailed spatial units such as neighbourhoods. Literature with a wide range of research designs is used throughout this research to engage with fields of knowledge from several relevant disciplines such as industrial ecology, urban ecology and environmental history.

After the introduction in **chapter 1**, **chapter 2** firstly explores how comprehensiveness of analysis affects the usefulness of UM assessments. The hypothesis underlying this chapter is that MFA does not account for all relevant resource flows and thus falls short in providing a full understanding of a city's metabolism, which is essential to inform the transition toward a more sustainable metabolism. The metabolism of Amsterdam was quantified employing the established Eurostat MFA method and a modified version of this method, which can be considered a comprehensive 'grey box' MFA. A comparison of the results from both assessments shows that the proposed methodological advancements provide a more complete and detailed understanding into Amsterdam's metabolism. The comprehensive assessment discloses key flows and internal processes that support Amsterdam's functioning and those that only flow through the city, i.e. port-related trade flows. The comprehensive assessment also facilitated evaluation of changes of Amsterdam's UM in time and benchmarking the results, to identify city characteristics that cause metabolic differences between cities. To inform sustainable urban resource management, it is thus beneficial to assess UM in more comprehensively than a conventional MFA does.

Chapter 3 investigates at which spatial and temporal resolution UM should be assessed to generate results that can inform the implementation of resource-conscious urban planning and design interventions. To question stakeholders on this matter, the so-called SIRUP tool was developed and applied in interviews and workshops. Stakeholder input on how detailed water and energy flow variability needs to be understood was compared to the resolution of available data and to the resolution of current MFA studies. Results show that most urban planning and design interventions envisioned in Amsterdam require information on a higher spatiotemporal resolution than the resolution that is common for MFA, i.e., more detailed than the city level and at time steps smaller than a year. For the majority of these interventions, data is needed on a higher resolution than available. This chapter shows that there is not one particular resolution of analysis at which UM assessments should be performed to generate meaningful results for resource-conscious urban planning and design. Rather, the appropriate scale of UM assessment depends on the intervention envisioned and the resource flow of interest.

Chapter 4 begins with the notion that if UM assessments aim to inform the design of policies and plans that effectuate sustainable resource management, they should not only reveal what the UM looks like, but also why it looks that way if it. Hence, UM literature was systematically reviewed to synthesize the scientific understanding on factors and mechanisms underlying spatiotemporal variability in UM generally and energy and water consumption specifically. The results show that a broad range of factors can influence energy and water consumption, comprising small-scale infrastructural system components, such as sanitary fittings, to large scale societal changes, such as changes in economic development. These factors of influence are categorized as (I) drivers, changes in societal context that shape consumption patterns; (II) needs of individuals and communities, and (III) facilitators/constraints, consumer, resource and urban landscape characteristics that affect resource consumption by facilitating or constraining specific activities. This chapter also describes six different types of relationships between factors of influence that can potentially influence the direction and magnitude of effects and thereby contribute to case specific variability in consumption patterns.

Chapter 5 continues with a high-resolution, multi-level case study of Amsterdam to acquire understanding of the relative importance of the factors underlying spatial variability in water and energy consumption and their scale- and city-dependent behaviour. Multiple linear regression analysis was used to examine the explanatory power of sixteen factors for spatial variation in residential electricity, gas and water consumption. Four regression models per resource were used based on distinct spatial units aggregating high-resolution data at four levels: neighbourhoods, districts, 1ha and 2.5 ha square units. Overall, twelve factors with significant explanatory value were identified, and consumption of each resource was correlated with nine or ten out of these twelve factors. Results show that different facilitators and constraints are interlinked and jointly influence consumption. Explanatory variables for resource consumption showed to be sensitive to size and shape of spatial units used. These findings not only imply that some factors might be more relevant to consider than others at a specific scale, but also that these effects are not apparent when taking a one-scale perspective.

Finally, **chapter 6** discusses the potential of UM assessments for resource-conscious urban planning and design, and the contributions of this thesis to the *UM field* of research. The value of this thesis for the various stakeholders involved in urban planning and design is discussed, including its usefulness for formulating strategic visions for urban development, planning infrastructural networks, and commissioning and designing neighbourhood (re)development plans. The novelty

of the methodological approach is highlighted and it is recommended that future research uses a '*research through designing*' approach to explore how UM assessments can be integrated in the design process. This chapter discusses how this thesis contributes to methodological alignment in UM assessments and argues that in future research methodological attention should shift towards spatially explicit UM assessments that focus on optimization potentials. An overview is given of the contributions of this thesis with regards to advanced understanding of the systemic characteristics of cities. It is concluded that an interdisciplinary, place-based and multi-scale perspective in UM research is essential to advance our understanding of (case-specific) consumption patterns and the factors and their interconnections in time and space of which these patterns are an expression. It is argued that a '*landscape – SETS*' approach enables taking such a perspective in future research.

Samenvatting

Met het oog op verstedelijking, klimaatverandering, en de uitputting van grondstoffen, is het essentieel dat steden *resources* (hulpbronnen) op een meer duurzame wijze gaan beheren. Planologen, stedenbouwkundigen, landschapsarchitecten en andere ontwerpdisciplines spelen hierin een belangrijke rol, omdat de vorm en functie van de stad van invloed zijn op resource-stromen en -voorraden. Bovendien is ontwerpen integraal en probleemoplossend van aard. De integrale en probleemoplossende eigenschappen van ontwerpen zijn essentieel om vorm te geven aan plannen en strategieën voor het duurzame beheer van resources. Voor het maken van deze plannen en strategieën is wetenschappelijke kennis van stedelijke resource-stromen onmisbaar. Inzicht in stedelijke resource-stromen kan worden verkregen door middel van analyses van het stedelijk metabolisme. De term 'stedelijk metabolisme' (*Urban Metabolism*) verwijst naar de resource voorraden en -stromen door steden en de gerelateerde processen die de instroom aan ruwe grondstoffen, energie en water omzetten in o.a. bebouwing, menselijke biomassa, en afval. Gebruikelijke analyses van het stedelijk metabolisme, zoals stofstroomanalyses (*Material Flow Analysis, MFA*), kwantificeren resource stromen om inzichtelijk te maken hoe een bepaalde stad functioneert op een specifiek moment in de geschiedenis.

Wetenschappers erkennen het potentieel van stofstroomanalyses voor stedelijke planologie en ontwerp. Ze wijzen echter ook op de tekortkomingen van deze analyses, die de benutting van dit potentieel in de weg staan. Een belangrijke tekortkoming van MFA is de zogenaamde '*black box*' benadering: een MFA geeft geen inzicht in de aanwezige variatie in het stedelijk metabolisme en ook niet in de stedelijke karakteristieken die dit metabolisme beïnvloeden – zoals de stedelijke vorm, het type bedrijvigheid dat aanwezig is, en de bevolkingssamenstelling. Daarom is het doel van dit onderzoek: (I) Bepalen hoe de mate van volledigheid (dekking) en resolutie van analyse van stedelijk stofstroomanalyses van invloed zijn op het potentieel van deze analyses om inzicht te verschaffen in het stedelijk metabolisme, en (II) Het in kaart brengen van de factoren en mechanismen die resource voorraden en -stromen beïnvloeden, om zo beter te begrijpen hoe het stedelijk systeem en haar metabolisme samenhangen.

De resources energie en water staan centraal in dit onderzoek.

Dit onderzoek ondersteunt het ontwerp of ontwerpproces en kan als zodanig beschouwd worden als *'research for design'*. Het doel van dit proefschrift is namelijk om met methodische ontwikkeling en systeemkennis bij te dragen aan de kennisbasis voor stedelijke planologie en ontwerp dat bewust rekenschap geeft van resources. Dit onderzoek is multi-methodisch en transdisciplinair: er wordt gebruik gemaakt van onderzoeksmethoden en kennis vanuit verschillende wetenschappelijke disciplines, maar ook van de kennis van partijen die werkzaam zijn in de planologie, het stedelijk ontwerp en resource beheer. Het empirische deel van het onderzoek heeft zich gericht op Amsterdam. Naast het verkrijgen van de input van stakeholders zijn er verschillende soorten data geanalyseerd voor een stofstroomanalyse op gemeentelijk niveau en analyses op een gedetailleerder niveau, waaronder buurt- en wijkniveau. Binnen het onderzoek is de verbinding gelegd met de kennisbasis van diverse relevante disciplines zoals *industrial ecology*, *urban ecology* en *environmental history* door gebruik te maken van de literatuur uit deze disciplines.

Na de introductie in **hoofdstuk 1**, wordt in **hoofdstuk 2** onderzocht hoe de dekking van een stofstroomanalyse van invloed is op de bruikbaarheid van een dergelijke analyse. De onderliggende hypothese van dit hoofdstuk is dat MFA niet alle relevante resource stromen meeneemt, waardoor het geen compleet inzicht in het metabolisme van een stad – hetgeen essentieel is om de stad duurzamer in te richten. In deze studie is het metabolisme van Amsterdam gekwantificeerd met zowel de algemeen erkende Eurostat methode voor MFA als met een aangepaste versie van deze methode, welke beschouwd kan worden als een meer volledige en nauwkeurige, *'grey box'* MFA. Een vergelijking van de resultaten van beide analyses laat zien dat er dankzij de methodologische verbetering een completer en gedetailleerder inzicht wordt verkregen in het metabolisme van Amsterdam. De volledige analyse geeft inzicht in belangrijke stromen en interne processen die het functioneren van Amsterdam ondersteunen. Ook worden de resources die enkel door de stad heen stromen zichtbaar, de zogenoemde haven-gerelateerde handelsstromen. De volledige analyse maakte het ook mogelijk om de verandering van het Amsterdamse metabolisme in de tijd goed te beoordelen en de MFA te vergelijken met de resultaten van andere steden. Zo zijn stedelijke karakteristieken te identificeren die de verschillen tussen de steden met betrekking tot hun metabolisme veroorzaken. Voor de bruikbaarheid voor duurzaam stedelijk resource beheer is het dus waardevol om het stedelijke metabolisme vollediger te analyseren dan het geval is met een conventionele MFA.

Hoofdstuk 3 onderzoekt welke ruimtelijke en temporele resolutie nodig is voor het analyseren van het stedelijke metabolisme om tot resultaten te komen die gebruikt kunnen worden als input voor stedelijke planologie- en ontwerpingrepen die bewust rekenschap geven van resources. Om

stakeholders op dit onderwerp te bevragen, is de zogenoemde *SIRUP tool* ontwikkeld en toegepast in interviews en workshops. Stakeholders gaven aan hoe gedetailleerd de informatie over de dynamiek van water en energiestromen voor hen zou moeten zijn om ontwerpingrepen te informeren. Dit is vergeleken met de resolutie van beschikbare data en huidige MFA studies. Resultaten laten zien dat voor de meeste ontwerpingrepen die stakeholders zouden willen toepassen in Amsterdam, informatie van een hoger detailniveau nodig is dan de tijd-ruimte resolutie die gebruikelijk is voor MFA (hetgeen inhoudt: gedetailleerder dan op stadsniveau en op jaarbasis). Voor het merendeel van de interventies is bovendien data nodig van een hogere resolutie dan dat er beschikbaar is. Verder laat deze studie zien dat er niet één specifiek schaalniveau is waarop het stedelijke metabolisme zou moeten worden geanalyseerd om resultaten te genereren die gebruikt kunnen worden als input voor stedelijke planologie en ontwerp. Het schaalniveau van de analyse hangt af van de beoogde ontwerpingreep en de betreffende resource. Dit onderschrijft het belang van een systeemgerichte benadering in metabolisme analyses als kennisbasis voor ontwerp.

Het vertrekpunt van **hoofdstuk 4** is dat wanneer analyses van het stedelijk metabolisme als doel hebben beleid en plannen die uitvoering geven aan duurzaam resource beheer te informeren, deze analyses niet alleen inzichtelijk moeten maken hoe het metabolisme er uit ziet, maar ook waarom het er op die manier uit ziet. Voor een duurzaam beheer van resources is het namelijk van belang om te weten welke factoren en processen een rol spelen in de resource stromen van een stad. Om deze vraag te kunnen beantwoorden is de literatuur over Urban Metabolism systematisch geanalyseerd. Deze analyse heeft geleid tot een synthese van de wetenschappelijk kennis van de factoren en mechanismen die ten grondslag liggen aan tijd-ruimte variatie in het stedelijke metabolisme in zijn algemeenheid en in water en energieverbruik in het bijzonder. De resultaten laten zien dat een grote diversiteit aan factoren van invloed kunnen zijn op energie en waterverbruik, waaronder kleinschalige infrastructurele elementen (zoals sanitair), tot aan grootschalige maatschappelijke veranderingen (zoals veranderingen in de mate van economische ontwikkeling). De factoren van invloed zijn gecategoriseerd als (I) drijvende krachten (*drivers*), veranderingen in de maatschappelijke context die verbruikspatronen beïnvloeden, (II) de behoeften (*needs*) van individuen en gemeenschappen, en (III) faciliterende/beperkende factoren (*facilitators/constraints*), te weten karakteristieken van consumenten, resources en het stedelijke landschap die bepaalde activiteiten faciliteren of beperken. Daarnaast zijn er zes verschillende soorten relaties geïdentificeerd tussen de factoren die potentieel de richting en grootte van effecten beïnvloeden, en zo bijdragen aan casus-specifieke variatie in verbruikspatronen. Zodoende biedt dit hoofdstuk een overzicht van de factoren en mechanismen die het *urban metabolism* bepalen, wat een kader kan bieden om de resultaten van toekomstig empirisch onderzoek te interpreteren en te vergelijken.

Hoofdstuk 5 bouwt door op de resultaten van hoofdstuk 4, door de gevonden factoren te toetsen in een hoge resolutie casestudy van Amsterdam, op meerdere schaalniveaus. Hiermee wordt inzicht verkregen in het relatieve belang van de factoren die ten grondslag liggen aan ruimtelijke variatie in stedelijk water- en energiegebruik en in het schaal- en stads-specifieke gedrag van deze factoren. Meervoudige lineaire regressie analyse is gebruikt om zestien factoren te toetsen op hun verklarend vermogen voor huishoudelijk elektriciteits-, gas- en waterverbruik. Per resource zijn vier regressiemodellen gebruikt, die elk gebruik maken van een andere ruimtelijke aggregatie-eenheid voor hoge resolutie data: buurten, wijken, 1 hectare en 2,5 hectare eenheden. In totaal zijn er twaalf factoren met een significant verklarende waarde geïdentificeerd, en het verbruik van iedere resource bleek gecorreleerd met negen of tien van deze twaalf factoren. De resultaten laten zien dat verschillende *faciliterende* en *beperkende* factoren met elkaar verbonden zijn en gezamenlijk verbruik beïnvloeden. Verklarende variabelen voor resource verbruik bleken afhankelijk te zijn van de grootte en vorm van de gebruikte ruimtelijke eenheden. Deze bevindingen houden in dat niet alleen op een specifiek schaalniveau sommige factoren relevanter zijn om mee te nemen dan anderen, maar ook dat deze schaal-afhankelijkheid niet zichtbaar zou zijn wanneer er slechts één schaalniveau in ogenschouw wordt genomen.

Tot slot bediscussieert **hoofdstuk 6** het potentieel van analyses van het stedelijk metabolisme voor stedelijke planologie en ontwerp, en het behandelt de bijdrage van dit proefschrift aan het *urban metabolism* onderzoeksveld. De waarde van dit proefschrift voor de diverse stakeholders die een aandeel hebben in stedelijke planologie en ontwerp wordt bediscussieerd, waaronder de bruikbaarheid van de resultaten voor het formuleren van strategische visies voor stedelijke ontwikkeling, het plannen van infrastructurele netwerken en het ontwerpen van stedelijke (her) ontwikkelingsplannen. Het vernieuwende van de methodologische benadering wordt onder het voetlicht gebracht en er worden aanbevelingen gedaan om in toekomstig onderzoek te bestuderen hoe analyses van het stedelijke metabolisme kunnen worden geïntegreerd in het ontwerpproces met ‘ontwerpend onderzoek’. Ook wordt in dit hoofdstuk besproken hoe dit proefschrift bijdraagt aan methodologische afstemming in stofstroomanalyses en wordt beargumenteerd dat in toekomstig onderzoek een andere methodologische insteek nodig is: ruimtelijk expliciete analyses die de mogelijkheden om het metabolisme te optimaliseren in kaart brengen. Er wordt een overzicht gegeven van de bijdragen van dit proefschrift aan een beter begrip van het systemische karakter van steden. De conclusie is dat een interdisciplinaire aanpak nodig is, die plaats-specifiek is en door schalen heen kijkt om tot een beter begrip van (casus specifieke) verbruikspatronen te komen en van de in tijd en ruimte verbonden factoren waar deze patronen een uiting van zijn. Tot slot wordt uiteengezet dat een landschappelijke systeem benadering (*‘landscape – SETS’ approach*) een dergelijke aanpak mogelijk maakt in toekomstig onderzoek.

List of key terms and abbreviations

Evidence-based urban planning and design refers to *environmental designers* making decisions in the context of planning and designing of the urban environment, based on the deliberate and explicit use of scientific information (Brown and Corry, 2011; Nisha and Nelson, 2012). **Planning** refers to planning with a spatial or geographical component, aimed at managing urban development. **Designing** entails giving three-dimensional form and function to the living environment to improve the functioning and experience of a place (Kempenaar et al., 2016; Lenzholzer et al., 2017).

Environmental design refers to “the disciplines concerned with the design and spatial organization of the built environment; for instance, architecture, civil engineering, urban planning, spatial planning and *landscape architecture*” (Stremke, 2010).

Landscape refers to “an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors.” (European landscape Convention, 2000). Landscapes can include natural, rural, peri-urban and urban areas.

Landscape architecture is the discipline “concerned with mankind’s conscious shaping of his external environment. It involves planning, design and management of the landscape to create, maintain, protect and enhance places so as to be both functional, beautiful and sustainable (in every sense of the word), and appropriate to diverse human and ecological needs” (ECLAS, 2020).

MFA refers to **Material Flow Analysis**, a method for *UM assessment* that provides a quantitative overview of a city’s stocks and flows in terms of mass units. MFA entails the “systematic assessment of the flows and stocks of materials within a system defined in space and time” (Brunner, P. H.; Rechberger, 2004).

Research for design refers to research in support of *evidence-based urban planning and design*, to improve the quality of the outcome or product of the design process (i.e. ‘the design’) (Lenzholzer et al., 2013; Lenzholzer et al. 2017; Lenzholzer and Brown 2016). Research for design can generate evidence that informs the product of a design process, known as substantive knowledge for design,

and/or evidence that aids the structuring of design processes, known as procedural knowledge for design (Lang, 1994; Lenzholzer et al., 2017).

Research through design(ing) refers to research that uses the act of *designing* as main research component (Lenzholzer et al., 2013; Prominski, 2017).

Resource-conscious urban planning and design entails *evidence-based urban planning and design* that guides and effectuates *sustainable urban resource management*.

Resource management entails the utilization of infrastructure, logistics and technology to extract, transform, distribute, consume, use and manage end of life of natural resources as well as of man-made products from these natural resources (Agudelo-Vera et al., 2011).

SETS is an abbreviation of **Social-Ecological-Technological Systems**, a means to conceptualise urban environments that relies upon acknowledging the following system characteristics: cities constitute of physical/built, social-economic and ecological subsystems that encompass multiple and diverse actors. Across these subsystems, causally interlinked urban processes result in intended and unintended consequences. Likewise, cities are open systems, that are influencing and influenced by the broader structures they are embedded in. They are self-organizing, dynamic and evolving, and have non-linear pathways (Bai et al. 2016).

Sustainable development is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987).

Sustainable metabolism, or circular UM, entails an optimization of the urban system from a resource efficiency point of view, including reduction of urban resource consumption and waste production. To realize such optimizations, the following interventions and strategies are implemented: (I) demand minimization, with resource saving measures, (II) output minimization, by maximizing cascading, recycling and resource recovery, (III) multi-sourcing renewable and local sources to provide the remaining demand (Agudelo-Vera et al., 2012b; Tillie et al., 2009). Cascading refers to the direct reuse of waste streams, recycling entails reuse after treatment and resource recovery is extracting useful substances from waste flows, e.g. heat (Agudelo-Vera et al., 2012b). It should be noted that recycling is not applicable in the context of energy flows and that cascading not only implies maximizing resource re-use but also entails using low(er)-quality flows

for low(er) quality demands. This thus includes system optimization from a resource quality point of view, or in the case of energy, an exergetic point of view (Vandevyvere and Stremke, 2012).

Sustainable urban resource management refers to the conscious and purposeful handling of resources to fulfil the needs of the current citizens, without compromising the ability for future generations to meet theirs. It entails implementing interventions and strategies in realization of a more *sustainable urban metabolism*.

Transdisciplinary research refers to research that involves scientists from different disciplinary backgrounds and experts from outside academia, “with all parties contributing to, and benefiting from, a mutual knowledge and experience base” (Ahern, 2013).

Urban planners and designers refers to professionals who are trained and educated in an *environmental design* discipline and whose field of work is the urban environment.

UM is an abbreviation of **urban metabolism**, which serves as a conceptual model for various disciplines to describe and analyse the urban system, urban processes and interactions between society and the environment (Castán Broto et al., 2012; King et al., 2019; Newell and Cousins, 2015). The term relies upon the metaphorical comparison of a city as an organism, drawing parallels to the inputs (food) that fuel the internal processes in the human body, which sustain its functioning and result in growth and outputs (wastes and emissions). In this thesis urban metabolism (UM) or *a city’s metabolism*, is used to refer to the resource stocks and flows through cities and the affiliated processes that transform raw materials, energy, and water into the built environment, human biomass, and waste.

UM assessments refers to empirical studies quantifying the flows and stocks of energy and materials of a city in terms of mass fluxes at a specific moment in time, associated with the discipline of industrial ecology and the engineering fields.

UM field is used to refer to the engineering branch of research on urban systems that employs *urban metabolism* as conceptual model or metaphor and predominantly consists of quantitative *UM assessments*. It is made explicit in the text when *UM field* is used to refer to UM research in the broader sense (figure 1.3, p.29), i.e. research from different disciplinary backgrounds that ascribe different meanings to *urban metabolism* and use different models and methods in their research.

1.

Introduction

1.1 The need for sustainable resource management - background

1.1.1 Day Zero

In January 2018, the city of Cape Town received worldwide media attention as the city announced that they were ninety days away from “Day Zero”. At “Day Zero” Cape Town would turn off municipal water supply, because its reservoirs were running out of water (Maxmen, 2018). Luckily, “Day Zero” was averted thanks to drastic water demand minimization, to almost half of the average water use (Muller, 2019). This was realized, amongst others, through strict use restrictions, an increase in the water tariffs, water pressure reduction as well as extensive water-saving efforts by the city’s residents, who changed their water-use behaviour over a relative short period of time (Booyesen et al., 2019).

Various factors seem to have contributed to causing this unprecedented situation (Muller, 2019; Taing et al., 2019). Although the water crisis in Cape Town became particularly known when the threat of waterless taps was in view, the period of water shortage had already started in 2015 and the city had water restrictions in place since November 2016 (Booyesen et al., 2019; Muller, 2019). On the demand side, the growing urban population and the increasing water demand from various sectors may have contributed to the water crisis (Taing et al., 2019). On the supply side, the crisis can be partly attributed to severely low rainfall in the period between 2015 – 2017, whilst alternative supply options to the rainfall-dependent ones were absent (Taing et al., 2019; Wolski, 2018; Zhang et al., 2019). So, management-related vulnerabilities coincided with severe and rare climatic conditions (Muller, 2019).

In many parts of the world, urban droughts are expected to become more severe and frequent in the future due to changing climatic circumstances and urbanization (Zhang et al., 2019). Climate change is expected to increase water demand globally and to significantly alter the pattern and distribution of water supply, while at the same time global urban water use is growing as a result of urban population growth (Vörösmarty et al., 2000; Zhang et al., 2019). Hence, Cape Town is not the only city that will face substantial future changes, nor are the urban development and resource management challenges that cities face limited to water management. Urbanization and the interlinked processes of change – including, but not limited to, climate change - pose a complex challenge to resource managers, urban planners and decision makers worldwide (McPhearson et al., 2016a).

“Day Zero” was a wake-up call for Cape Town that new water management practices are needed to ensure water security in times of drought (Muller, 2019; Richman et al., 2018; Taing et al., 2019). At the same time, “Day Zero” illustrates something much bigger. It shows us that we should not take the capacity of the earth to supply our resource demands for granted. There are limits to this capacity and far-reaching measures are needed in order to prevent a “Global Day Zero”. Seen from this bigger perspective, “Day Zero” points to the unsustainability of our current societies. It signifies that we need to rethink the relationships between our society and the landscapes that provide the resources upon which our society relies. We need to take a long-term perspective and (re)develop out societies with global sustainability in mind rather than only act when there is a looming “Day Zero”.

This chapter explains that cities are key locations to achieve global sustainability and that it is therefore imperative that cities foster sustainable resource management. To effectuate sustainable urban resource management, urban planning and design has an important contribution to make. For this contribution, it is essential to design urban plans and development strategies on the basis of an in-depth understanding of urban resource flows. Therefore, this thesis focuses on the systemic and detailed understanding of urban resource flows and stocks as knowledge base for urban planning and design that guides and effectuates the sustainable management of resources.

1.1.2 Cities: expanding hotspots of resource use and emissions

More sustainable urban development processes and patterns are key for global sustainability, because cities are hotspots for resource consumption and waste generation (McPhearson et al., 2016a). Whereas 55% of the world’s population was living in cities in 2018, this number is projected to increase to 68% by 2050 (UN, 2019). Vast amounts of resources are required to facilitate the growth and maintenance of the built-up area, and a steady supply of resources such as water, energy and food are essential to sustain urban activities (Agudelo-Vera et al., 2011; Huang et al., 2010; Yeh and Huang, 2012). As urbanization continues, “it is likely to be accompanied by dramatic increases in the consumption of water, land, energy, and mineral resources” (Huang et al., 2010). The capacity of the earth system to supply these resources is not unlimited and the availability and reliable supply of resources is under pressure of current consumption patterns (Agudelo-Vera et al., 2011; Prior et al., 2012).

According to Pulido Barrera et al. (2018) cities consume nowadays “approximately 75% of global material resources and 80% of the global energy supply”, making them global hotspots for material

and energy consumption. Urban energy consumption comprises residential and industrial consumption, as well as the energy needed to maintain and operate urban infrastructure, such as sewage networks, lighting, and water treatment facilities (Yeh and Huang, 2012). As cities expand, not only the energy demand by urban residents and industrial processes increases, but also the demands that originate from the enlarged infrastructural networks (Yeh and Huang, 2012). In the case of water, urbanization implies that more water resources need to be appropriated to supply the increasingly concentrated industrial and residential demands. According to Darrel Jenerette and Larsen (2006), the growing water footprint of cities implies that cities will need areas several hundred times the size of the urban area itself to supply their water needs. In these hinterlands cities increasingly compete with other cities for fresh water, as well as with agricultural production and with the environment that provides essential ecosystem functions such as climate regulation (Huang et al., 2010).

Cities do not only appropriate a disproportionate share of ecosystems to supply their resource inputs, but they also put ecosystem functioning under pressure with the waste and emissions that they generate (Huang et al., 2010). Cities generate about 75% of total carbon emissions and half of the world's waste (Pulido Barrera et al., 2018). Urban resource consumption is thus also a concern for global sustainability because of the environmental impacts associated with resource use, as well as the environmental and social impacts of resource extraction and processing (Höök and Tang, 2013; Prior et al., 2012; Watari et al., 2020). Together with the land use conversions that take place to build cities and to support their resource demands, urban emissions contribute to local as well as global environmental impacts, such as changes in biogeochemical cycles, water contamination, air pollution and climate change (Dijst et al., 2018; Grimm et al., 2008). These human-driven impacts are reaching unprecedented levels, threatening the planetary capacity to handle these impacts without destabilizing the current state of the earth system (Rockström et al., 2009; Steffen et al., 2015).

In view of urbanization, climate change, resource depletion and the impacts associated with resource extraction, processing and consumption, it is thus of great importance that cities foster the sustainable management of resources (Agudelo-Vera et al., 2011). This means that *sustainable urban resource management* – the conscious and purposeful handling of resources to fulfil the needs of the current citizens, without compromising the ability for future generations to meet theirs – should be anchored in urban (re)development.

1.2 Urban planning and design for sustainable resource management – problem statement

1.2.1 Cities and urban development: opportunities for change

Cities and urbanization do not only pose a challenge for global sustainability, they also offer opportunities for *sustainable development*¹. Goals and targets associated with sustainable development are directly relevant to urban decision-makers. These decision-makers are, as opposed to national governments, “generally in direct contact with their constituents, and are embedded in their local urban geographic and social context” (Bai et al., 2016). These local governments are therefore committed to lead the shift towards sustainable development, illustrated by city initiatives such as the ‘Covenant of Mayors for climate and energy’ and ‘ICLEI Local Governments for Sustainability’ that connect up to thousands of cities (Rosales Carreón and Worrell, 2018). Moreover, the fact that cities are hotspots of consumption and emissions makes it possible to have a large impact within a relatively confined area. As urbanization comes with extensive modifications of the landscape, the urban environment yet to be built represents a key opportunity for design, architecture, and planning that embraces sustainability (Huang et al., 2010; McPhearson et al., 2016b).

Indeed, *landscape architects* and other *environmental designers*² have an important contribution to make in the sustainable development of cities (Van den Brink and Bruns, 2014). Complex societal challenges such as sustainable urban development require change in the physical landscape and it is at the heart of environmental design disciplines to propose intentional landscape changes (Bruns et al., 2019; Meijering et al., 2015; Nassauer, 2012; Steinitz, 1995). In the context of such complex issues, it is of particular importance that designers are trained to formulate coherent ideas out of different kinds of information (Kempenaar et al., 2016). So how do they do that? What does *designing* actually refer to?

1.2.2 Evidence-based urban planning and design

Designing entails giving three-dimensional form and function to the living environment to improve the functioning and experience of a place (Kempenaar et al., 2016; Lenzholzer et al., 2017). A design

¹ *Sustainable development* is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987).

² *Designers* are professionals who are trained and educated in an environmental design discipline (Kempenaar et al., 2016). *Environmental design* refers to “the disciplines concerned with the design and spatial organization of the built environment; for instance, architecture, civil engineering, urban planning, spatial planning and landscape architecture” (Stremke, 2010). *Landscape architecture* is the discipline “concerned with mankind’s conscious shaping of his external environment. It involves planning, design and management of the landscape to create, maintain, protect and enhance places so as to be both functional, beautiful and sustainable (in every sense of the word), and appropriate to diverse human and ecological needs” (ECLAS, 2020). The discipline addresses the urban, peri-urban and rural environment.

process constitutes firstly of mapping, analysing and visualizing the existing situation. This helps to understand the situation, issues at hand and interactions among them, and is instrumental to identifying opportunities for change. This understanding of the existing situation informs the development of alternative proposals for the envisioned future spatial organization of the environment and its aesthetic appearance. These proposals are subsequently evaluated and refined to come up with the preferred solution, i.e. ‘the design’ (Kempenaar et al., 2016; Milburn and Brown, 2003; Steinitz, 1990). In this design process, designers make use of embodied knowledge and situational knowledge of the site-specific conditions of the project at hand. To provide solutions for complex problems, scientific information is also needed with regards to the underlying causes, effects, and possible solutions to important issues (Brown and Corry, 2011; Bruns et al., 2019).

Environmental design that uses scientific information as basis for decision-making is being referred to as ‘evidence-based decision-making’ (Frantzeskaki et al., 2019; Nisha and Nelson, 2012), ‘evidence-based landscape architecture’ (Brown and Corry, 2011), ‘evidence-based urban design’ (Razzaghi-asl and Zarei, 2013) or ‘evidence-based planning’ (Krizek et al., 2009). Considering the focus of this thesis on the urban environment, I will use the notion ‘evidence-based urban planning and design’, referring to: environmental designers making decisions in the context of planning and designing of the urban environment, based on the deliberate and explicit use of scientific information (Brown and Corry, 2011; Nisha and Nelson, 2012). Energy-conscious design and climate-responsive design are two fields of evidence-based urban planning that demonstrate how the integrative character of design is beneficial to formulate coherent and comprehensive plans and strategies for complex problems (see textbox 1.1). For both fields, a sound evidence base is essential to inform and justify planning, design, and management decisions (Meijering et al., 2015). In the case of climate-responsive design, this is for example knowledge on urban climate and microclimate, whereas energy-conscious design requires for example empirical evidence with regard to feasible energy transition targets (Lenzholzer and Brown, 2013; Oudes and Stremke, 2018).

1.2.3 *Resource-conscious urban planning and design*

The integrative and strategic problem-solving capacity of evidence-based urban planning and design is also essential to create plans and development strategies for the urban environment that guide and effectuate the sustainable management of resources. Urban form and function affect resource flows (Cousins and Newell, 2015; Rode et al., 2014; Salat, 2009; Thomson and Newman, 2018) and the way we lay out our cities today will thus affect urban resource flows for the coming tens, potentially hundreds of years. It is essential to understand how urban areas function with respect

³ *Planning* refers here to planning with a spatial or geographical component, aimed at managing urban development.

Textbox 1.1: Energy-conscious design and climate-responsive design – an illustration of evidence-based planning and design

Energy-conscious design and climate-responsive design are two fields of evidence-based urban planning and design. Energy-conscious design considers how spatial planning and design can support the energy transition from fossil fuels towards renewable energy sources (Stremke and Koh, 2010). Environmental designers are for example involved in the placement of renewable energy technologies as well as in formulating strategic, long-term energy scenarios (Pistoni and Stremke, 2019; Waal and Stremke, 2014). Waal and Stremke (2014) point out that “landscape is indeed an integrative concept in which the ecological/functional, social and aesthetic aspects of energy-related interventions can be approached together. Because of that, landscape architecture, among other disciplines, can help to integrate the multiple dimensions of energy transition.” Also in the context of urban climate adaptation, this integration is an important contribution that environmental designers can make. Against the backdrop of heat stress as a result of increasing temperatures and enhanced urban heat islands, climate-responsive design is concerned with creating urban environments that are thermally comfortable (Brown et al., 2015; Klemm et al., 2017). These designs consider the microclimate effects of, amongst others, the orientation of streets and buildings, type of surface materials, and types and locations of vegetation, whilst also accounting for aspects such as functionality, aesthetic appeal and maintenance (Jacobs et al., 2020; Klemm et al., 2017; Lenzholzer and Brown, 2013).

to resource flows to formulate strategic visions for sustainable cities and to inform implementation of sustainable resource management interventions (Decker et al., 2000; John et al., 2019; Perrotti and Stremke, 2020; Yetano Roche et al., 2014). Hence, *resource-conscious urban planning and design* requires insight in resource patterns in cities and the underlying urban processes and forms associated with these patterns (figure 1.1). As formulated by Ahern (2013): “By virtue of their professional focus on urban form, planners and designers intrinsically and historically understand the pattern:process dynamic and have readily applied this thinking to address sustainability challenges”. Scholars stress the potential of urban metabolism analyses as evidence base for urban planning and design that aims to contribute to sustainable resource management (Castán Broto et al., 2012; Kennedy et al., 2011).

Analysis of the existing situation with regards to resources

a. mapping patterns and flows

b. visualising processes

Envisioned future situation

c. design proposal future

Figure 1.1: Designing spatial strategies and plans for sustainable resource management (c), requires insight in resource patterns and flows in cities (a) and the underlying processes associated to these patterns (b)

1.3 The potential of urban metabolism - theoretical framework

1.3.1 Urban metabolism – the metaphor and the scientific field

‘Urban Metabolism’ serves as a conceptual model for various disciplines to describe and analyse the urban system, urban processes and interactions between society and the environment (Castán Broto et al., 2012; King et al., 2019; Newell and Cousins, 2015). The term relies upon the metaphorical comparison of a city as an organism, drawing parallels to the inputs (food) that fuel the internal processes in the human body, which sustain its functioning and result in growth and outputs (wastes and emissions). The appropriateness of this analogy is disputed and some stress that cities are more similar to ecosystems (Golubiewski, 2012; Zhang et al., 2015). Nevertheless, metabolism has shown a powerful metaphor in research on urban systems for scholars from different disciplinary backgrounds– notwithstanding that these scholars ascribe very different meanings to urban metabolism (UM) and use different models and methods in their research (Newell and Cousins, 2015; Pincetl et al., 2012).

The field of research that employs the UM metaphor has developed in three main directions. These fields of research following after the work by Wolman (1965), who quantified the metabolism of a hypothetical American city (figure 1.2a) (Newell and Cousins, 2015). These research areas are affiliated to the fields of industrial ecology, urban ecology and Marxist ecologies (figure 1.3). The first scholars that followed Wolman in the quantitative analysis of UM were system ecologists that described UM in terms of solar energy equivalents or emergy – a school of thought brought forward by Eugene Odum (Barles, 2010; Castán Broto et al., 2012; Zhang et al., 2015). However, in the 70s several empirical studies were published, such as the work on Brussels (figure 1.2b) and Hong Kong (Newcombe et al., 1978), that marked the starting point of a second quantitative approach. This ‘mass balance accounting’ research is primarily associated with the discipline of industrial ecology and the engineering fields (Castán Broto et al., 2012). After slower development of this field in the 1980s, interest rose again in the 90s, and the last 20 years showed a significant increase in research in this engineering field (Cui, 2018; Restrepo and Morales-Pinzón, 2018; Zhang et al., 2015). The starting point of this thesis is this engineering strand of UM research, also known as the ‘traditional industrial ecology approach’ (dark blue in figure 1.3).

a.

b.

Figure 1.2: Illustrations of the results of two of the earliest quantitative UM analyses

a. Quantification of the inputs (left) and outputs (right) of a hypothetical American city, Abel Wolman (1965)

b. The resource flows and affiliated processes of Brussels' UM, Duvigneaud & Denaeyer-De Smet (1977)

Visuals via <https://multimedia.metabolismofcities.org/datavisualizations/>

Figure 1.3: Development of the scientific UM field over time
(based on Newell and Cousins (2015) and Castán Broto et al (2012))

1.3.2 The engineering approach to urban metabolism

Up till now, no standardized definition for UM exists (King et al., 2019). Yet, the definition provided by Kennedy et al. (2007) is considered clear and comprehensive and it is frequently used within this field of UM research (Beloin-Saint-Pierre et al., 2017; Cui, 2018). Kennedy et al. (2007) define UM as “the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste”. In line with this definition and the use of the term UM in the engineering field (Decker et al., 2000; Yetano Roche et al., 2014), I will use the term UM to refer to the resource stocks and flows through cities and the affiliated processes that transform these raw materials, energy, and water into the built environment, human biomass, and waste.

UM research from an engineering approach focuses on quantifying the flows and stocks of energy and materials of a city in terms of mass fluxes (Castán Broto et al., 2012; Kennedy et al., 2011; Pincetl et al., 2012). Accordingly, research mostly consist of ‘UM assessments’: empirical studies that quantify resource flows to disclose how a particular city functions at a specific moment in time (Kennedy et al., 2011). These assessments rely upon methods such as material flow analysis

(MFA), substance flow analysis and ecological footprint analysis (Barles, 2010; Li and Kwan, 2018). MFA is the most widely used method for UM assessment (Castán Broto et al., 2012; Cui, 2018); it entails the “systematic assessment of the flows and stocks of materials within a system defined in space and time” (Brunner, P. H.; Rechberger, 2004). MFA is based on the conservation of mass, with mass in = mass out + stock changes (Pincetl et al., 2012), and it thus relies upon quantifying stocks and flows in terms of mass units, e.g. kilotons per year. When MFA is applied to quantify the resource flows of an urban system, it is common practice to report nutrient, water and material flows in terms of mass and energy flows in terms of joules (Kennedy et al., 2011). MFA thus assesses a material flow *system*, as opposed to the assessment of a particular material flow (Graedel, 2019). The latter is what substance flow analysis can be used for, for example, to quantify the pathway of nitrogen or phosphorous flows through an urban system. Lastly, MFA provides a quantitative overview of a city’s metabolism, but it does not entail a characterisation of the impacts of UM. For such a quantification of impacts, ecological footprint is for example used. This method quantifies the amount of productive land surface needed to produce the inputs that a society relies upon and the surface needed to absorb its output flows (Barles, 2010).

1.3.3 Urban metabolism and sustainable urban development

UM research increasingly engages explicitly with sustainability (John et al., 2019; Van Den Berghe and Vos, 2019). Key foundations for this were made in the late 1990’s (see figure 1.3), with the publication of Rees and Wackernagel (1996) on urban ecological footprints and the plea of Newman (1999) to include liveability indicators in UM assessments. Also at that time, Girardet published ‘The Gaia Atlas of Cities’ (Girardet, 1996). This work has strongly influenced the idea of “sustainable urban metabolism”, as he distinguished linear and circular metabolism (Van Den Berghe and Vos, 2019; Wachsmuth, 2012). Accordingly, making a city’s metabolism more sustainable refers to reducing urban resource consumption and waste production and shifting from a linear metabolism to a circular metabolism (figure 1.4). Such optimizations can be realized with: (I) demand minimization, with resource saving measures; (II) output minimization, by maximizing *cascading*, *recycling* and *resource recovery*⁴, and (III) multi-sourcing renewable and local sources to provide the remaining demand (Agudelo-Vera et al., 2012b; Tillie et al., 2009). The challenge ahead is to realize these optimizations and design cities and their neighbourhoods in such a way that UM processes are changed in line with this envisioned circular metabolism (Chrysoulakis et al., 2013).

⁴ *Cascading* refers to the direct reuse of waste streams, *recycling* entails reuse after treatment and *resource recovery* is extracting useful substances from waste flows, e.g. heat (Agudelo-Vera et al., 2012b). It should be noted that recycling is not applicable in the context of energy flows and that cascading not only implies maximizing resource re-use but also entails using low(er)-quality flows for low(er) quality demands. This thus includes system optimization from a resource quality point of view, or in the case of energy, an exergetic point of view (Vandevyvere and Stremke, 2012).

Figure 1.4 Linear and circular urban metabolism, illustrated with the city of Amsterdam

1.4 Urban metabolism for resource-conscious urban planning & design

1.4.1 Potential and shortcomings of UM assessments – State of the Art

UM assessments are considered valuable for urban planning and design in several ways. A key application of UM assessments is as accounting framework for sustainability reporting and benchmarking, as these assessments provide indicators of the environmental performance of a city (Kennedy et al., 2011; Yetano Roche et al., 2014; Zhang et al., 2015). Findings of MFAs can be used as a baseline for formulating resource efficiency targets and policies, to be used later on to monitor UM development over time and evaluate the impact of measures (González et al., 2013; John et al., 2019; Yetano Roche et al., 2014; Zhang et al., 2015). MFA is a particularly useful method for such assessments because it employs measurement units that are easy to understand for practitioners such as policymakers (Castán Broto et al., 2012; Cui, 2018; Yetano Roche et al., 2014). In addition, it is stressed that MFA has potential to inform strategies and interventions aimed at optimization of urban resource flows (Codoban and Kennedy, 2008; Galan and Perrotti, 2019; Kennedy et al., 2011; Moffatt and Kohler, 2008; Pistoni and Bonin, 2017). Nevertheless, UM research with a solution-oriented perspective that engages with designing solutions in support of sustainable urban development is still at its infancy (John et al., 2019; Li and Kwan, 2018).

Scholars acknowledge the potential of UM assessments generally and MFA specifically for informing resource-conscious urban planning and design, but they also point to the shortcomings that hinder the exploitation of this potential. The most significant shortcoming of MFA is the 'black box' approach that characterizes the method (Athanasiadis et al., 2015). MFA only provides insight into the exchange of resources between the city and its environment; it does not describe internal components and dynamics that shape the city and its UM (Athanasiadis et al., 2015; Yetano Roche et al., 2014; Zhang, 2013; Zhang et al., 2015). According to Li and Kwan (2018b) this 'black box' approach reflects that "UM methods have their origins from outside the realm of urban studies, planning or geography. They are 'merely' adapted so as to be applicable to the urban context. However, being urban also has inherent spatial and social connotations, which tend to be ignored or oversimplified". As a result, 'black box' assessments such as MFAs provide insufficient insight into UM to identify key points for interventions, nor do they provide the evidence needed to formulate and implement strategies for sustainable urban development (Cui, 2018; Rosales Carreón and Worrell, 2018; Zhang et al., 2015).

1.4.2 Overcoming the 'black box' approach – Knowledge Gaps

Overcoming the 'black box' approach is thus crucial to make UM assessments a useful evidence base for resource-conscious urban planning and design. Hence, it is essential that UM assessments provide more detailed understanding of UM. I see three promising directions to acquire this insight and to advance the emerging field of UM research that is concerned with application of UM assessments for urban planning and design:

- I. Taking a comprehensive, 'grey box' approach in city-level MFA;
- II. Analysing UM at a higher spatial resolution;
- III. Accounting for the mechanisms underlying UM.

Literature reveals that a first step to get a more in-depth understanding of the UM, is to carry out a comprehensive UM assessment. Such a comprehensive assessment entails accounting for as many flows as possible, disaggregating the input and output flows and revealing key internal processes (Athanasiadis et al., 2015; Beloin-Saint-Pierre et al., 2017; Zhang et al., 2015). According to Beloin-Saint-Pierre et al. (2017), such a 'grey box' approach "offers an interesting balance between a detailed description and the required efforts for modelling". Such an approach thus enables a first understanding of the key urban metabolic processes and the most relevant environmental impact flows of UM. Such understanding can support those working at the urban scale in making decisions with regards to improvement of resource efficiency (Beloin-Saint-Pierre et al., 2017; Cui,

2018; Zhang et al., 2015). Although the potential of MFAs for comprehensive assessment of UM is known and ‘grey-box’ MFAs studies (e.g. Barles 2009; Niza et al. 2009) are already performed for over a decade (Beloin-Saint-Pierre et al., 2017), these MFAs still have shortcomings regarding comprehensive assessment of UM. They provide for example little insight into locally sourced resources, whereas these resources are highly relevant inputs to consider for sustainability of UM.

Various scholars argue that it is also vital to analyse UM at a higher spatial resolution, when aiming to facilitate urban planners and designers in formulating sustainable solutions. A higher spatial resolution is said to be essential to align UM assessment with the target audience and to match UM assessments with the level at which planners and designers operate (Beloin-Saint-Pierre et al., 2017; Li and Kwan, 2018; Moffatt and Kohler, 2008; Pincetl et al., 2012; Spiller and Agudelo-Vera, 2011). A more detailed level of analysis should “provide more direct support for diagnosing problems and suggesting measures to solve the problems” (Zhang et al., 2015). Higher spatial resolutions may enable the identification of differentiation in consumption patterns and associated priorities among key sectors, locations and even groups of people (Athanassiadis et al., 2015; John et al., 2019; Zhang, 2013). Indeed, efforts are made to downscale flow accounting to higher spatiotemporal resolutions within the city (e.g. Pincetl et al. 2014; Mehta et al. 2013; Porse et al. 2016), but so far this type of UM studies are still rare (John et al., 2019; Li and Kwan, 2018).

It is furthermore considered important to know which city characteristics and mechanisms underlie UM patterns (Cui, 2018; John et al., 2019; Minx et al., 2011; Restrepo and Morales-Pinzón, 2018). Knowing these underlying factors is especially relevant for formulating context-specific solutions in cities, because the urban landscape shows complex and unique configurations in terms of economic, social, cultural, and spatial characteristics (Athanassiadis et al., 2015; Li and Kwan, 2018). Hence, scholars agree that it is a key priority to analyse which factors are influencing UM and in what way (Athanassiadis et al., 2015; Metzger et al., 2016; Pincetl et al., 2012; Rosales Carreón and Worrell, 2018; Yetano Roche et al., 2014; Zhang et al., 2015). As stated by Minx and colleagues (2011): “unless we know how specific determinants such as urban form, lifestyles or the available infrastructure manifest in metabolic differences across cities and other urban settlements, the knowledge about size and types of metabolic in- and outflows is of very limited use for understanding urban systems and informing local decision making processes”. So far, few UM studies researched the relationship between environmental, social and economic factors and the metabolic flows of a city (e.g. Kalmykova et al. 2016; Athanassiadis et al. 2017; Kennedy et al. 2015). Empirical evidence that is considered particularly relevant for urban planning and design, is the influence of urban forms and urban morphology on urban resource use (Perrotti, 2019; Vandevyvere and Stremke, 2012) and the link between urban structures, lifestyle and UM (Barles, 2010; Weisz and Steinberger, 2010).

1.4.3 Research objectives

This research addresses abovementioned knowledge gaps with a twofold research aim. This thesis aims to inform methodological development of UM assessments to enhance their usefulness for resource-conscious urban planning and design and to acquire an advanced understanding of the systemic characteristics of cities and their metabolism. Therefore, the objectives of this research are to:

- I. examine how comprehensiveness and spatiotemporal resolution of UM assessments affect the potential of these assessments to provide insightful evidence of resource flows and stocks;
- II. investigate the factors and mechanisms that underlie spatiotemporal variability in resource flows and stocks.

1.5 Methodological approach

1.5.1 Research for design

This research thus aims to make methodological contributions and generate substantive knowledge⁵ that can support planning, design, and management decisions with respect to urban resource flows. Accordingly, this research can be considered ‘research for design’ (see e.g. Lenzholzer et al. 2017; Lenzholzer and Brown 2016): research that aims to support evidence-based urban planning and design to improve the quality of the outcome or product of the design process (i.e. ‘the design’) (Lenzholzer et al., 2013). It is relevant to point out that ‘research for design’ does *not* imply that research findings can be readily and directly applied by planning and design practitioners. Firstly, ‘research for design’ consists of research that contributes to an evidence base of relevant knowledge about the world; secondly, this evidence needs to be communicated to practitioners in a format that is understandable and useful for them (Brown and Corry, 2011). This research thus aims to contribute to the evidence base for resource-conscious urban planning and design with methodological advancements and system knowledge. Practical outlooks and strategic recommendations are given to operationalize this knowledge for stakeholders involved in resource-conscious urban planning and design.

⁵ Evidence that informs the product of a design process; as opposed to *procedural* knowledge for design, which refers to evidence that aids the structuring of design processes (Lang, 1994; Lenzholzer et al., 2017).

1.5.2 Amsterdam case study

This thesis largely comprises case study research of Amsterdam, the capital city of The Netherlands. A case study is: “an empirical enquiry that investigates a contemporary phenomenon (the “case”) in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident” (Yin, 2014, p.16). As stressed in 1.3.4, empirical case studies are common in UM research. Case study research is a suitable research approach for UM research because the urban landscape and its metabolism cannot be separated from their context. Moreover, study designs are relevant for acquiring a holistic understanding of a phenomenon (Kumar 2014, p.155).

Amsterdam is a relevant case to study because enhanced understanding of Amsterdam’s metabolism may prove valuable for a better understanding of the UM of medium-sized cities and delta cities more generally. Amsterdam Metropolitan Region (AMR) is the biggest metropolitan area in The Netherlands in terms of inhabitants, with almost 2.5 million citizens living in the AMR in 2019 (AMR, 2020). It is important to gain understanding of small and medium-sized cities, i.e. up to 5 million inhabitants, because this is where more than three quarters of urban dwellers lives (UN, 2019; Yetano Roche et al., 2014). Additionally, the majority of global cities is located at coast lines and in the estuary of river systems, where urbanization is expected to happen fast (Elmqvist et al., 2013; UN, 2017). Amsterdam is also located in a highly urbanised delta. Already 91.6% of The Netherlands can be considered urban, yet this number is expected to be 96.6% in 2050 (UN 2019, p38-40). Further urbanization is also expected to happen in the AMR, with an expected population increase of twenty percent in 2035 compared to 2019 (CBS, 2020, 2019). Accommodating this growth is challenging, given the manifold (and competing) spatial claims in an already highly urbanized environment. In such a context it is of utmost importance to have the scientific information needed to make evidence-based planning and design decisions that ensure sustainable urban development.

Amsterdam is also selected as case because of data availability and approachability of stakeholders. The City of Amsterdam makes urban data openly available on their online portals, including geospatial data and long-term statistical data. Access to such data is essential for the research approach (described in 1.5.4). Data availability benefitted also from performing this research under the auspice of the Amsterdam Institute of Advanced Metropolitan Solutions (AMS). The AMS Institute works in close collaboration with the City of Amsterdam and industrial, governmental and societal partners in Amsterdam. Accordingly, performing this research in AMS context safeguarded vital elements of the research approach, such as collaboration with stakeholders (see 1.5.3), access to non-open data sets and stakeholder input (see 1.5.4).

1.5.3 Transdisciplinary research

Expertise from different academic disciplines needs to be integrated to address sustainability issues. Given the complexity of such issues, it is also essential to engage and collaborate with non-academic stakeholders to benefit from their expertise and experience (John et al., 2019; Lang et al., 2012; Wei et al., 2015). The value of such *transdisciplinary*⁶ research is also acknowledged in the UM field, amongst others to: come to a better understanding of the UM; ensure comprehensibility and transparency of UM assessments for stakeholders; give effective guidance for practical application; and facilitate access to and availability of data (Dijst et al., 2018; John et al., 2019; Perrotti, 2019; Wei et al., 2015; Zhang et al., 2015). Hence, a *transdisciplinary* research approach is taken in this research that integrates knowledge from different academic disciplines with knowledge from actors outside academia.

Stakeholders and academics from different backgrounds were involved in this research. Many stakeholders are working on sustainable resource management projects in Amsterdam (Dalla Fontana and Boas, 2019; Van der Hoek et al., 2017). These stakeholders include big as well as small players, such as the municipality, the port of Amsterdam, the main water and energy companies, architecture and landscape architecture firms and citizen initiative groups (Dalla Fontana and Boas, 2019; Gravagnuolo et al., 2019). In this research a selection of the abovementioned stakeholders were involved, including strategic advisors from the port, resource managers from utilities, urban planners and designers, and landscape architects. In addition, this research engages with academics from different disciplinary backgrounds, such as environmental engineering, landscape architecture and geo-information science (figure 1.5). This research integrates knowledge and methodological approaches from abovementioned disciplines with those from different thought traditions within the overall UM research field. Literature was used to connect with expertise from these fields, including industrial ecology, urban ecology, and urban environmental history⁷.

Background &
methodological approach

Figure 1.5: The interdisciplinary nature of this thesis

⁶ “Transdisciplinary research involves stakeholders and scientists throughout a project, with all parties contributing to, and benefiting from, a mutual knowledge and experience base” (Ahern, 2013).

⁷ Urban environmental history studies are most strongly related to the ‘Vienna School’ of UM research (figure 1.3).

1.5.4 Mixed-methods

Within this transdisciplinary case study research, I make use of different data sources as well as multiple methods for data collection and analysis to arrive at the most complete picture possible (table 1.1). I label the three main sources of data: ‘stakeholder input’ (primary data source), ‘databases’ (secondary data source) and ‘literature’ (secondary data source) (bottom row table 1.1). In the initial research stages, facilitated group discussions are used to acquire stakeholder input that helps focussing the research, for example, to inform formulation of hypotheses and the scope of the research. Later, structured interviews and stakeholder workshops are used to collect stakeholder input for case study research in chapter 2 and 3. Databases are also used extensively in case-specific parts of this research (chapter 2 and 5). Quantitative methods are used to analyse these sources of empirical data, including data on the municipal level and at more detailed spatial levels. These data include for example port-related statistical data, residential water and energy consumption data, demographic statistical data and geographic data on building characteristics. Scientific literature is the main data source in chapter 4 and it is also a source for chapter 2. Moreover, literature is used throughout this thesis to contextualize the research and to position findings in the existing field of knowledge. UM-related literature with a wide range of research designs are taken into account, including studies that present quantitative and qualitative findings. This research thus engages with different forms of data and multiple methods for data collection and analysis to arrive at the most complete picture possible. Hence, this research makes use of a so-called ‘mixed-methods approach’ (Creswell, 2014; Kumar, 2014), which is common in case study research (Creswell and Plano Clark, 2018).

Table 1.1: Overview of methods used in this thesis (top), the chapters in which they are used (left) and the data sources they rely upon (bottom)

	Interviews	Stakeholder workshops	Material flow analysis (MFA)	Multiple linear regression	Literature review *: systematic
Chapter 2		✓	✓		✓
Chapter 3	✓	✓			
Chapter 4					✓*
Chapter 5				✓	
	Stakeholder input Amsterdam case study		Databases Amsterdam case study		Literature

1.6 Thesis Outline

The research approach outlined above, has resulted in four research chapters. Accordingly, this thesis consists of six chapters: an introduction, four chapters that have been published in or are in review by international scientific journals, and a discussion chapter. Figure 1.6 schematically represents the connections between these chapters, as well as their connection to the main data sources they rely upon.

The hypothesis that underlies **chapter 2** is that MFA does not account for all relevant resource flows and thus falls short in providing a full understanding of a city's metabolism. To examine this, the UM of Amsterdam was assessed employing the established Eurostat MFA method and a modified version of this method, which can be considered a comprehensive 'grey box' MFA. After application of these methods, the results of both assessments were compared. This comparison reveals how the proposed advancements provide a deeper understanding of the UM, which is beneficial for informing sustainable urban resource management.

Chapter 3 investigates at which spatial and temporal resolution UM should be assessed to generate results that are useful for implementation of urban planning and design interventions. To question stakeholders on this matter, the so-called SIRUP tool was developed and subsequently applied in interviews and workshops. Results show which information on resource flows stakeholders need to inform planning and design interventions and on which spatiotemporal resolution this information is required. Resolutions are compared to the resolution of available data and to the resolution of current MFA studies.

Chapter 4 departs from the notion that if UM assessments aim to inform the designing of policies and plans that effectuate sustainable resource management, they should not only reveal what the UM looks like, but also why it looks that way if it. Accordingly, the UM literature was systematically reviewed on factors that influence spatiotemporal variability in resource consumption. This chapter presents the factors influencing urban water and energy consumption and their effect on consumption. It also describes relationships between factors of influence that can potentially influence the direction and magnitude of their effects.

Subsequently, in **chapter 5**, the findings from the systematic literature review are empirically tested in a high-resolution case study of Amsterdam. Multiple linear regression analysis was used to examine sixteen factors on their explanatory power for spatial variation in residential electricity, gas and water consumption. Four regression models per resource were used based on distinct spatial units: neighbourhoods, districts, 1ha and 2.5 ha square units. Results reveal which

factors are significant explanatory variables for spatial variability in water and energy consumption in Amsterdam. The relative importance of these explanatory variables is shown as well as their dependencies on the scale of observation.

Finally, **chapter 6** synthesizes how the findings from the previous chapters contribute to answering the two overarching research objectives. Subsequently, this chapter discusses the contributions of this research to the UM field and it highlights the value of this thesis for the stakeholders involved in urban planning and design. This chapter closes with recommendations for future research and conclusions.

Figure 1.6: Schematic representation of the main chapters in this thesis and the sources of data that they foremost rely upon

Abstract

Sustainable urban resource management depends essentially on a sound understanding of a city's resource flows. One established method for analysing the urban metabolism (UM) is the Eurostat material flow analysis (MFA). However, for a comprehensive assessment of the UM, this method has its limitations. It does not account for all relevant resource flows, such as locally sourced resources, and it does not differentiate between flows that are associated with the city's resource consumption and resources that only pass through the city. This research sought to gain insights into the UM of Amsterdam by performing an MFA employing the Eurostat method. Modifications to that method were made to enhance its performance for comprehensive UM analyses. A case study of Amsterdam for the year 2012 was conducted and the results of the Eurostat and the modified Eurostat method were compared. The results show that Amsterdam's metabolism is dominated by water flows and by port-related throughput of fossil fuels. The modified Eurostat method provides a deeper understanding of the UM than the urban Eurostat MFA attributed to three major benefits of the proposed modifications. First, the MFA presents a more complete image of the flows in the UM. Second, the modified resource classification presents findings in more detail. Third, explicating throughput flows yields a much-improved insight into the nature of a city's imports, exports, and stock. Overall, these advancements provide a deeper understanding of the UM and make the MFA method more useful for sustainable urban resource management.

2.

Comprehensive assessment of the urban metabolism

A material flow analysis of Amsterdam

A slightly modified version of this chapter has been published as:

Voskamp, I.M., Stremke, S., Spiller, M., Perrotti, D., van der Hoek, J.P., Rijnaarts, H.H.M., 2017
Enhanced performance of the Eurostat method for comprehensive assessment of urban metabolism:
A Material Flow Analysis of Amsterdam.
Journal of Industrial Ecology 21, 887-902. <https://doi.org/10.1111/jiec.12461>

2.1 Introduction

Ongoing urbanization, resource depletion and climate change emphasize the need to design and plan cities that foster sustainable urban resource management (Agudelo-Vera et al., 2011). In order to plan cities that generate less environmental pressure it is essential to understand how urban systems function with respect to resource flows (Decker et al., 2000). One key approach to researching the material flows and stocks of urban systems is urban metabolism (UM) (Kennedy et al., 2011; Zhang, 2013). The body of quantitative UM research includes studies that assess particular subflows, such as food, energy, and water (e.g. Kim and Barles 2012) and those that consider fluxes of particular elements, such as phosphorous, nitrogen, and specific metals (e.g. Forkes 2007) (Kennedy et al., 2011; Zhang, 2013). However, only comprehensive analyses that account for all relevant urban resource flows can provide a full understanding of a city's metabolism. This knowledge is essential for developing resource management practices that do not shift the burden of resource extraction and use from one resource to another (Kenway et al., 2011). Only few of such "comprehensive" UM studies, which have quantified all or nearly all material flows of cities, exist. Kennedy and Hoornweg (2012) found that only twenty relatively comprehensive UM studies have been published since the work of Wolman (1965).

The limited number of comprehensive UM studies and the lack of standardization among them restricts the opportunities for comparative research into metabolic similarities and differences between cities (Decker et al., 2000). Yet, such comparative analyses offer opportunities to interpret city-specific findings and enables decision-makers to compare the effects of measures and policies adopted in one city with those applied in other cities. Kennedy et al. (2015) show that comparative research also contributes to a more general understanding of UM and the factors that affect it, advancing the body of UM knowledge beyond predominantly city-specific knowledge.

One of the key methods used for systematic assessment of UM is material flow analysis (MFA) (Castán Broto et al., 2012; Zhang, 2013). Also among MFAs there is a lack of standardization, mainly due to the absence of standardized resource classifications (which goods, substances, and processes are to be investigated) and established principles for setting system boundaries. Kennedy et al. (2014) address the need for conventions by proposing an indicator set for comprehensive UM studies of megacities aimed at standardizing data collection and reporting. Another significant contribution to the standardization of MFA is the method described in the MFA guide of the European Statistical Office (Eurostat, 2001). The majority of comprehensive European urban MFA studies are based on this Eurostat method (Table 2.1). However, as the original Eurostat method was designed for MFAs on the national level, each of the reviewed studies tailored the Eurostat

method for application at the scale of the city (Barles, 2009; Browne et al., 2011; Hammer and Giljum, 2006; Niza et al., 2009; Rosado et al., 2014). In other words, there is no standardized Eurostat method for urban MFAs.

Moreover, past application of the Eurostat method to cities showed that the method has shortcomings regarding comprehensive assessment of UM. Partly this is because the method accounts for *material* flows rather than *resource* flows. Even though Eurostat states that water can be accounted for, none of the studies quantifies drinking water and wastewater flows, except a brief mention of water inputs for Lisbon by Niza et al. (2009). Although one can argue that this is not only a shortcoming of the method but also of its application, the method's focus on *material* flows

Table 2.1: Comprehensive MFA studies of European cities

Study	City	Base year	Specific MFA method used	System boundary	Type of publication
Gorree et al. 2000	Amsterdam	1998	-	Amsterdam; boundaries based on municipality	Report
Hendriks et al. 2000	Vienna	Not specified	-	Vienna city; boundaries not further specified	Scientific article
Barrett et al. 2002	York	2000	Eurostat, Mass Balance UK	City of York; boundaries not further specified	Report
IWM(EB) 2002	London	2000	Mass Balance UK	Greater London; boundaries based on boroughs (34 included)	Report
Hammer and Giljum 2006 ¹	Hamburg, Leipzig, Vienna	H: 1992–2001	Eurostat	City and Metropolitan region; boundaries based on administrative entities (Eurostat NUTS system)	Report
		L: 1992–2001			
		V: 1995–2003			
Pomázi and Szabó 2008	Budapest	2005	-	(Greater) Budapest; boundaries not further specified	Report
Barles 2009 ²	Paris	2003	Eurostat	Paris municipality, metropolitan area and administrative region; boundaries based on administrative areas	Scientific article
Niza et al. 2009	Lisbon	2004	Eurostat	Lisbon city; boundaries based on municipality	Scientific article
Browne et al. 2011	Limerick	1992–2002	Eurostat	Limerick City Region; boundaries based on electoral districts	Scientific article
Rosado et al. 2014	Lisbon	2003–2009	Eurostat	Lisbon Metropolitan region; boundaries based on municipalities (18)	Scientific article

¹ The methodology used is described in Hammer et al. (2003a).

² The study was also published in more detail as report (in French) (Barles, 2007a).

also limits the resource sourcing practices it considers. The only locally sourced resources that the Eurostat method accounts for are biomass, minerals, and fossil fuels, implying that for example local generation of renewable energy is not considered. Additionally, the Eurostat method falls short in comprehensively accounting for local resource sourcing due to its black-box character. The method does not account for processes that occur within the system boundary other than sourcing of abovementioned primary resources, effectively excluding sourcing of secondary resources from the analysis. However, insights into locally sourced resources are of particular importance for sustainable resource management. Locally sourced renewable and secondary resources can replace virgin, non-renewable resources and thus contribute to the transition toward a more circular metabolism that reduces environmental pressures (Agudelo-Vera et al., 2012a). Another shortcoming of the Eurostat method is that it does not differentiate between flows that are associated with the city's resource consumption and resources that only pass through the city. Making this differentiation is essential to avoid that trade-related flows through a city are erroneously included as consumption flows, which would lead to overestimating the actual resource consumption of that city (Niza et al., 2009). Explicating throughput flows is of particular importance for port cities as previous studies have shown that the material flows of such cities are dominated by trade flows (Hammer et al., 2003b; Schulz, 2007).

The research presented in this chapter is motivated by the need for more comprehensive UM research and for the establishment of a comprehensive and standardized MFA method that can inform urban policymakers and planners striving for sustainable urban resource management. The objective of this chapter is twofold:

- I. to gain insights into the UM of Amsterdam by performing an MFA employing the Eurostat method;
- II. to identify modifications to the Eurostat method that will enhance the performance of this method for comprehensive UM analyses.

This chapter is structured as follows. First, the case study is introduced. Second, the Eurostat MFA is introduced, results of the Amsterdam MFA are presented and benchmarked against other European cities. Third, the modified Eurostat MFA is presented and the findings of the Amsterdam MFA employing this modified method summarized, including a comparison with other European cities. Finally, the outcomes of both MFAs are compared to ascertain whether the modified method offers a richer understanding of the UM of Amsterdam.

Figure 2.1: Location of Amsterdam in Europe and The Netherlands, and boundaries of Amsterdam municipality

Table 2.2: Amsterdam – key statistics (2012) (CBS, 2015; City of Amsterdam, 2013; KNMI, 2011)

Indicator	Unit	Value
POPULATION	(number)	790,000
LAND AREA	(km ²)	219
POPULATION DENSITY	(ca/km ²)	3,607
GDP	(million euros)	56,912
CLIMATE ZONE		Moderate maritime climate (Cf-climate)
ANNUAL PRECIPITATION	(mm/year)	900–925

2.2 Introduction to the Amsterdam case

This research departs from a case study of Amsterdam, the capital of The Netherlands (see figure 2.1 for the location and table 2.2 for key statistics of the city). An earlier study of Amsterdam's metabolism (Gorree et al., 2000) showed that the UM is dominated by water flows (table 2.3). Water, fossil fuels, and oxygen account for over 95% of all inputs. Outputs are dominated by emissions of water and CO₂. The analysis did not employ the Eurostat method, but specified Amsterdam's inputs and outputs according to ten sectors.⁸ The 1998 MFA also has its limitations. The analysis, for example, excluded port-related material flows. Another limitation is that the majority of findings are rough estimations based on indirect data rather than data specific to Amsterdam.

Table 2.3: Summary of the 1998 Amsterdam MFA (based on Gorree et al. 2000)

	Input	Accumulation	Output
Total	138,431	1802	136,824
Drinking water	99,402		27,651
Building materials	1,548		
Industrial materials	4,401		
Fossil fuels	2,691		34
Products	836		4,128
Waste	253*		681
Storm water	22,000		
O ₂	7,553		
Water losses/effluent			94,695
CO ₂			7,732
H ₂ O from combustion			1,511
Other emissions			392

*Includes imported waste only

⁸ The following ten sectors were considered: industry, gas, water, electricity, transport, building and construction, consumers, offices, waste treatment, and sewage treatment.

2.3 Eurostat MFA

2.3.1 Method

The Eurostat method that Hammer et al. tailored for the urban scale (Hammer et al., 2003a; Hammer and Giljum, 2006), was selected to perform the MFA of Amsterdam. This method was chosen because Hammer et al. adapted the original Eurostat method to a limited extent; they merely explicated terminology so that the Eurostat method could be applied to cities and regions. Moreover, because it was the first Eurostat application on the urban scale, later urban studies build on this work. It is also the only Eurostat-based urban method that has been applied to more than one city. In the following, we will refer to this method as ‘urban Eurostat method’. The method considers only flows that enter or originate from economic processes (production, consumption) as inputs and outputs of the system. Moreover, processes that take place within the system are not specified - the system is studied as ‘black box’. Figure 2.2 and table 2.4 specify the flows and indicators considered by the urban Eurostat method. For Amsterdam, we calculated local extraction, imports, exports, and a physical trade balance (imports minus exports) in kilotons (1 kt = 106 kilograms), which is consistent with Hammer and Giljum (2006). Also in line with the method, the system boundaries of the Amsterdam case study correspond to those of an administrative entity, the Amsterdam municipality (figure 2.1). The year 2012 was chosen as the base year for the study because this was the most recent year for which reasonably complete datasets were available (see Supplementary material S1 for more insights on the datasets).

Figure 2.2: Material flows according to urban Eurostat method (based on Eurostat 2001)

Table 2.4: Definitions of terminology used by Eurostat (based on Eurostat 2001; Hammer et al. 2003a)

Term	Definition
Unused local extraction	Materials that were moved during extraction of resources, but do not enter the economic system; they are considered to have no economic value (e.g. residuals from agricultural production).
Local extraction	Materials that are extracted (through mining or agricultural production) from the natural environment within the geographical boundaries of the system and that enter the economy.
Imports	Flows coming from another socioeconomic system.
Flows to nature	Flows that leave the economy and enter the environment.
Exports	Material flows that leave the system, feeding another economy.
Indirect flows	Upstream resources that were required to harvest, process, and transport imported and exported resources.
Material accumulation	Addition of stock to the system when inputs exceed outputs.
DMI	Direct Material Input: the total amount of direct material inputs that have economic value. DMI equals local extraction plus imports.
DMC	Domestic Material Consumption: the total consumption of direct material flows of an economy. DMC equals DMI minus exports.

To facilitate interpretation of the findings, the results of the Amsterdam MFA were benchmarked with Hamburg and Vienna⁹ (Hammer and Giljum 2006). Because the MFAs of Hamburg and Vienna have the base year 2001, the results of all three MFAs were normalized for the Gross Domestic Product (GDP) in the base year of each study. Also, the indicators Direct Material Input (DMI) and Domestic Material Consumption (DMC) were used for comparison, normalized per capita and per GDP.

2.3.2 Results of the Urban Eurostat MFA

The results of the MFA employing the urban Eurostat method show that fossil fuels and fossil-fuel products dominate the material balance of Amsterdam, representing 58.3% of total imports and 61.0% of total exports (table 2.5). The predominance of fossil fuels reflects that the trans-shipment of coal and refined oil products is one of the main activities of the Port of Amsterdam. The port is the world's largest gasoline port and Europe's second largest coal port (Port of Amsterdam, 2012a)¹⁰. The comparison of Amsterdam's material flows with those of Hamburg and Vienna (material flows/GDP) confirms that this is specific to Amsterdam (table 2.5).

Further, the benchmark shows that Amsterdam's total imports and exports as well as its DMI/GDP are similar to those of Hamburg, which also has an extensive harbor area largely located within the city's administrative boundaries. The differences between the two cities in the types of materials imported and exported show that the cities' ports differ in their core activities. For instance, the amounts of Hamburg's imports and exports of 'other industry products' are four times

⁹ Hammer et al. (2003a) also studied the UM of Leipzig using this method, but this MFA was excluded from the comparative analysis because it was conducted at the metropolitan scale level.

¹⁰ The MFAs only take into account the material imports and exports attributed to the port area that is located within Amsterdam municipality. However, the Port of Amsterdam as an entity covers the entire port region, including the ports of Zaanstad, Beverwijk, and IJmuiden.

Table 2.5: The UM of Amsterdam according to the urban Eurostat MFA (in kt) and compared with Hamburg and Vienna for material flows, DMI, and DMC (t/GDP)

	Amsterdam		Hamburg	Vienna
Base year of study	2012		2001	2003
City characteristics in base year of study				
Population	790,000		1,726,000	1,590,000
Land area (km²)	219		755	415
Population density (capita/km²)	3,607		2,286	3,831
GDP (million euro)	56,912		70,994	56,728
GDP/capita (euro)	72,041		41,132	35,678
MATERIAL FLOWS				
	(kt)	(t/GDP)	(t/GDP)	(t/GDP)
Inputs				
TOTAL LOCAL EXTRACTION	24	0.4	2.5	4.6
Biomass	24	0.4	2.1	2.8
Agricultural	3	0.0	1.4	2.5
Forestry	4	0.1	0.1	0.3
Grazing	17	0.3	0.6	-
Fishery	-	-	-	-
Minerals	-	-	-	1.8
Metal ores	-	-	-	-
Industrial minerals	-	-	-	-
Construction minerals	-	-	-	1.8
Fossil fuels and fossil products	-	-	0.4	-
Coal	-	-	-	-
Crude oil	-	-	0.4	-
Natural gas	-	-	-	-
TOTAL IMPORTS	82,322	1,446	1,415	444
Biomass and biomass products	10,177	179	235	51
Total ores and industrial minerals	12,631	222	352	132
Fossil fuels and fossil products	48,025	844	294	153
Chemical products	5,827	102	113	10
Other industry products	4,533	78	318	-
Other imports	1,129	20	104	98
Outputs				
TOTAL EXPORTS	69,583	1,223	1,219	309
Biomass and biomass products	10,083	177	217	32
Total ores and industrial minerals	9,644	169	282	91
Fossil fuels and fossil products	42,420	745	183	89
Chemical products	1,988	35	146	17
Other industry products	4,199	74	295	-
Other exports	1,250	22	95	80
Physical trade balance				
	12,738			
Biomass and biomass products	94			
Ores and industrial minerals	2,987			
Fossil fuels and fossil products	5,605			
Chemical products	3,839			
Other industry products	334			
Other exports	-121			
INDICATORS				
DMI/GDP (t/million euro)	1,491		1,417	449
DMI/capita (t)	104		58	16
DMC/GDP (t/million euro)	231		198	140
DMC/capita (t)	16		8.2	5.0

those of Amsterdam owing to Hamburg's specialization in container traffic (Merk and Hesse, 2012). Moreover, both Amsterdam and Hamburg have a higher DMC/GDP than Vienna, which may be explained by the medium to long-term storage of large shipments of bulk materials in these harbour cities. Because the MFA is a yearly analysis, port-related bulk storage that extends across different years (for instance materials imported in 2012 and exported in 2013) appears in the material balance as consumption or addition to stock. This implies that the material balance of a port city with substantial storage facilities, such as Amsterdam, can show a rather high DMC as a result of material storage for periods extending over different years. The effect of this long-term storage on the yearly material balance can only be addressed by means of longitudinal studies over several years. In spite of the similarities in the UM of Amsterdam and Hamburg, Amsterdam has less than half the number of inhabitants of Hamburg, resulting in a DMI/capita and DMC/capita that are about twice that of Hamburg.

2.4 Modified Urban Eurostat MFA

2.4.1 Method

A literature review and stakeholder consultations were used to identify potential modifications to the urban Eurostat method that will enhance the performance of this method for comprehensive analyses of the UM. We first reviewed the five exclusively Eurostat-based European studies (Barles, 2009; Browne et al., 2011; Hammer and Giljum, 2006; Niza et al., 2009; Rosado et al., 2014). These studies examined six different cities (locations shown in figure 2.1). We then modified the original Eurostat resource classification in the light of insights obtained from the literature review. To verify the proposed modifications we organized stakeholder workshops. Representatives from academic, societal, and industry partners¹¹ were grouped according to their expertise, each group focusing on one of the four main types of resources (organic materials, inorganic materials, water, and energy). The groups then discussed the modified resource classification and evaluated its completeness and appropriateness for the Amsterdam case. Subsequently, the stakeholder input was processed and the resulting resource classification was used during data collection. Insights that arose during data collection and processing were shared in a subsequent meeting and the classification was updated accordingly. The process resulted in seven modifications to the urban Eurostat method (summarized in figure 2.3 and discussed below). Finally, the modified method was used to quantify the 2012 UM of Amsterdam.

¹¹ Affiliations of the stakeholders involved were: AEB Amsterdam, City of Amsterdam (Department of Urban Planning and Sustainability); Delft University of Technology (Engineering Systems and Services, Water Management); Port of Amsterdam; Waag Society, institute for art, science and technology, Amsterdam; Wageningen University and Research Centre (sub-department of Environmental Technology; Laboratory of Geo-information Science and Remote Sensing; Landscape Architecture Group; LEI research institute); Waternet.

Figure 2.3: Resource flows according to the modified urban Eurostat method

A full comparison of the findings of the modified MFA with Vienna and Hamburg was not feasible due to the lack of similar MFAs of these two cities. Instead, the amount of locally generated renewable energy (in total, per GDP, and per capita) for 2012 (Hamburg) and 2011¹² (Vienna) was used as an exemplary category for benchmarking the cities on the basis of the modified MFA method.

2.4.2 Data

Almost all resource flows of the modified resource classification could be quantified using reliable datasets containing local data on Amsterdam for 2012 (see supplementary material, S1.1). To identify and obtain these datasets, the stakeholders' commitment and workshops played a crucial role. Industrial and construction waste, however, could not be quantified because no data were accessible. Apart from CO₂ emissions, detailed information on emissions was not available either. This made it unfeasible to quantify all flows to nature. Consequently, net addition to stock could not be calculated. To enable comparison between the different resource flows, all flows were expressed in the same unit (kiloton), which is also the most widely used unit in (urban) Eurostat MFAs. Locally sourced energy was expressed both in kilotons and Joules, because the latter is the most appropriate metric for energy. To convert locally sourced energy from Joules to tonnes, we used tonnes of oil equivalents (toe)¹³.

¹² No 2012 data were available for Vienna.

¹³ One tonne of oil equivalent (toe) equals 41.868 Gigajoules (GJ).

2.4.3 Modifications

1. Including drinking water and wastewater flows

In order to gain comprehensive understanding of an UM, drinking water and wastewater flows must be accounted for. Indeed, Eurostat (2001) advises quantifying water flows, but presenting these separately from the other material flows because of the magnitude of these flows. None of the reviewed UM studies, however, included drinking water and wastewater flows in their analysis. The modified urban Eurostat method therefore incorporates drinking water and wastewater flows in the resource classification.

2. Accounting for storm water and groundwater entering the sewer

Stakeholders pointed out that not only drinking water and wastewater should be quantified, but storm water that enters the combined sewer as well as groundwater seeping into the sewer¹⁴ should also be accounted for. Both flows increase the amount of wastewater entering the socioeconomic system at wastewater treatment plants. These flows are therefore considered local sourcing of resources¹⁵.

3. Incorporating renewable energy (local sourcing, import, export)

Another category of locally sourced resources¹⁶ included in the modified urban Eurostat classification is renewable energy. The urban Eurostat method includes only fossil fuels and fossil-fuel products (including electricity) as energy flows. At present, however, generating energy from renewable sources is at the forefront of “green” agendas of most Western cities and these internally generated flows are crucial when aiming to reduce urban environmental pressures. Hence, it is essential to include renewable energy in the modified method.

4. Categorizing waste according to its origin, type, process, and location of treatment

Both literature and stakeholders indicated that a detailed classification of waste flows is desirable. Barles (2009) emphasizes that the original Eurostat method falls short of providing insight into urban waste generation because urban waste treatment is often located outside the municipal boundaries, which means that waste is classified as an export. Therefore, Barles (2009) proposes categorizing exported waste explicitly and indicating the share of the exported waste that is recycled (external recycling). Browne et al. (2011), Niza et al. (2009), and Rosado et al. (2014) introduced waste

¹⁴ Because many of the Amsterdam sewers are below the water table and pipes can crack, groundwater seeps into the sewer system.

¹⁵ Although ‘local extraction’ is a suitable category in which to include new categories of locally sourced primary resources, ‘local extraction’ is an inappropriate term to describe local renewable energy generation, which is one of the additional categories. Therefore the ‘local extraction’ has been renamed ‘local sourcing of primary resources’ in the modified urban Eurostat method.

categories that refer to the type of waste. Additionally, Niza et al. (2009) provide an analysis of the waste composition and waste treatment (recycling, incineration, controlled landfill). Stakeholders pointed out that it is relevant to indicate whether waste is locally generated or imported, because Amsterdam's waste incinerator treats waste from other municipalities in The Netherlands and from abroad. The modified method categorizes waste according to its origin (imported versus locally generated), type (municipal solid waste, industrial waste, construction and demolition waste, other waste), treatment method (landfilling, incineration without energy recovery, incineration with energy recovery, recycling, composting, anaerobic digestion, method unknown) and destination location of treatment (local treatment versus export for treatment outside the system).

5. Incorporating recovered materials and energy from waste as a local sourcing category

Materials and energy recovered from local treatment processes are included in an additional local sourcing of secondary resources category. This modification ensures that practices for sourcing secondary resources other than recycling, namely energy recovery from incineration and organic materials from composting and anaerobic digestion, are revealed. These practices have to be accounted for, as they are essential processes in making the transition toward a more circular urban metabolism and sustainable cities.

6. Classifying import and export flows in less aggregated categories

We agree with Rosado et al. (2014) that the Eurostat representation of imports and exports in six categories too broad. Presenting the MFA results in this aggregated manner hampers interpretation of the findings and comparative analysis with other cities. To increase the usability of the MFA results for informing sustainable urban resource management practices and policies, the modified urban Eurostat method presents resource flows in less aggregated categories. Import and export are described in 32 categories instead of six.

7. Explicating throughput flows

Niza et al. (2009) and Rosado et al. (2014) discuss the issue of "flows crossing through" the city of Lisbon in their MFAs. Explicating trade-related flows that are not consumed nor processed within the city but simply pass through the city (throughput), can help to avoid overestimation of local resource consumption. Nevertheless, excluding throughput flows entirely from the MFA (e.g. Niza et al. 2009) or only stating the combined overall amount of throughputs (e.g. Rosado et al. 2014) results in an incomplete picture of the UM. Therefore, the resource classification of the modified urban Eurostat method explicates for each resource flow what share of the import is exported at

the same quality during the same year. This share is labelled as throughput. This modification is in particular important for port cities such as Amsterdam where throughput flows are key to the city's economy.

2.4.4 Results of the Modified Urban Eurostat MFA

The results of the modified urban Eurostat MFA (see table 2.6) show that the material balance of Amsterdam is dominated by throughput flows. About 77% of imported fossil fuels and fossil-fuel products, for example, are throughput (see figure 2.4). A share of the remaining 23% of imported fossil fuels may also pass through the city without being used. Fossil fuels are namely stocked in the harbour for lengthy periods of time, causing export to occur in a later year than import. Because import and export take place in different years, these flows are not labelled as throughput. Among the imported fossil fuel that is utilized locally, is coal that feeds the coal-fired power plant in Amsterdam. The electricity generated by that plant exceeds local consumption, making the city virtually self-sufficient in terms of electricity generation and a net exporter of electricity.

Similar to fossil fuels and fossil-fuel products, the main share of biomass and ores & industrial minerals flows cannot be ascribed to local consumption. The MFA reveals that 81% of biomass imports and 47% of ores & industrial minerals imports are throughput flows to the hinterland. These throughput flows result from port activities, considering that the Port of Amsterdam primarily handles (besides fossil fuels) bulk shipments related to minerals, recycling, and agri-bulk (Port of Amsterdam, 2012b). These bulk shipments amount to 8,267 kt of imports and 6,404 kt of exports of industrial/ construction minerals (for example stone, sand, and gravel) and to large flows of plant and animal products, which mainly consist of raw materials for fodder.

In the modified urban MFA study, major additional inputs and outputs appear as a result of the inclusion of water flows (shown in more detail in figure 2.5). Water imports amount to a total of 81,354 kt, the same order of magnitude as all other imports combined. The input side reveals two sources for drinking water: water that is imported at drinking water quality and pre-treated water that is processed by the drinking water treatment plant within the municipality to produce drinking water. The drinking water exports comprise water that this treatment plant supplies to nearby municipalities (6,858 kt) as well as drinking water that is distributed via the Amsterdam drinking water network to these municipalities (throughput of 5,438 kt). About 92% of the drinking water distributed in Amsterdam ends up at the two wastewater treatment plants, due to non-revenue water and household losses¹⁶. In addition, the influent of the wastewater treatment plants consists

¹⁶ Non-revenue water includes leakage from the drinking water distribution system and drinking water used as fire extinguishing water; household loss includes water used for watering plants and evaporation from laundry and cooking.

Table 2.6: Results of the MFA Amsterdam 2012 using the modified urban Eurostat method - findings are structured according to the resource classification of this method (summarized in figure 2.3)

	INPUT		INTERNAL FLOW		OUTPUT	
	(kt)	(TJ)	(kt)	(TJ)	(kt)	(TJ)
LOCAL SOURCING OF PRIMARY RESOURCES (input) & SECONDARY RESOURCES (internal flow)	19,014		675			
Water	18,965					
Storm water inflow into sewer	12,483					
Groundwater infiltration into sewer	6,482					
Biomass	24					
Agricultural	3					
Forestry	4					
Grazing	17					
Fishery	-					
Minerals	-					
Metal ores	-					
Industrial minerals	-					
Construction minerals	-					
Fossil fuels	-					
Coal	-					
Crude oil	-					
Natural gas	-					
Renewable energy	25	1,010	58	2,408		
Electricity	14	572	46	1,929		
Wind energy	14	560				
Solar energy: PV	0	12				
Incineration of green waste			44	1,846		
Biogas combustion			2	83		
Heat and cold	11	438	12	479		
Solar heat	n.a.	n.a.				
(Geo)thermal	7	288				
Incineration of green waste			6	231		
Biogas combustion			5	214		
Biomass-fuelled stoves and boilers			1	34		
Cold extracted from surface water	4	150				
Fuels	0	0				
Hydrogen	0	0				
Recovered materials & energy from waste			617			
Materials			403			
Rubber products			30			
Metals			25			
Non-metal minerals			344			
Fertilizer			4			
Electricity and heat			44	1,842		
Electricity from waste incineration			39	1,633		
Heat from waste incineration			5	209		
Fuels			170	7,138		
Fuel pellets from industrial waste			60	2,512		
Biodiesel (second generation)			110	4,605		
Green gas from sludge digestion			0	21		

Table 2.6 continued

	INPUT (kt)	INTERNAL FLOW (kt)	OUTPUT (kt)
IMPORT / THROUGHPUT / EXPORT	163,742	61,873	81,967
Piped water	81,354	5,438	12,296
Industry water	1,932	-	-
Drinking water	71,098	5,438	12,296
Pre-treated	24,978	-	-
Treated	46,120	5,438	12,296
Wastewater (untreated)	8,324	-	-
Biomass and biomass products	10,246	8,339	10,111
Agricultural and Fishery	9,672	8,117	9,700
Crops	1,114	843	951
Plant and animal products	8,504	7,245	8,720
Leather and clothing	54	29	29
Forestry	539	222	397
Raw wood, cork, and rubber	311	115	275
Wooden, cork, and rubber (semi-manufactured) products	41	0	1
Paper and board	152	107	107
Sewage sludge	35	-	14
Ores and industrial minerals	12,631	5,937	9,644
Metal ores	262	184	428
Metallic (semi-)manufactured products	1,720	734	2,324
Industrial and construction minerals	8,267	4,532	6,404
Building materials	2,383	486	487
Fossil fuels and fossil products	48,019	37,025	42,470
Solid fuels	15,501	10,802	10,802
Hard coal and derivatives	15,318	10,771	10,771
Peat and derivatives	183	31	31
Liquid and gaseous fuels	32,478	26,223	31,668
Crude oil and derivatives	31,701	26,223	31,668
Natural gas	777	0	-
Other: heat	40	0	-
Chemical products	5,827	1,760	1,988
Cellulose and paper waste	361	52	268
Chemical raw materials	4,723	1,119	1,130
Chemical products	743	590	590
Other industry products	4,017	2,873	4,190
Machines and vehicles	1,098	804	898
Other goods	2,919	2,069	3,293
Waste	516	-	9
Municipal Solid Waste	516	-	9
To be landfilled	-	-	0
To be incinerated with energy recovery	516	-	2
To be recycled	-	-	7
Industrial Waste	n.a.	n.a.	n.a.
Construction and Demolition waste	n.a.	n.a.	n.a.
Other	n.a.	n.a.	n.a.
Other import/export	1,132	501	1,259
Fertilizers	868	366	1,102
Renewable electricity	1	-	9
Cold extracted from surface water	2	-	-
Unknown	261	135	148

Table 2.6 continued

	INPUT (kt)	INTERNAL FLOW (kt)	OUTPUT (kt)
LOCAL WASTE TREATMENT		1,625	
Municipal solid waste		926	
Incinerated with energy recovery		889	
Household waste locally generated		272	
Commercial waste locally generated		21	
Imported waste		516	
Sewage sludge		80	
Recycled		34	
Composted		-	
Anaerobically digested		3	
Industrial waste		699	
Incinerated with energy recovery		599	
Anaerobically digested		100	
Other		n.a.	
Construction and Demolition waste		n.a.	
Other		n.a.	
FLOWS TO NATURE			92,737
Emissions to air			4,712
CO ₂			4,712
Waste landfilled			-
Emissions to water			83,256
Treated wastewater discharge			81,324
Industry water			1,932
Dissipative flows			4,769
Drinking water			4,769
Non-revenue water			2,730
Household loss			2,039

Note: “o” is a rounded number, whereas “-” means not existing and “n.a.” means not assessed. Locally sourced secondary resources and locally treated waste are presented as internal flows within the socio-economic system to avoid double counting. All sewage sludge is stated as the weight at 21% dry matter content, which is the final weight after dewatering. Locally produced biofuel does not appear as an export because it is blended with fuels from fossil-fuel origin and is accounted for in the category “crude oil and derivatives”.

of 8,324 kt wastewater generated outside Amsterdam and 18,704 kt water that originates from storm water inflow and infiltration of groundwater into the sewer. After treatment, water is discharged to surface water (flow to nature).

Almost all municipal solid waste generated within Amsterdam is incinerated locally at the waste-to-energy plant. In 2012, this plant incinerated 293 kt locally generated household/commercial waste and 516 kt municipal solid waste from outside Amsterdam. A total of 192 kt waste was imported from adjacent municipalities and 324 kt from abroad. In addition, 599 kt industrial waste was incinerated. Recycling of municipal solid waste occurs mainly outside Amsterdam (34 kt locally recycled versus 7 kt exported to be recycled), whereas anaerobic digestion takes place within Amsterdam. The latter predominantly comprises digestion of sewage sludge and biogenic industrial waste. This process yields biogas that is used for the production of an equivalent of 83 TJ electricity and 214 TJ heat, as well as 4 kt fertilizer.

Figure 2.4: Overview of energy flows in the Amsterdam UM;

a. including throughput, b. a zoom-in, excluding throughput and bulk storage (in TJ)

Furthermore, the modified urban MFA shows that in 2012 the equivalent of 24 kt biomass, 83 kt (3,418 TJ) renewable energy, and 617 kt secondary resources were sourced locally. They appear as relatively small flows because the large volumes of imports and exports dominate the overall picture. Local biomass extraction, for example, amounts to as little as 0.2% of the total biomass import while it does equal 18% of the net biomass import. Likewise, the renewable energy sourced locally equals as much as 7% of the electricity and gas consumed in Amsterdam. Of the 12,398 TJ energy generated locally, about 8% (1,010 kt) is generated on the basis of biophysical flows (from water, wind, solar, and geothermal energy), 19% (2,408 kt) is derived from biomass, and the remaining 72% (8,980 kt) originate from secondary resources.

The comparison with Vienna and Hamburg (see table 2.7) shows that the total amount of renewable energy generated in Amsterdam is relatively low and that the cities use renewable energy from different sources. However, normalized per inhabitant, Amsterdam generates an equal amount as Vienna and two-thirds of the renewable energy generated in Hamburg. In terms of sources, energy generation from biomass is relatively low in Amsterdam, in particular compared with Hamburg. Amsterdam generates a relatively high amount of wind energy, whereas Vienna strongly relies on hydropower. This suggests that Amsterdam's delta location and the presence of the river Danube in Vienna are key explanatory variables for the renewable energy performance of both cities. These findings highlight that city characteristics are valuable to understand a city's UM and to explain metabolic differences between cities.

Table 2.7: Locally generated renewable energy in Amsterdam, Hamburg, and Vienna

Energy source	Amsterdam	Hamburg	Vienna
Renewable energy (TJ)	3,384	11,329	7,239
Electricity	2,501	6,149	4,586
Wind energy	560	294	42
Solar energy: PV	12	184	-
Incineration of biomass and green waste	1,846	4,887	585
Biogas and landfill gas combustion	83	782	36
Hydropower	-	2	3,923
Heat and cold	883	4,887	2,653
(Geo)thermal	288	-	-
Incineration of biomass and green waste	231	4,887	2,653
Biogas combustion	214	-	-
Cold extracted from surface water	150	-	-
Other	-	293	-
Renewable energy per GDP(GJ/million euros)	59	123	93
Renewable energy per capita (MJ/capita)	4,284	6,532	4,182

Note: "0" is a rounded number, whereas "-" means not existing. The category "biomass-fuelled stoves and boilers" is excluded from the Amsterdam results because it is also not considered for Hamburg and Vienna. For Hamburg only energy totals for biomass incineration were known; half was allocated to electricity and half to heat.

Figure 2.5: Overview of water flows in the Amsterdam UM (in kt, excluding industry water)

2.5 MFA comparison and discussion

In this section, the results of the two MFAs are compared on the basis of the modifications made to improve the urban Eurostat method. Moreover, findings are discussed in light of the 1998 MFA of Amsterdam (Gorree et al., 2000). The comparison of the urban Eurostat MFA and the modified MFA shows that the latter quantified a large amount of additional inputs and outputs. This is mainly due to the inclusion of drinking water and wastewater in the modified MFA. Accounting for storm water and groundwater entering the sewer increased the total amount of locally sourced resources by more than 800 times. The results of the modified MFA confirm the finding of the 1998 MFA (Gorree et al., 2000) that water flows make up a significant share of Amsterdam's metabolism. In comparison with 1998, the input of industry water increased by about one-third (1,932 kt in 2012 versus 1,540 kt in 1998), whereas drinking water consumption decreased from 63,632 to 56,074 kt, despite a population increase of 72,000 people. The amount of treated wastewater also decreased (from 82,400 to 81,324 kt), but the difference is much less because in 2012 additional wastewater imports took place.

With the inclusion of locally generated renewable energy, the MFA now provides insight into biophysical flows and geochemical processes that are starting to sustain the local economy. Although these additional local sourcing categories resulted in relatively small changes in the overall balance for 2012, Amsterdam's internal sourcing of renewable energy is likely to increase in the near future. It is the city's ambition to increase the amount of per capita generation of renewable energy by 20% in 2020, compared to 2013 (City of Amsterdam, 2014). Such ambitions support the need to account for renewable energy as standard flow in UM analyses (see also Kennedy et al. 2014). To improve the integration of biophysical processes that support a system's economy into MFA, the definition of system boundaries is an important issue to be addressed. Emergy-based analysis may offer a relevant framework in this regard. As the emergy¹⁷ synthesis of Beijing shows (Zhang et al., 2009), the socioeconomic system is considered a subsystem embedded in the whole "urban metabolic system". This system definition acknowledges that cities require the biophysical environment within and outside of their administrative boundaries to sustain their metabolism. When aiming for a circular UM, it is crucial to take such a systems perspective and to acknowledge that the densely populated space within urban administrative boundaries is insufficient to realize self-sufficiency.

The advanced classification of waste flows allows comparison of Amsterdam's 2012 waste flows with those of 1998 (Gorree et al., 2000). This comparison shows that the household waste generated in

¹⁷ Emergy is defined as the total amount of solar energy that is used directly and indirectly to make a product or a service (Odum 1996). Emergy-based analyses use solar equivalent joule as a common metric (SEJ).

Amsterdam decreased from 308 kt to 272 kt, equivalent to a decrease from 429 kg/ca to 344 kg/ca. Nonetheless, over the past 14 years the amount of recycled municipal solid waste increased only slightly, from 39 kt to 41 kt. The waste imported from adjacent municipalities is in the same order of magnitude for both years. Yet, in 1998 no waste was imported from abroad and the amount of industrial waste incinerated was less than half the amount in 2012 (259 versus 599 kt).

Explicating sourcing of secondary resources from internal waste treatment processes increases understanding of the metabolic processes occurring within the system boundary. Cases were identified in which synergetic resource recovery solutions have been implemented, such as the conversion of biogas derived from wastewater sludge digestion into electricity and heat. This example confirms that including water and wastewater in the UM analysis and increasing the transparency of the system is critical to reveal the potential to source secondary resources.

Due to the more specific classification of flows, the modified urban Eurostat MFA provides more detailed information on Amsterdam's metabolism than the urban Eurostat MFA. This detailed classification enables a more thorough analysis of which material flows affect the material balance of a city, emphasizing case-specific consumption and production processes, and allows for a more in-depth comparison of cities. Although the detailed classification proved useful for identifying city characteristics that cause metabolic differences between cities, benchmarking cities on their degree of sustainable resource management also requires new performance indicators. These indicators should, for example, explicate what share of DMIs and consumptions is non-renewable and what share is renewable. A distinction should be made between Direct non-renewable Material Inputs/Consumption (DnMI/DnMC) and Direct renewable Material Inputs/Consumption (DrMI/DrMC).

Indicating throughput flows helped to reveal that Amsterdam's material balance shows the so-called "Rotterdam-Antwerp effect" (Peffekoven, 1994). This means that materials are attributed as imports and exports to port cities, even if these cities are not the final destination of those materials but rather a transit location where materials are discharged and transhipped. This knowledge is of special value to local decision-makers because it reveals that the metabolism of the city is dominated by trade flows instead of consumer-related consumption flows. More importantly, it brings to the attention that the envisioned increased circularity (the "circular economy") of Amsterdam will affect the metabolism of the city only to a limited extent. In the transition towards a circular economy and a sustainable metabolism, it is therefore important to take the harbour and its trade-related flows into consideration.

2.6 Conclusions and Recommendations

The first objective of this research was to gain insight into the UM of Amsterdam by performing an MFA of this city. The results of this case study show that Amsterdam's metabolism is dominated by water flows and port-related throughput of fossil fuels and fossil-fuel products. Although the city's environmental pressure has decreased since 1998 in terms of per capita waste generation and drinking water consumption, the majority of the city's municipal waste is still incinerated.

The second objective of this research was to enhance the performance of the Eurostat method for comprehensive UM analyses. On the basis of the Amsterdam case study, we can conclude that the findings of the modified urban Eurostat method provide a deeper understanding of a city's metabolism than those of the original urban Eurostat MFA. This modifications resulted in (at least) three benefits. First, the adjustments and additions to the resource classification result in an MFA that presents a more complete image of resource flows. The modifications result in 23 additional local sourcing categories and a significant amount of additional inputs and outputs to Amsterdam's material balance. Second, the modified resource classification presents findings in more detail. Benchmarking selected results showed that this can be valuable for interpreting the MFA findings and identifying explanatory variables for metabolic differences and similarities between cities. Third, explicating throughput flows reveals a much-improved insight into the nature of a city's imports, exports, and stock. In cases of harbour cities such as Amsterdam, it can disclose the significance of port-related flows and long-term harbour stocks on the overall material balance of the city.

In order to support decision-makers in bringing about a transition toward a more circular urban metabolism, additional work will be required. This work includes analyses of how much of a city's resource demands can be met by local sourcing. In other words, the potential of key biophysical and geochemical processes within the city as well as the potential of stocks to serve as urban mines have to be determined. Another important challenge for future research is to unravel the urban metabolism within the "black box", to provide insight both into the temporal and spatial dynamics of resource flows and interconnectedness between flows. High spatial and temporal resolutions will show more precisely where and when resources are present in the system, offering opportunities for coupling demand and supply and optimizing the sourcing of secondary resources. These can be valuable fields of further research to support the planning and design of sustainable urban environments.

Abstract

The research presented here examined at which spatial and temporal resolution urban metabolism should be analysed to generate results that are useful for implementation of urban planning and design interventions aiming at optimization of resource flows. Moreover, it was researched whether a lack of data currently hampers analysing resource flows at this desired level of detail. To facilitate a stakeholder based research approach, the SIRUP tool - “*Space-time Information analysis for Resource-conscious Urban Planning*” - was developed. The tool was applied in a case study of Amsterdam, focused on the investigation of energy and water flows. Results show that most urban planning and design interventions envisioned in Amsterdam require information on a higher spatiotemporal resolution than the resolution of current urban metabolism analyses, i.e., more detailed than the city level and at time steps smaller than a year. Energy-related interventions generally require information on a higher resolution than water-related interventions. Moreover, for the majority of interventions information is needed on a higher resolution than currently available. For energy, the temporal resolution of existing data proved inadequate, for water, data with both a higher spatial and temporal resolution is required. Modelling and monitoring techniques are advancing for both water and energy and these advancements are likely to contribute to closing these data gaps in the future. These advancements can also prove useful in developing new sorts of urban metabolism analyses that can provide a systemic understanding of urban resource flows and that are tailored to urban planning and design.

3.

Space-time information analysis for resource-conscious urban planning and design

A stakeholder based identification of
information needs and data gaps

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a stakeholder based identification of urban metabolism data gaps

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3.1. Introduction

The notion of urban metabolism (UM) has inspired new ideas about how cities can be made sustainable and it has fostered quantitative approaches to the analysis of urban resource flows (Agudelo-Vera et al., 2012a; Castán Broto et al., 2012; Zhang, 2013). UM refers to the processes whereby cities transform raw materials, energy, and water into the built environment, human biomass, and waste (Decker et al., 2000). UM can be traced back to Marx in 1883, who used the term metabolism to describe the exchange of materials and energy between society and its natural environment (Pincetl et al., 2012; Zhang, 2013). In 1965 Wolman re-launched the term as he presented the city as an ecosystem, and later others also used the term UM in representing a city as an organism (Barles, 2010; Castán Broto et al., 2012; Pincetl et al., 2012; Zhang, 2013). Since Wolman's early study of urban metabolic processes, two distinct quantitative UM approaches have developed that aim to describe and analyse the material and energy flows within cities. One describes the UM in terms of solar energy equivalents ('emergy'). Related school of scholars emphasizes the earth's dependence on the sun as an energy source and the qualitative difference of mass or energy flows. The second and most widely used approach, is associated with the fields of industrial ecology and engineering (Barles, 2010; Castán Broto et al., 2012; Pincetl et al., 2012). Related research largely consist of empirical studies that account for the energy and material/mass flows of a city, using methods such as material flow analysis (MFA), mass balancing, life cycle analysis (LCA) and ecological footprint analysis (Castán Broto et al., 2012; Kennedy et al., 2011; Pincetl et al., 2012; Zhang, 2013).

Multiple scholars have argued that the latter type of UM analyses, the flow quantifications associated with the mainstream UM approach, are useful for urban planning and design (Castán Broto et al., 2012; Chrysoulakis et al., 2013; Kennedy et al., 2011; Moffatt and Kohler, 2008; Pincetl et al., 2012). However, these authors also argue that major efforts are still needed to make UM analyses useful for informing urban planning and design aiming at optimization of urban resource flows (Kennedy et al., 2011). Indeed, only three examples of application of UM for designing more sustainable urban infrastructures are referred to in literature (Codoban and Kennedy, 2008; Oswald and Baccini, 2003; Quinn, 2008), of which just one is a peer-reviewed article¹⁸. The only recent scientific contributions on this topic all discuss the planning support system developed in the BRIDGE project (Blecic et al., 2014; Chrysoulakis et al., 2013; Mitraka et al., 2014). In professional literature, some other recent examples can be found. In The Netherlands, research on the resource flows of Rotterdam was conducted and used as a basis for urban design strategies, in the context of the International Architectural Biennale 2014 *Urban by Nature* (Tillie et al., 2014). In the *Circular*

¹⁸ Although Codoban & Kennedy (2008) were the first to refer to Oswald et al. (2003) in this light, Kennedy et al. (2011) were the first to mention all three examples.

Buiksloterham project in Amsterdam an ‘Urban Metabolism Scan’ was performed and used as foundation for a vision for the Buiksloterham area, including site-specific technical interventions and a design concept (Gladek et al., 2015). So, although the theoretical potential of UM analysis for urban planning and design is increasingly addressed in the scientific literature, scientific reports that illustrate how this potential can be realised with practical implementation remain limited thus far.

Possibly, UM analyses are still of limited use for urban planning and design because they are performed on a scale level that does not match urban planning and design practice (Moffatt and Kohler, 2008; Pincetl et al., 2012; Spiller and Agudelo-Vera, 2011). The UM is usually analysed for a period of a year on city or regional scale (Kennedy et al., 2011; Niza et al., 2009); analyses on a more detailed level are said to be hampered by lack of data (Codoban and Kennedy, 2008; Pincetl et al., 2012; Shahrokni et al., 2015). Such large-scale analyses, however, do not reveal which metabolic processes and functions are operating at various spatial and temporal scales. Yet, planners and designers need such information to decide upon the appropriate interventions to realize a resource-conscious strategy. In other words, they need this information to inform their planning and design decision-making regarding interventions aimed at urban climate adaptation, climate mitigation and/or resource efficiency. To be useful for urban planners and designers, UM analyses should thus provide detailed and spatial and temporal explicit data on the scale at which these practitioners work (Chrysoulakis et al., 2013; Golubiewski, 2012; Moffatt and Kohler, 2008; Pincetl et al., 2012; Vandevyvere and Stremke, 2012).

Therefore, the study presented here aims to answer the following questions: (I) “at which spatial and temporal resolution should resource flows be analysed to generate results that are useful for implementation of urban planning and design interventions?” and II) “is UM analysis at this desired level of detail currently hampered by a lack of data?”. To answer these questions, the “*Space-time Information analysis for Resource-conscious Urban Planning*” (SIRUP) tool was developed and applied in a case study of the city of Amsterdam, The Netherlands. The SIRUP tool enables an analysis on two levels: (I) assessing on which level of detail in space and time stakeholders need information on resource flows to inform urban planning and design decision-making aimed at developing resource-conscious strategies, and (II) evaluating whether existing data can provide the information needed or that there is a data gap. The qualitative tool facilitates information and knowledge sharing and discussion between stakeholders. Stakeholder involvement in UM research is essential to leverage availability of and access to urban resource data and it allows identifying the information needs of urban planning and design practitioners (Voskamp et al., 2017).

3.2 Methods and materials¹⁹

3.2.1 Development of the SIRUP tool

The “*Space-time Information analysis for Resource-conscious Urban Planning*” (SIRUP) tool is based on the work of Vervoort et al. (2014), who developed the tool *Scale Perspectives* to elicit societal perspectives and generate dialogue on governance issues. Their tool consists of a frame with pre-defined spatial and temporal scales in which stakeholders can outline the relevant scales for a particular governance issue. For the SIRUP tool, this frame is adapted for the purpose of identifying on which spatiotemporal resolution stakeholders need information on resource flows and for assessing whether existing data can provide this information on the resolution needed (Supplementary material, figure S2.1). The SIRUP tool is applied in four steps (figure 3.1). These steps aim to (I) generate an inventory of UM interventions, (II) determine the information needed for implementing each of these interventions, (III) describe the spatiotemporal resolution of existing data relevant for the intervention and (IV) identify whether the resolution of identified data can satisfy the stakeholders’ intervention information needs.

3.2.2 Application of the SIRUP tool

The SIRUP tool was applied in a case study of Amsterdam. As part of this case study, stakeholders were involved that are engaged with urban planning and design decision-making aimed at developing resource-conscious strategies for the city of Amsterdam. The stakeholders comprised researchers, environmental managers from utilities, landscape architects and urban planning & design practitioners. Eleven of these stakeholders were interviewed, using semi-structured interviews, and thirteen stakeholders participated in a workshop.

Step I and II of the SIRUP tool were used to identify on which spatiotemporal resolution stakeholders need information on resource flows. In step I, the stakeholders were asked to describe a resource-conscious intervention that they envision to be implemented in Amsterdam. Participants were also asked to specify in the SIRUP frame (Supplementary material, figure S2.1) at which spatial scale level the intervention would take places and which time frame they envisioned for implementation. In step II, participants were asked to specify the information needed for implementing the intervention mentioned and to indicate the required spatial and temporal resolution of this information in the SIRUP frame (figure 3.1). The interviewer or workshop facilitator had to ensure that participants described the information on resource flows that is necessary to enable the intervention. Pen-and-

¹⁹ A more elaborate description of the method is provided as Supplementary material (S2, p.192).

Figure 3.1: The four steps of the SIRUP tool

Note: The figure includes as subfigures a schematic representation of the potential outcome of the different steps. The green, red and blue circles/ellipses, rectangles and arrows represent respectively three different information needs, existing data sets and data gaps for a single intervention on the SIRUP frame (in grey). See also Supplementary Material S2.

paper format was used because this allows for greater flexibility than a digital setting (Vervoort et al., 2014). After the workshop, all contributions were digitalized and labelled to enable the selection of interventions that are within the scope of the research. The interventions were labelled according to the type of intervention and the resource flow(s) for which information is needed. We limited the research to spatial and technical interventions aimed at urban climate adaptation, climate mitigation and/or resource efficiency, focussing on energy and water flows because these are strongly related to such interventions (Mitraka et al., 2014; Pincetl et al., 2012) (see also Supplementary Material S2).

In step III a desk study was conducted to identify which data exist on Amsterdam's energy and water flows and to compose an overview of these data, including a description of the spatiotemporal resolution of these data. In the study, data portals, databases and reports were considered that contain open or restricted data on Amsterdam's energy and water flows. Expert consultation was used to identify relevant datasets and to obtain access to restricted datasets. Metadata was described for all datasets obtained, using a format that was based on the ISO 19115 and the INSPIRE, Infrastructure for Spatial Information in the European Community, metadata standards to ensure compatibility with other datasets in the world. The mandatory elements of the metadata standard used were, amongst others, the level of detail of the data in the spatial dimension and in the time dimension, i.e. the spatial and temporal resolution of the data. Moreover, it was required to state the limitations and rules on accessing, use and publishing of the existing data to indicate whether the data is open or restricted (Supplementary material, table S2.1). Based on the metadata-description on spatial and temporal resolution, the datasets were placed in the SIRUP frame (figure 3.1).

In the final step, step IV, the data inventory was used to analyse whether the identified data can satisfy the stakeholders' information needs. For each intervention it was evaluated whether the attributes of each data set were relevant for the information needed. Then, the relevant data and the information needs for the intervention were combined in one SIRUP frame and arrows were drawn from the dataset to the information needed (figure 3.1). When the spatiotemporal resolution of information needs are equal to the resolution of existing data, these exact matches were indicated by a circle (●) in the SIRUP frame. Subsequently, the size and dimension of the arrows were analysed to assess the presence and severity of data gaps. An arrow either indicates a two-dimensional data gap, when both the spatial and temporal resolution of existing data are insufficient, or it indicates a one-dimensional data gap, when either the spatial or the temporal resolution of existing data is lower than required. A two-dimensional data gap is indicated by arrows pointing towards the lower left corner (↙). Arrows pointing downwards or to the lower right corner (↓, ↘) indicate a

one dimensional data gap, in the spatial dimension only. The reason for this is that the arrows indicate that the temporal resolution is equal to or higher than needed. Because aggregation from higher temporal resolution to lower resolution is possible without an information loss, the required temporal resolution can be derived from this information. For example, hourly totals can be derived from data on minute level by summing all available minute data points. Arrows pointing to the left or higher left corner ($\leftarrow$, $\nwarrow$) represent a gap in the temporal dimension only, because the spatial resolution of the data is sufficient or higher than needed. There is no data gap when existing data has either the right resolution in one dimension and a higher resolution in the other or a higher resolution in both dimension, implying that data can be aggregated to get to the required resolution. These matches are indicated by arrows pointing up ($\uparrow$), to the right ($\rightarrow$), or diagonally in the upper right direction ($\nearrow$).

3.3 Results

3.3.1 *Inventory of interventions*

In this case study a total of 52 different interventions were suggested by the stakeholders during the interviews and workshop. We selected fourteen of these interventions for further analysis, namely the spatial and technical interventions for which information on energy and/or water flows is required. The selected interventions have a total of 26 information needs that relate to energy and/or water flows. These information needs were categorized into four different clusters to facilitate interpretation: (I) piped water, including waste water and drinking water; (II) non-piped water, including groundwater, surface water, storm water and rainwater; (III) energy demand; and (IV) energy supply (table 3.1).

3.3.2 *Piped water*

Results show that out of the five information needs related to piped water, two can be met by existing open data and one by restricted data (figure 3.2). Figure 3.2a shows that the information needs that were expressed for piped water are scattered over the SIRUP frame. However, no information needs appear in the lower left corner of the frame, up to 12 hours and district, nor at the highest scale levels, that is metropolitan region and five years and higher. The SIRUP frame of existing data, on the other hand, shows a different pattern (figure 3.2b). In terms of temporal resolution, these data fall in the range ‘minutes’ to ‘one year’. In terms of spatial resolution, open data ranges from the scale of a small neighbourhood to the metropolitan region. Additionally, one restricted access

Table 3.1: The 14 interventions and 26 related information needs that were considered in this research

		Interventions and intervention ID (#)													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Information needs		Converting cellulose in waste into power	Dike reinforcement	More concentrated sewage flows	Park on a brownfield-site	Parking garage as battery	Phytoremediation of green areas	PVs on roofs for public lighting	Rainwater buffering and infiltration	Recovery of protein from sewage	Regional smart grid	Small-scale parks	Usage of cold from drinking water for cooling	Water-robust vital infrastructure	Water square
Piped water	Drinking water quantity	-	-	-	-	-	-	-	-	-	-	-	I	-	-
	Waste water quantity	-	-	I	-	-	-	-	-	I	-	-	-	-	-
	Waste water quality	-	-	I	-	-	-	-	-	I	-	-	-	-	-
Non-piped water	Fluvial flooding risk	-	-	-	-	-	-	-	-	-	-	I	-	-	-
	Groundwater quantity	-	-	-	II	-	II	-	-	-	-	-	-	-	-
	Groundwater quality	-	-	-	I	-	II	-	-	-	-	-	-	-	-
	Intensity and repeat time of extreme rains	-	-	-	-	-	-	-	I	-	-	-	-	-	I
	Surface water level and flow rate	-	I	-	-	-	-	-	-	-	-	-	-	II	-
Energy demand	Household cooling demand	-	-	-	-	-	-	-	-	-	-	-	I	-	-
	Electricity demand of public lighting	-	-	-	-	-	-	I	-	-	-	-	-	-	-
	Total urban electricity demand	I	-	-	-	I	-	-	-	-	I	-	-	-	-
Energy supply	Cooling supply by drinking water network	-	-	-	-	-	-	-	-	-	-	-	I	-	-
	Electricity supply in a regional smart grid	-	-	-	-	-	-	-	-	-	II	-	-	-	-
	Potential electricity supply by PV panels	-	-	-	-	-	-	I	-	-	-	-	-	-	-

Note: '-' means that no information need is expressed in the corresponding category for the indicated intervention; 'I' means that one information need is expressed in the corresponding category for the indicated intervention; 'II' means that two information needs are expressed in the corresponding category for the indicated intervention.

database provides drinking water quantity data on building level. No piped-water data has been identified that has both high temporal and spatial resolution. When the resolution of information needs and existing data are compared, it appears that two information needs can be met: (I) the quantity and (II) the quality of waste water that enters Amsterdam's waste water treatment plants at seasonal up to yearly level (indicated as **O**, figure 3.2c). For the remainder of the data gaps, it shows that the size and dimension of the gaps depend on which existing data source is considered. The drinking water data gaps, for instance, are either two dimensional (**L**), using dataset 3, or with a spatial dimension only (**↓,↘**), when using the open data from source 4 or 6. Yet, with access to restricted datasets, there is a data gap with a temporal dimension only (**←**). Nevertheless, when using the restricted data, the size of the gap in the temporal dimension remains the same as when dataset 3 is used, from 'one year' to 'month'. On the other hand, restricted data can close the data gap regarding waste water quantity at municipal and minute level entirely. Regarding waste water quality, there is a two dimensional data gap when using open data (**L**) and a data gap in the spatial dimension only when using restricted data (**↘**). The size of the gap in the spatial dimension remains equal when restricted data can be used.

3.3.3 Non-piped water

In the case of non-piped water, the spatiotemporal resolution of existing open data meets the resolution of six out of the twelve information needs (figure 3.3). Regarding the resolution of these twelve information needs, a cluster of six shows on the right side of the field at the temporal scales 'quarter of a year' till 'five years' (figure 3.3a). Of the remaining six information needs, four appear in the lower left corner of the SIRUP frame, delineated by week and district. Two of these information needs are rainwater related, the other two relate to groundwater quality and quantity. For these four information needs a data gap exists, because existing rainfall and groundwater data have a lower resolution than required (figure 3.3bc). In the case of groundwater quantity, this is an exception because the resolution of the existing data - small neighbourhood to small district at seasonal level - is sufficient for the other three groundwater quantity related information needs. By contrast, the resolution of groundwater quality data, which is the metropolitan region and one to four year resolution, is insufficient for the two related information needs. Likewise, the resolution of rainfall data - in between municipality and metropolitan region for a day to half a year - is inadequate for all rainwater related information needs. The resolution of existing surface water data is sufficient to meet the three related information needs (**↗,→**). Overall, six data gaps for non-piped water remain, including two data gaps in both dimensions (**L**), one data gap with a temporal dimension only (**↖**) and three gaps with a spatial dimension only (**↓,↘**) (figure 3.3c).

3.3.4 Energy demand

Out of the five information needs on energy demand detected, one can be met by existing restricted data (Figure 3.4). The information need that can be met, electricity demand of a neighbourhood at yearly basis ($\nearrow$), is the only one that is not part of the cluster in the lower left corner of the SIRUP frame, delineated by week and district (figure 3.4a). Existing data sources on Amsterdam's energy demand, on the contrary, primarily provide data on yearly totals, within a spatial range of building to country level (figure 3.4b). The exception to this is a restricted dataset that provides data on the electricity demand of a streetlight per day. Accordingly, for all four information needs in the high-resolution cluster there is a data gap (figure 3.4c). Although these data gaps are similar because they have a temporal dimension only ($\leftarrow, \nwarrow$), they differ in the size of the gap. The data gap is smallest for household cooling demand, from one year to month resolution, whereas the data gap regarding total urban electricity demand is more substantial, from one year to week up to from one year to one hour.

3.3.5 Energy supply

Results for energy supply show that out of the four defined information needs, one can be met by existing open data (figure 3.5). All four information needs appear on the lower half of the SIRUP field, that is a spatial resolution of district level or higher (figure 3.5a). In terms of temporal resolution the information needs cover a larger range, namely from 'seconds' to 'one year'. When the temporal resolution of existing energy supply data is considered, it appears that data is primarily available for yearly totals (figure 3.5b). The exceptions to this are a restricted database that provides electricity supply data on a monthly temporal resolution and open data on drinking water cooling supply with a half yearly resolution. In terms of the spatial resolution of existing data, findings show that open data with a resolution as high as the building level exists. As a result, energy supply related data gaps have a temporal dimension only ($\leftarrow, \nwarrow$) (figure 3.5c). When only open data is considered, the gap for household cooling supply is the smallest, from one year to month resolution. The data gaps regarding total urban electricity demand range from one year to one hour or minutes. These gaps reduce in terms of the number of temporal scale levels to be bridged when there is access to the restricted database of the electricity supply of the waste-to-power plant. The information need that can be met, potential yearly electricity supply by PV panels on neighbourhood level ($\uparrow$), relates to the same intervention for which the energy demand related information need can be met, namely "PVs on roofs for public lighting".

Figure 3.2: Results for piped water

a. information needs; b. existing data; c. data gaps (results of SIRUP step II, III, IV)

Figure 3.3: Results for non-piped water

a. information needs; b. existing data; c. data gaps (results of SIRUP step II, III, IV)

Figure 3.4: Results for energy demand

a. information needs; b. existing data; c. data gaps (results of SIRUP step II, III, IV)

Figure 3.5: Results for energy supply

a. information needs; b. existing data; c. data gaps (results of SIRUP step II, III, IV)

3.4 Discussion

3.4.1 *Patterns in information needs and existing data*

To inform resource-conscious urban planning and design, information on water and energy is required on a higher spatiotemporal resolution than the resolution of current UM analyses. For 12 out of 14 interventions, stakeholders require information on a higher level of detail than the city/region scale and the annual time interval at which UM analyses are currently performed (Kennedy et al., 2011; Niza et al., 2009). In detail, three of the 26 expressed information needs are on the city-annual resolution. Ten information needs have either only a temporal resolution that is higher than annual or only a spatial resolution that is higher than city level, including six information needs on the neighbourhood-annual level. Another 13 information needs are on a high resolution in both the temporal and spatial dimension. The temporal resolution of these information needs is within the range seconds to week and the spatial resolution is between building and district level. The required spatiotemporal resolution appears to be linked to the resource flow targeted by an intervention. The resolution of water related information needs is scattered across the SIRUP frame, including a large range of both low and high spatiotemporal levels, whereas energy related information needs are on a high spatiotemporal resolution.

In contrast, energy-related interventions require information on a high spatiotemporal resolution. Unlike water, decentralisation of energy services is becoming more frequent. This shows, for example, in the increasing penetration of renewable energy in the urban energy system – a consequence of current efforts to decarbonize the urban energy infrastructure (Chu and Majumdar, 2012; Manfren et al., 2011). The two-way flow of energy that comes with this decentralization and the periodicity in both energy demand and in generation of renewable energy, call for a design and management of energy infrastructure that avoids negative impacts on the network, such as fluctuations in voltage or power output (Franco and Salza, 2011; Manfren et al., 2011; Passey et al., 2011). Accordingly, to enable an optimal management of energy generation, distribution and storage, highly detailed data is needed about when and where energy is generated as well as when and where it is required (Manfren et al., 2011). This is evident for the intervention “Regional smart grid” that aims to optimize energy management on the metropolitan scale. To implement this intervention, energy demand and supply data is needed on a spatial resolution of the building up to the district level and a temporal resolution of seconds to one hour.

The inventory of existing data reveals another difference between water and energy flows, namely, in Amsterdam, high-temporal resolution data is available for water but not for energy. This gap

is partly due to diverging data protection policies of water and energy utilities. Our energy data providers indicated that a strict data sharing policy is applied. One of the stakeholders indicated that this is due to their high stakes in the energy market - data have high commercial value in a competitive open energy market. As water utilities operate in a natural monopoly, their data have less commercial value. Further investigation is needed in order to facilitate a more in-depth explanation of these findings. With regard to the inventory of existing data in Amsterdam it should be noted that more sources might exist, especially databases with restricted data. Moreover, the scope of the present research was limited to an analysis of existing data on its spatiotemporal *resolution*. Nevertheless, the usefulness of data for urban planning and design may also be affected by the *accuracy* of the data and the spatiotemporal *extent* of the data, i.e., the geographical area and time period that the data cover. When aiming to compare different datasets on their information value, the SIRUP tool can also be employed to plot datasets according to their spatiotemporal extent.

3.4.2. Implications of data gaps

The findings show that the majority of resource-conscious interventions envisioned in Amsterdam require information on a more detailed spatial and temporal resolution than existing data can provide. Data gaps are absent for four out of the 14 interventions, including three water-related interventions: “Dike reinforcement”, “Recovery of protein from sewage”, and “Water-robust vital infrastructure”. The intervention “PVs on roofs for public lighting” is the only energy-related intervention without a data gap. One should keep in mind that the presence and/or size of data gaps of an intervention can depend on the objective of the stakeholder. The information need of the designer for the intervention “PVs on roofs for public lighting”, for example, was related to a hypothetical demand-supply matching. Namely, supplying a yearly amount of energy by PV panels in a neighbourhood that is equal to the amount used by the streetlights in that area on a yearly basis. When the objective would have been to implement PVs to make the neighbourhood self-sufficient in terms of its electricity for public lighting, a more detailed insight in the temporal differences in electricity supply and demand would be needed to design a reliable energy system. In that case, there would have been a data gap. Overall, the findings seem to imply that water-related interventions face fewer data barriers for implementation compared with energy-related interventions, such as “Parking garage as battery” and “Regional smart grid”. For energy-related interventions, the combination of high-resolution information needs and a lack of (open) data may impair implementation.

It must be emphasised that there are possibilities to close identified water and energy-related data gaps. In both fields technological advancements in sensor technology and modelling are likely

to generate more high-resolution data in the future. For households monitoring, instalment of water smart-meters could yield water consumption data on the building level on a real-time or near real-time basis. These high resolution water demand data can inform both the planning of drinking water and waste water infrastructure (Stewart et al., 2010), such as the intervention “More concentrated sewage flows”. Smart meters could also provide high(er)-resolution energy demand data. The privacy issues that come with the sharing and use of high spatial-temporal resolution smart meter data can be minimized when appropriate data selection and 'privacy friendly' processing techniques are applied (McKenna et al., 2012). For non-piped water too, new high-resolution monitoring systems are being developed. The potential of X-band radar and the microwaves that serve mobile networks as new sources for measuring precipitation on a high resolution is currently being researched (Beek et al., 2009; Fletcher et al., 2013). Furthermore, modelling techniques are advancing fast for both water and energy to provide high time resolution and high spatial resolution data (Fletcher et al., 2013; Widén et al., 2009). To assess the cooling supply of drinking water for the intervention “Usage of cold from drinking water for cooling”, for example, a model that calculates the temperature change of drinking water in the supply system could be used (Moerman et al., 2014). Although models are a simplification of reality and are therefore not fully accurate, the information value of these data may be accurate enough to inform the implementation of interventions. Further investigations are needed to understand which data accuracy is necessary for different resource-conscious interventions and UM analyses, and which data sources can provide data at this level of accuracy. Besides data accuracy, the potential impact of an intervention on the UM as well as the cost-effectiveness of an intervention are two other relevant aspects to consider when aiming to evaluate the feasibility and urgency of closing the different data gaps. These aspects were beyond the scope of this research.

3.4.3 *Disclosing UM knowledge for urban planning and design*

Finally, results indicate that a fine scale approach to UM analyses alone will not suffice to disclose UM knowledge for urban planning and design practice. There is not ONE scale level of analysis that will serve all information needs. Rather than pursuing a linear, fine-scale approach to UM analysis, we suggest that a multi-scale, systemic approach to UM analysis is needed to provide the required information on resource flows from fine to coarse scale levels. The need for a systemic understanding of urban resource flows is supported by stakeholders expressing for half of the interventions that, next to insights on resource flows, information about the urban infrastructure is needed too. One of the stakeholders explicitly indicated that insight in the urban infrastructure is essential to evaluate the effects of an intervention on the functioning of the entire system.

Moreover, this systemic approach should also account for socio-ecological processes that influence the actual resource flows of cities. After all, a better understanding of the multi-scale processes of human-environment interactions that affect this behaviour is essential for sustainable resource management (Pahl-Wostl, 2007). Stakeholder input revealed that insight in biophysical processes underlying the urban system, such as solar irradiation, rain and the infiltration capacity of the soil, is needed for implementing resource-conscious interventions. Indeed, it has been suggested that socio-ecological processes should be accounted for to improve the usefulness of UM analyses for urban planning and design that contributes to the sustainable management of resource flows (Pincetl et al., 2012). UM analyses should describe the complexity of urban systems more accurately, by linking the physical, quantitative knowledge of resource flows to its interaction with (current and historic) environmental, social and economic conditions (Castán Broto et al., 2012; Golubiewski, 2012; Moffatt and Kohler, 2008; Pincetl et al., 2012). In order to disclose UM knowledge for resource-conscious urban planning and design, it is thus of key importance to develop a systemic understanding of urban resource flows. This systemic understanding should provide insight in the socio-ecological processes that affect resource flows and in the interlinkages between processes and resource flows at different spatial and temporal scale levels.

3.4.4 Conclusion

In conclusion, our results suggest that there is not one particular scale level of UM analysis that will generate meaningful results for urban planning and design aiming at optimizing resource flows. The relevant scale of analysis appears to depend on the nature of the intervention and the resource flow targeted. Findings do show that the current resolution of UM investigation, on city level and per year, is of insufficient detail to provide the information that is needed to inform resource-conscious urban planning and design decision-making. Moreover, the spatiotemporal resolution of existing data is a limiting factor for performing UM analyses that provide useful information for implementation of resource-conscious interventions. The SIRUP tool, proposed in this study, proved to be a practical tool for identifying these data gaps. The tool may also prove helpful to understand UM information needs and data gaps in other cities.

Rather than performing conventional UM analyses on a finer, more detailed scale level, other types of UM analyses are required to disclose UM knowledge for urban planning and design. Further research is needed to investigate what type of analyses can provide a systemic understanding of resource flows and are tailored to inform urban planning and design aimed at optimizing resource flows. In such research, the accessibility of UM analyses for urban planners and designers should have a central position.

Abstract

Understanding which factors influence urban metabolism is a prerequisite for designing policies and plans that effectuate sustainable resource management. A growing number of publications is concerned with these factors. Yet, this emerging field of research lacks a common framework that supports researchers in interpreting their findings, such as generalizability to other cities, and making informed decisions on their research design. Aiming to contribute to building such a framework, we systematically reviewed urban metabolism literature. This review paper presents an overview of factors influencing urban water and energy consumption and their effect on consumption, and it describes the interconnectedness of these factors for six different types of relationships. Results disclose fourteen *drivers*, changes in societal context that shape consumption patterns, and twenty-one *facilitators/constraints*. The latter type of factors include consumer, resource and urban landscape characteristics that affect resource consumption by facilitating or constraining specific activities. Findings indicate commonalities between primary studies in terms of prevalent observed effect direction for a given factor. However, the interconnections between different factors can influence the direction and magnitude of effects and thereby result in case-specific variability in consumption patterns. Future research should enhance the understanding of these interconnections, strengthen the evidence for the factors presented here and provide insight in additional factors of influence. It is essential to align these studies in terms of a common terminology, transparent quality assessment and a unified approach to measuring and expressing factors of influence. Connecting with related disciplines working on a common systems approach is key to realize the full potential of urban metabolism research to advance our understanding of cities.

4.

Factors influencing spatiotemporal variability in urban water and energy consumption

A systematic review of urban metabolism literature

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A systematic review of factors influencing spatiotemporal variability in urban water and energy consumption

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4.1 Introduction

Cities have become focal areas for sustainable resource management due to the concentration of human activities in urban areas. These activities transform and consume the majority of global resources (Pulido Barrera et al., 2018), thereby generating waste and emissions that contribute to environmental issues such as climate change, air pollution and water contamination (Dijst et al., 2018). Yet, realising sustainable resource management is complicated due to feedback effects, non-linearity and interactions between multi-scale processes that characterize social-ecological-technological systems²⁰ (Pahl-Wostl, 2007). Moreover, resource flows in urban ecosystems are strongly shaped by human induced mechanisms such as the organization of urban space, societal priorities, management methods and urban practices at hand (Castán Broto et al., 2012; Pincetl et al., 2014). Just like ecological processes, these mechanisms continuously influence the urban landscape (Grimm et al., 2008), which is heterogeneous with respect to environmental, demographic, cultural and socio-economic characteristics as well as urban forms and functions. As a result, the distinctive heterogeneity of urban ecosystems dynamically develops over time (Alfsen et al., 2011). This “dynamic heterogeneity” (Pickett et al., 2017) shows both in variation between cities and within cities. Namely, in inter-city differences in terms of size and political, economic and social organization but also in intra-city differences, such as functional specialization of neighbourhoods (Pincetl et al., 2012; Pulido Barrera et al., 2018).

The need to understand how these dynamic and heterogeneous characteristics affect urban resource flows, generating spatial variations and changes in resource flows over time, is increasingly recognized in the field of urban metabolism (UM) (Zhang et al., 2015). UM refers to the processes whereby cities transform raw materials, energy, and water into the built environment, human biomass, and waste (Decker et al., 2000). Various scholars argue that UM analyses should better capture the complex nature of cities by providing insight in how different factors influence consumption patterns and how they are interlinked and operated at different spatial and temporal scales (Golubiewski, 2012; Metzger et al., 2016; Voskamp et al., 2018). Researchers particularly advocate these adjustments to UM assessment methods to enhance the suitability of UM analyses to support resource-conscious design, planning and management of urban areas (Cui, 2018; Perrotti and Stremke, 2018). Understanding the factors that influence resource consumption, is a prerequisite for designing policies and plans that map out the route to sustainable management of urban resources (Castán Broto et al., 2012). After all, formulating effective policies and plans

²⁰ According to Bai et al. (2016), conceptualising cities as social-ecological-technological systems relies upon acknowledging the following system characteristics. Cities constitute of physical/built, social-economic and ecological subsystems that encompass multiple and diverse actors. Across these subsystems, causally interlinked urban processes result in intended and unintended consequences. Likewise, cities are open systems, that are influencing and influenced by the broader structures they are embedded in. They are self-organizing, dynamic and evolving, and have non-linear pathways.

requires not only insight into *what* a city's metabolism looks like – 'how much resource consumption occurs where and when?' –, but also, *why* the metabolism looks the way it does – 'which are the mechanisms behind the resource flow patterns?'. For example, if a city aims to reduce its natural gas usage, it is not only relevant to know the quantity of gas used per neighbourhood. It is also essential to understand what underlies these consumption patterns. This knowledge can support the identification of the most effective strategy to realize reduction goals: retrofitting the building stock, upgrading the heating appliances in place, increasing the natural gas price or starting educational campaigns. Recently, new approaches in UM studies are emerging that pay attention to informing urban planning practice and aim to investigating the spatiotemporal dynamics of UM and the relationship between so-called 'drivers' and UM (Bai, 2016).

This emerging field of UM analyses requires a common framework that supports researchers in designing their research and that enables interpretation of their findings, such as the generalizability of their findings to other cities. Hitherto, studies on factors influencing UM are generally limited to selected factors of influence and they are incomplete in motivating why these factors are the appropriate ones to study. An overview of potential factors of influence enables researchers making an informed decision which factors are the relevant ones to assess in their case. At the same time, it supports interpretation of their findings by showing which additional factors, that are excluded from their analysis, could still affect their results. The framework should thus also provide insight into whether factors are connected and how they can influence one another. Aiming to support building such a framework, we conducted a systematic literature review that synthesizes the scientific understanding on factors that influence the spatiotemporal variability of the UM generally and water and energy consumption specifically²¹. The aim of this review was thus to provide an overview of the factors influencing urban water and energy consumption and their effect on consumption; and to give insight in the interconnectedness of these factors over spatial and temporal scale levels. In addition, the aim was to describe the characteristics of this body of UM literature to interpret the validity of findings and to identify relevant directions for future research.

4.2. Conceptual framework:

Drivers, needs, facilitators and constraints

The basis of this review is a conceptual framework that portrays: (I) what kind of factors influence the spatiotemporal variability of urban water and energy, and (II) in what way. Thereby, this framework facilitates the categorization, interpretation and comparison of findings from different studies. At

²¹ In this review we focus on final water and energy consumption because of the relevance for resource-conscious design, planning and management of urban areas. Water and energy are key resources when it comes to implementing spatial and technical interventions in the urban landscape in support of urban climate adaptation, climate mitigation and/or resource efficiency (Mitraka et al., 2014; Pincetl et al., 2012).

present, such an elaborated conceptualisation is absent in UM literature, but the work by Dijst et al. (2018) proved a valuable starting point to build on. Dijst et al. (2018) identified five interrelated elements of urban metabolism (figure 4.1). Resource flows through and stocks in a city are the effect of activities that are undertaken within the urban environment. The causal determinants of those activities constitute three elements: needs, facilitators/constraints, and drivers (Dijst et al., 2018). We classified these elements further into different categories of factors to facilitate the categorization of our findings, using the cross-disciplinary review by Poças Ribeiro et al. (2019). We took their review as point of departure, which is focused on the factors that influence consumption of goods and services rather than resources, because the UM literature lacks such a comprehensive and coherent overview. In line with Dijst et al. (2018), we thus distinguish three elements that affect the spatial and temporal characteristics of urban energy and water consumption patterns: needs, facilitators/constraints, and drivers (see table 4.1).

Figure 4.1: The five interrelated elements of urban metabolism (Dijst et al., 2018)

Table 4.1: Categorisation of factors affecting resource consumption in relation to the elements needs, facilitators/ constraints and drivers. Elaborated on the work of Dijst et al (2018) and Poças Ribeiro et al. (2019)

Elements	Needs	Facilitators / constraints			Drivers
		Consumer characteristics	Resource characteristics	Urban landscape characteristics	
Categories of factors	Individual survival	Personal	Quality	Spatial	Demographic
	Individual aspirations	Psychological	Price	Infrastructural	Economic
	Satisfaction	Social context	Availability		Political
	Social	Cultural context			Cultural
	Practical	Decision making			Technological
	Political				Geographical

First, the *needs* of individuals and communities prompt particular activities (Dijst et al., 2018). For example, thirst (need) might trigger drinking (activity) and accordingly result in water consumption (flows and stocks). *Needs* are thus an attribute of consumers. Poças Ribeiro et al. (2019) found that these needs can be very diverse and can be categorised as factors related to individual survival, individual aspirations, satisfaction as well as social, practical and political purposes (table 4.1). As UM analyses generally do not assess these factors, we did not consider needs in our review²².

Second, there are *facilitators/constraints* that increase or decrease the probability or degree to which specific activities are triggered, and in doing so they shape particular consumption patterns. They are “two sides of the same coin, depending on whether a given factor is present in a positive or negative sense” (Dijst et al., 2018). In case of the example above, the health conditions of the consumer, the quality of available water or distance to a tap with potable water can influence the drinking of tap water. Facilitators/constraints can thus relate to either the consumer, the resource or the physical urban landscape (table 4.1). With regard to the consumer; the personal and psychological characteristics as well as social and cultural context of consumers influence his/her consumption patterns, along with his/her way of decision making (Poças Ribeiro et al., 2019). Consumer behaviour also depends on the product consumed and its so-called “marketing mix” (Poças Ribeiro et al., 2019), which translate in the categories resource quality, price, and availability in the context of resource consumption. With *facilitators/constraints* related to the urban landscape, we refer to urban patterns that facilitate or constrain particular activities to occur, comprising both spatial and infrastructural factors.

Third, *drivers* can influence and set the context for needs, facilitators/constraints, activities and resource flows and stocks at the level of an individual or a community. We define *drivers* as large scale developments in the societal context in which the physical urban landscape is embedded, that cause a particular activity to occur. Without (a) driver(s), facilitators/constraints will not result in activities (Dijst et al., 2018). In line with Poças Ribeiro et al. (2019), we distinguish *drivers* related to the demographic, cultural, economic, political/institutional, technological, and geographical context (table 4.1). *Drivers* intrinsically have a temporal characteristic as they comprise local up to global processes. It should be noted that although Dijst et al. (2018) explicitly refer with ‘*drivers*’ to macro developments that can be either endogenous or exogenous to a system, other scholars also commonly use the term ‘*driver*’ in the UM literature, but without providing a definition of the term. Consequently, it remains unclear whether they consider ‘*drivers*’ as the only type of causal determinants or that they also acknowledge the influence of facilitators/constraints and needs.

²² Analyses within the UM field that investigate the factors that influence urban resource consumption are generally not concerned with factors at the level of individuals and communities, except for key descriptive characteristics of consumers such as income. Rather, characteristic of the urban system, such as those describing the societal context and spatial set-up of the city at hand, are within the scope of those studies. Note that our results confirm that predominantly those kind of factors are studied.

4.3 Methods and materials

The method underpinning this paper is a systematic review of the literature. This involves searching, selecting as well as critically appraising the literature in a systematic manner and synthesizing the findings into a coherent statement (Gough et al., 2012). By closely adhering to a set of scientific methods, such a review explicitly aims to limit error (bias) (Petticrew and Helen, 2005). Accordingly, our review consisted of three steps, as described below: (I) search strategy development and implementation; (II) relevance and quality assessment; (III) data extraction and synthesis. A detailed description of these steps is provided as Supplementary material S3.1 (p.200).

4.3.1 Search strategy development and implementation

The first step of the review process was to develop and implement a search strategy to identify studies eligible to answer the research questions. Three study types were considered: (I) Case studies discussing temporal variation in urban water and/or energy consumption, (II) Case studies discussing spatial variation in urban water and/or energy consumption, and (III) Review studies that mention case studies focussing on the temporal or spatial variation of the UM. A Boolean search string was formulated, using keywords based on two inclusion concepts and several exclusion terms (see table 4.2). Then, this search string was applied to the databases Scopus and Web of Science, yielding 474 unique items.

Table 4.2: Elements of the search string

Search string elements	Keywords
Inclusion concept 1	"Urban metabolism / ecology"
Inclusion concept 2	"Water / energy use"
Exclusion terms	

An additional search strategy that was employed, was 'reference list checking' the selected review papers (see 4.3.2), by scanning the titles of citations in the reference lists of those papers (Gough et al., 2012). Non-review papers were not considered for this strategy to avoid that the number of irrelevant items in the sample would extensively grow, a known issue associated to this strategy that can be prevented this way (Gough et al., 2012).

4.3.2 Relevance and quality assessment

The second step of the review process entailed screening the retrieved publications and deciding which ones to be examined in detail. This is also known as critical relevance and quality appraisal (Gough et al., 2012; Petticrew and Helen, 2005). For this, criteria were formulated to either ex- or include publications for further review based the relevance of the publications and their appropriateness in answering our research questions and drawing conclusions. A detailed description of our process and the eligibility criteria used is provided in Supplementary material S3.1.2.

The 474 unique items that were obtained were screened in several steps to judge their eligibility using exclusion criteria (figure 4.2). First, all items were screened on title and abstract and appraised on the criteria: publication year, topic, scope, resource flow, and study design. Each item was coded accordingly in the EPPI-Reviewer software (Thomas et al., 2010). Based on this first screening 75 items were directly included for full text screening. Another 75 items were additionally screened on the introduction, methods and/or conclusion section, because screening of the abstract and title of these items did not provide sufficient information on the scope and study design to decide whether these articles should be included for full text screening or not. Through this second screening phase, twenty-three items were additionally included, giving a total of 98 items for full text screening. During the full text screening, the same exclusion criteria as in the earlier screenings were employed. In addition, publications were excluded when they did not discuss factors influencing resource consumption and case studies were also excluded when the scale level of analysis was less detailed than the metropolitan level. Based on this final screening step, forty-three items remained. Finally, reference list checking of the four included review studies identified an additional six eligible items. Accordingly, in total forty-nine items were to be considered for further quality assessment.

Figure 4.2: The steps of relevance assessment

After the relevance assessment, the next step was quality assessment. Inclusion criteria were used to evaluate whether the forty-nine publications that remained met quality requirements on the basis of which they should be included in the final sample. Accordingly, reviews were only included if they discuss how factors are related to consumption, thus mentioning their effect. Case studies were evaluated on two characteristics of the quality of the data used: reliability and resolution (see also supplementary material S3.1.3). After this final step of quality assessment the final sample totalled thirty publications.

4.3.3 Data extraction and synthesis

The next step in the review process was data extraction from publications and finally synthesizing these data. Two types of data were extracted: (I) descriptive characteristics of the research and (II) data on the relationship between spatiotemporal variability of water and/or energy consumption and the factors that generate these geographical variations and changes over time. The elements of data extraction are described in more detail in S3.1.4. Both types of data were recorded in a Microsoft Excel spreadsheet because tabulation was identified as a valuable tool for data synthesis. It can be used to “develop an initial description of the included studies and to begin to identify patterns across studies” (Popay et al., 2006), thereby informing our narrative synthesis. This is an approach to the “synthesis of findings from multiple studies that relies primarily on the use of words and text to summarise and explain the findings of the synthesis” (Popay et al., 2006)²³. Narrative synthesis is suitable to synthesize studies that have a wide range of research designs and yield both quantitative and qualitative findings (Popay et al., 2006) – which is the case for our review. We followed the narrative synthesis approach as described by Popay et al. (2006) and describe this in detailed in Supplementary material S3.1.5.

4.4. Results

4.4.1 Descriptive characterization of the body of literature

UM research on the factors that influence urban water and/or energy consumption is growing and diversifying in terms of research design (figure 4.3). The oldest publication reviewed is from 2001 and most research dates from recent years, with half of the publications from the period 2014-2018 (see figure 4.3a). This sample composition reflects the general development in the UM field that

²³ Narrative synthesis refers to a specific approach to combining the findings of multiple studies as part of a systematic review process in order to draw conclusions based on the body of evidence. It should not be mistaken for a narrative review.

empirical case studies have become more frequent since 2000 (Beloin-Saint-Pierre et al., 2017; Cui, 2018). Moreover, the sample shows a diversification of research designs in recent years. The oldest half of the sample, up to 2014, consists for two-thirds of flow analyses and environmental history studies. These type of studies are not specifically designed to establish quantitative correlations between consumption figures and factors explaining them. Since 2014 research has been published that is specifically designed to with this aim, namely ‘regression analyses’ and ‘trend analyses’, i.e. multi-year flow analyses using indicators to explain temporal differences, that specifically aim to establish those correlations (see figure 4.3b).

Mapping the case studies on the geographic location of their embedded case(s) reveals that this body of literature is dominated by case studies of mature cities in the global north and in temperate climates (figure 4.3c). Sixteen publications, 57% of the case studies, research one or several cities in Europe. For North America, Asia and Australia this is respectively six, four and one publication(s). In addition, one publication covers several cities in Europe, North-America, South America and Africa (see supplementary material S3.2). These 28 case studies cover in total 31 unique cities: fourteen European cities, six cities in North America, six cities in Asia, three cities in Australia, one city in Africa and one city in South America (see figure 3b). Twenty-two of those cities are located in a temperate climate, seven in a continental climate and two in a tropical climate zone (see also supplementary material S3.2). Most frequently studied urban areas are Los Angeles, covered by four case studies and one meta-study, and Barcelona, covered by four case studies. Four of these five publications of Los Angeles present results from the same research project (Pincetl et al., 2016, 2014; Pincetl and Newell, 2017; Porse et al., 2016), as do the three trend analyses covering the three biggest Swedish cities (Kalmykova et al., 2016, 2015; Rosado et al., 2016).

A further breakdown of the case studies according to spatiotemporal resolution revealed five clusters within the sample (see figure 4.4), with each cluster having another focus when it comes to understanding the factors influencing consumption. Clusters 1 and 2 include research that assesses the temporal variation in consumption across decades or even centuries, namely ‘environmental history studies’ (cluster 1) and multi-year ‘material flow analyses’ and ‘trend analyses’ (cluster 2). These type of studies analyse primarily the effect of drivers and the facilitating or constraining role of infrastructure on consumption. Cluster 3 includes research aimed at explaining differences in consumption between cities.

Some publications have one focal city of research that is compared with other cities to bring context related effects into view (e.g. Voskamp et al. 2017), whereas other research is aimed at assessing and comparing several cases from the start (e.g. Renouf et al. 2018). Both this cluster

Figure 4.3: Sample composition, according to: a. year of publication, b. research design (in absolute numbers and percentages), and c. geographic location of the cities researched in the case studies

Note that a legend is provided at page 98 that indicates the references corresponding to the numbers in the map

of ‘city comparisons’ and that of ‘intra-urban comparisons’ (cluster 4) focus on the influence of urban spatial characteristics. Only two studies in these clusters provide spatially explicit data of consumption patterns, namely the publications by Ariza-Montobbio et al. 2014 (#1) and Mehta et al. 2013 (#14). Furthermore, research in cluster 4 also considers the effect of consumer characteristics, as do ‘high-resolution studies’ (cluster 5). This latter research cluster also provides insight in the spatial facilitators/constraints on building and plot level, and three publications support their findings with spatially explicit consumption data (Pincetl et al. 2014, 2016; Porse et al. 2016; #16-18). The role of resource characteristics is addressed by research from all five different clusters.

Legend

Colours indicate resource flow(s) analysed: ● UM overall ● Water ● Energy ● Water and energy

Numbers indicate corresponding references:

1 Ariza-Montobbio et al., 2014	8 Gorostiza et al., 2015	15 Núñez et al., 2010	22 Schulz, 2007
2 Athanassiadis et al., 2017a	9 Hall, 2011	16 Pincetl et al., 2014	23 Stergiouli & Hajib, 2012
3 Athanassiadis et al., 2017b	10 Kalmykova et al., 2015	17 Pincetl et al., 2016	24 Swaney et al. 2012
4 Barles, 2007b	11 Kalmykova et al., 2016	18 Porse et al., 2016	25 Tello & Ostos, 2011
5 Barles, 2009	12 Kim and Barles, 2012	19 Renouf et al., 2018	26 Voskamp et al., 2017
6 Domene et al., 2005	13 Marteleira et al., 2014	20 Rosado et al., 2016	27 Wang et al., 2017
7 Gingrich et al., 2012	14 Mehta et al., 2013	21 Sahely et al., 2003	28 Warren-Rhodes & Koenig, 2001

* these publications are outliers to the clusters

** the temporal resolution of the data underlying those studies was not indicated (completely) and positioning within the diagram should therefore be interpreted with care

Figure 4.4: Sample composition according to spatiotemporal resolution of analysis

4.4.2 Determinants of urban water and energy consumption

In the following two sections we present an overview of the factors that influence water and/or energy consumption and what this effect is. These findings are further explored in section 4.4.2.1, where we discuss all drivers, and section 4.4.2.2, focusing on facilitators/constraints. All factors are summarized in table 4.3; note that each factor mentioned in this table is indicated in bold in the text.

4.4.2.1 Drivers

Demographic drivers

Demographic drivers comprise changes in the overall characteristics of the urban population that affect resource consumption patterns. **Population size** was the only factor found to represent such a driver. The most frequent finding is increasing total consumption of both water and energy with increasing population size (Barles, 2007b; Gingrich et al., 2012; Gorostiza et al., 2015; Kim and Barles, 2012; Stergiouli and Hadjibiros, 2012; Swaney et al., 2012; Tello and Ostos, 2012; Warren-Rhodes and Koenig, 2001). Yet, Athanassiadis et al. (2017a) show that this is not always the case, as evidenced by absolute water and energy consumption in Brussels neither following the evolution of the population nor the evolution of consumption per inhabitant between 1970-2000. The findings of Athanassiadis et al. (2017b) suggest that with increasing population size, consumption of natural gas and electricity *per capita* actually decreases.

Economic drivers

Economic drivers include changes in the economic domain of a city, namely in its system of production and exchange of goods and services, that influence resource consumption patterns. Three economic drivers were identified: **level of economic development** and **economic specialisation** both signify more or less gradual changes in economic activities, while the third driver, **crises**, denotes disruptive events or periods. Five studies mention that consumption increases with an increasing **level of economic development**, for the UM in general, water and energy. Rosado et al. (2016) points this out for the UM in general with their analysis of three Swedish cities. They found that urban areas in a mature development stage, i.e. Stockholm and Gothenburg, consume fewer resources than urban areas in transition such as Malmo. Tello and Ostos (2012) found increasing water consumption with economic development. Likewise, three studies indicate increasing final energy consumption with increasing GDP (Gingrich et al. 2012, Wang et al. 2017, Warren-Rhodes

Table 4.3: Overview of factors influencing water and/or energy consumption

	Category	Factors influencing consumption	References for water	References for energy
Drivers	Demographic	Population size	Athanassiadis et al., 2017a; Barles, 2007b; Gorostiza et al., 2015; Stergiouli and Hadjibiros 2012; Swaney et al., 2012; Tello and Ostos, 2012; Warren-Rhodes and Koenig, 2001	Athanassiadis et al., 2017a; Athanassiadis et al., 2017b; Gingrich et al., 2012; Kalmykova et al., 2016; Kim and Barles, 2012; Warren-Rhodes and Koenig, 2001
	Economic	Level of economic development	Tello and Ostos, 2012	Gingrich et al., 2012; Kalmykova et al., 2016; Wang et al., 2017; Warren-Rhodes and Koenig, 2001
		Economic specialisation	Athanassiadis et al., 2017a; Tello and Ostos, 2012	Ariza-Montobbio et al., 2014; Athanassiadis et al., 2017a; Sahely et al., 2003; Warren-Rhodes and Koenig, 2001
		Crises	Tello and Ostos, 2012; Stergiouli and Hadjibiros 2012	Kim and Barles, 2012; Athanassiadis et al., 2017a
	Political	Educational campaigns	Gorostiza et al., 2015; Pincett et al., 2014; Pincett and Newell, 2017; Renouf et al., 2018; Stergiouli and Hadjibiros 2012	Kim and Barles, 2012
		Rules and regulations	Gorostiza et al., 2015; Pincett et al., 2014; Pincett and Newell, 2017; Renouf et al., 2018; Swaney et al., 2012	-
		Policy and planning	-	Kalmykova et al., 2016; Kim and Barles, 2012; Pincett et al., 2014; Warren-Rhodes and Koenig, 2001
	Cultural	Standard of living	Barles, 2007b; Stergiouli and Hadjibiros 2012	Athanassiadis et al., 2017a; Kim and Barles, 2012; Warren-Rhodes and Koenig, 2001
		Environmental awareness	Swaney et al., 2012; Tello and Ostos, 2012	Warren-Rhodes and Koenig, 2001
	Technological	Conversion efficiency	-	Gingrich et al., 2012; Kalmykova et al., 2015; Kim and Barles, 2012; Sahely et al., 2003
		Transition in energy system	-	Athanassiadis et al., 2017a; Kalmykova et al., 2015
		Technological inventions	Swaney et al., 2012	Gingrich et al., 2012; Kim and Barles, 2012
	Geographical	Natural resource availability	-	Gingrich et al., 2012; Kim and Barles, 2012; Voskamp et al., 2017
		Climate	-	Athanassiadis et al., 2017a; Weisz and Steinberger 2010
	Spatial	Population density	Athanassiadis et al., 2017a; Marteleira et al., 2014	Ariza-Montobbio et al., 2014; Athanassiadis et al., 2017a; Athanassiadis et al., 2017b; Barles, 2009; Hall, 2011; Porse et al., 2016; Weisz and Steinberger, 2010
		Spatial distribution of functions	-	Barles, 2009
		Presence of a port	-	Kalmykova et al., 2015; Schulz, 2007; Voskamp et al., 2017; Warren-Rhodes and Koenig, 2001
		Amount of productive tree canopy	-	Hall, 2011
		Garden typology	Domene et al., 2005; Pincett and Newell 2017	-
Facilitators / Constraints		Building size	-	Ariza-Montobbio et al., 2014; Hall, 2011; Pincett et al., 2014; Porse et al., 2016
		Building type	Núñez et al., 2010	Ariza-Montobbio et al., 2014; Porse et al., 2016; Pincett and Newell 2017; Pincett et al., 2016
		Building age	-	Pincett et al., 2014; Porse et al., 2016; Pincett and Newell 2017
	Infrastructural	Size of the supply network	Barles, 2007b; Gorostiza et al., 2015; Stergiouli and Hadjibiros, 2012; Swaney et al., 2012; Tello and Ostos, 2012	Kim and Barles., 2012; Gingrich et al., 2012
		Condition of the supply network	Swaney et al., 2012	Kim and Barles., 2012; Gingrich et al., 2012
		Sanitary fittings	Núñez et al., 2010; Swaney et al., 2012	-
		Metering	Swaney et al., 2012	-
		Presence of a pool	Núñez et al.; Tello and Ostos, 2012	Pincett et al., 2014
		Home appliances	-	Pincett et al., 2014
	Resource characteristics	Price	Stergiouli and Hadjibiros, 2012	Athanassiadis et al., 2017a; Gingrich et al., 2012; Kim and Barles, 2012; Sahely et al., 2003
		Availability	Gorostiza et al., 2015; Mehta et al., 2013; Renouf et al., 2018; Tello and Ostos, 2012	-
		Quality	Gorostiza et al., 2015	-
	Personal consumer characteristics	Income level	Domene et al., 2005; Pincett et al., 2014; Pincett and Newell., 2017	Ariza-Montobbio et al., 2014; Athanassiadis et al., 2017b; Hall., 2011; Pincett et al., 2014; Pincett and Newell, 2017; Porse et al., 2016; Weisz and Steinberger, 2010
		Lifestyle	-	Ariza-Montobbio et al. 2014; Hall, 2011; Kalmykova et al., 2016; Weisz and Steinberger 2010
	Social & cultural context	Household size	-	Ariza-Montobbio et al. 2016; Weisz and Steinberger, 2010
	Decision making	Behaviour	Renouf et al., 2018	-

Note that ' - ' indicates the sample does not provide evidence for a direct influence of that factor on the consumption of that resource

and Koenig 2001). The findings of Kalmykova et al. (2016) indicate quite the opposite. In Stockholm fuel consumption decreased to 63% of the 1996 fuel consumption level in 2011, despite population increase of 20% and GDP growth, hence showing that decoupling of resource consumption and economic growth took place.

Changes in **economic specialisation** do not have a univocal effect on overall water and/or energy consumption. Rather, shifts in economic sector composition can be observed in altering consumption *profiles*. Hence, although European and North-American cities that experienced de-industrialization in the last quarter of the 20th century decreased their industrial resource consumption (e.g. Athanassiadis et al. 2017a; Tello and Ostos 2012; Sahely et al. 2003), overall consumption did not necessarily decrease in these cities. The tertiarization process that took place simultaneously implied an increasing consumption by the service sector resulting in stable total consumption. Athanassiadis et al. (2017a) indicate those changes in consumption profile for water in the case of Brussels, and Warren-Rhodes and Koenig (2001) for energy consumption in Hong Kong. Ariza-Montobbio et al. (2014) identify the relationship between economic sector composition and consumption profiles specifically for electricity consumption. They found high electricity consumption levels among different municipality types in Catalonia, including 'industrial cities' with industry as a major consumer and 'service cities', which have a high consumption due to service activity and a high population density (see 4.4.2.2).

Different kinds of **crises** are mentioned in relation to declining consumption. Stergiouli and Hadjibiros (2012) illustrate for example the influence of war, indicating that Athens experienced a substantial reduction in water use during the second world war and the Greek civil war that followed (1939-1949). Two more recent examples of economic crises are the oil crisis in the 1970's (Kim and Barles, 2012) and the recent financial crisis (Athanassiadis et al., 2017a), both of which are associated with declining consumption of petroleum products in Paris and Brussels, respectively.

Political drivers

Political drivers comprise changes in governmental policy, effectuated by different sorts of policy instruments, that influence consumption patterns. Literature reveals that different types of policy instruments are being employed to target either consumption of water or of energy. **Educational campaigns** as well as **rules and regulations** are mentioned by six studies as intervention in response to drought, resulting in reduced water consumption (Gorostiza et al., 2015; Pincetl et al., 2014; Pincetl and Newell, 2017; Renouf et al., 2018; Stergiouli and Hadjibiros, 2012; Swaney et al., 2012). Pincetl et al. (2014) and Pincetl and Newell (2017) found that restricting irrigation

to specific days and times, i.e. mandatory conservation, was more effective in reducing water use than a voluntary program. The only example of **educational campaigns** with regards to energy consumption is given by Kim and Barles (2012), who mention political encouragement as one of the factors contributing to increased coal consumption, as a response to the wood crisis in 19th century Paris. Nation-wide and city-specific **policy and planning** interventions are drivers for decreasing energy consumption. **Planning and policy** interventions advocating substitution and diversification of energy sources are linked to declining consumption of petroleum products in Paris (Kim and Barles, 2012) and coal in Hong Kong (Warren-Rhodes and Koenig, 2001) since the 1970s. More recent interventions include the introduction of a congestion fee in Stockholm in 2007 (Kalmykova et al., 2016) and the implementation of the latest energy efficiency codes in Los Angeles (Pincetl et al., 2014). Both are related to reduced energy usage in those cities, for transportation and buildings respectively.

Cultural drivers

We speak of cultural drivers in case of changing consumption patterns under influence of changing cultural norms within society. Environmental history studies and long term flow analyses provide evidence of two types of cultural drivers: changes in **standard of living** and in **environmental awareness**. Firstly, five publications relate higher **standard of living** to increased consumption of either water or energy, with specific expressions of these higher standards for each resource (Athanassiadis et al., 2017a; Barles, 2007b; Kim and Barles, 2012; Stergiouli and Hadjibiros, 2012; Warren-Rhodes and Koenig, 2001). Higher expectations for health and hygiene express higher **standards of living** that are specific for water (Barles, 2007b), whereas increased demand for thermal comfort is specific for energy (Kim and Barles, 2012; Warren-Rhodes and Koenig, 2001). Secondly, three publications link increased **environmental awareness** among the general public to decreasing consumption patterns of water (Swaney et al., 2012; Tello and Ostos, 2012) and energy (Warren-Rhodes and Koenig, 2001) since the end of the twentieth century. Tello and Ostos (2012), for example, point out that since 1997 both total and per capita water consumption in Barcelona decreased, despite economic development and increasing population size. They ascribe this decrease to the emergence of a “New Sustainable Water Culture” in Catalonia and growing awareness of the risks of climate change.

Technological drivers

Technological drivers include changes or advancements in resource conversion and supply technologies that influence urban resource consumption patterns. These drivers range from

small-scale innovations that optimize existing technologies up to long-term, structural changes in the resource system. Small-scale innovations resulting in gains in **conversion efficiency** are mentioned in four studies as plausible explanations for reduced energy consumption (Gingrich et al., 2012; Kalmykova et al., 2015; Kim and Barles, 2012; Sahely et al., 2003). Kalmykova et al. (2015), for example, name increased energy-efficiency as one of the underlying causes of a 20% and 45% decrease in residential energy consumption per capita between 1996-2011 in Stockholm and Gothenburg, respectively. A system-wide change is also mentioned as explanation for these decreases, namely a **transition in energy system** for heating (Kalmykova et al., 2015). Athanassiadis et al. (2017a) also associate such a change in prevalent heating technology to a slow decrease in consumption of petroleum products and an increase of natural gas use in Brussels (1970-2010). **Technological inventions** that can fuel such transitions have shown to be drivers of energy consumption throughout history. Examples include increasing coal consumption in the nineteenth century with development of the steam engine and increasing petroleum consumption in the twentieth century with the rise of motorization and increasing mobility (Gingrich et al., 2012; Kim and Barles, 2012).

Geographical drivers

We speak of geographical drivers when consumption patterns are influenced by the geographic location of a city. The literature provides evidence for two of such drivers: **natural resource availability** and **climate**. Evidence of the effect of changing **natural resource availability** on consumption is found in the historical analyses of Paris and Vienna. These studies indicate reduced energy consumption is related to lower resource availability by the end of the 18th and beginning of the 19th century. In both cities, the depletion of nearby forests contributed to energy (i.e. firewood) scarcity (Gingrich et al., 2012; Kim and Barles, 2012). Moreover, Voskamp et al. (2017) argue that the presence of the river Danube in Vienna and Amsterdam's delta location are key features to explain "the renewable energy performance of both cities". The second geographic driver identified is **climate**. Athanassiadis et al. (2017a) and Weisz and Steinberger (2010) stress that **climate** clearly has an impact on energy use due to its influence on heating and cooling demand. Nevertheless, Weisz and Steinberger (2010) indicate that comparative studies found a substantial range in energy use when expressed in Wh/m² living space/heating-degree-day, confirming that non-climate factors have substantial effects on energy consumption.

4.4.2.2 Facilitators and constraints

Spatial characteristics

Spatial characteristics describe the characteristics of the built and non-built surfaces within the urban landscape and reflect the form and functions of these spaces. These characteristics range from very generic city level indicators such as **population density**, to specific building characteristics such as **building size**. The spatial factor analysed most frequently is **population density**. According to the review by Weisz and Steinberger (2010), the relationship between transport energy requirements and **population density** is frequently studied, with literature suggesting lower energy usage with higher densities. This would mean that a higher population density acts as a constraint for transport-related energy consumption: by restraining the activity ‘transportation’, higher densities have lower consumption levels. However, Weisz and Steinberger (2010) also stress that the causal factors of this correlation are debated and that other factors also play an important role, for example the quality of public transportation. Three studies mention either lower total residential energy (Hall, 2011; Porse et al., 2016) or electricity (Ariza-Montobbio et al., 2014) consumption with higher **population densities**. Athanassiadis et al. (2017b) also found that (residential) electricity and natural gas use decreased with increasing **population density** with their comparative analysis of ten cities. However, their results also indicate that the relationships vary significantly in intensity and that at the micro scale “a high degree of heterogeneity seems to exist across the cities”. Athanassiadis et al. (2017a) found in their long-term analysis of Brussels that changing **population density** correlated neither with variability in energy consumption nor with water consumption. Marteleira et al. (2014) found for Lisbon that areas with higher density have a higher water consumption per capita. Yet, these findings are difficult to interpret because they correspond to total potable water volumes rather than domestic use only.

Two other spatial characteristics were found at city level: **spatial distribution of functions** and **presence of a port**. Barles (2009) concludes that both the **spatial distribution of functions** and **population density** strongly impact the UM of Paris. She stresses that different parts of the city each have their specific function and that these different functions facilitate particular activities, thus creating intra-city differences in consumption. Fossil fuel consumption was found to be the lowest in the dense city centre of Paris where public facilities and housing are the dominant urban functions. The **presence of a port** gives Amsterdam, Gothenburg, Hong Kong and Singapore a distinct metabolic profile, by enabling resource-intensive, port-related activities. The UM of port cities in general is characterized by large volumes of trading flows, implying a relatively high import and export per capita and a high share of crossing flows (Kalmykova et al., 2015; Schulz, 2007;

Voskamp et al., 2017; Warren-Rhodes and Koenig, 2001). Warren-Rhodes and Koenig (2001) also indicate that transport sector energy use grew with increased trading volume in Hong Kong.

We also identified five spatial characteristics on a scale level more detailed than the city level. The literature indicates effects of vegetation on water and energy consumption at neighbourhood and plot level, whereas the facilitating/constraining role of building characteristics is primarily related to energy consumption at building level. In a comparison of three neighbourhoods in Syracuse, Hall (2011) found that the **amount of productive tree canopy** affects the energy demand for heating and cooling; a negative correlation was found between energy demand and tree canopy coverage. At plot scale, the **garden typology** can facilitate water consumption (Pincetl and Newell 2017; Domene et al. 2005). Domene et al. (2005) found a significant positive correlation between the proportion of grass occupying the garden and the garden water consumption. As for the building level, three studies report higher electricity consumption per household as well as per person with larger **building size** (Ariza-Montobbio et al., 2014; Hall, 2011; Pincetl et al., 2014). Porse et al. (2016) found for Los Angeles County that median annual total energy as well as electricity consumption per square-foot varies by **building type**, which reflects both the use and construction design of a building (e.g. a single-family detached building). Institutional and commercial buildings are among the largest consuming types per square foot in L.A. (Porse et al., 2016), which is in line with the findings by Pincetl et al. (2016). Núñez et al. (2010) indicate that also water consumption varies with the function of a building. Finally, **building age** and energy consumption are related across all building use types in L.A. (Pincetl et al., 2014; Porse et al., 2016).

Infrastructural characteristics

Infrastructural characteristics refer to the characteristics of the physical networks and their system components that are providing goods and services to a city, for instance systems for transport, resource supply and telecommunications. Infrastructural facilitators/constrains thus include specifications of the city networks as well as of specific system components. At the network level, factors such as the **size and the condition of the supply network** play a role. Five studies mention increasing total water consumption with increasing **size of the supply network** (Barles, 2007b; Gorostiza et al., 2015; Stergiouli and Hadjibiros, 2012; Swaney et al., 2012; Tello and Ostos, 2012). With regards to energy, the historical analyses of Paris and Vienna point out that the **size of the supply network** played a crucial role in the energy transition from fuel wood to coal (Gingrich et al., 2012; Kim and Barles, 2012). At first, wood supply could not keep up with the demand because forests were depleted (**natural resource availability**, 4.2.1) and transport routes were constraining supply from more remote places. Then, the opening of long-distance

railway lines facilitated coal consumption by giving access to coal supply regions. In addition, the switch to railway transport also meant an improvement in the **condition of the supply network** because it also enabled constant supply – as opposed to rivers, where weather conditions influenced navigability (Gingrich et al., 2012; Kim and Barles, 2012). With regards to the **condition of water infrastructure**, Swaney et al. (2012) mention reduction of leakage as one of the reasons for declining water consumption in New York City since the 1990s. They also link this decline in consumption to adjustments of system components that brought about a constraining effect, namely increased **metering** and changes in **sanitary fittings**, i.e. the installation of low-flow plumbing devices. Likewise, Núñez et al. (2010) and Tello and Ostos (2012) highlight that the **presence of swimming pools**, bathrooms at home, shower facilities and public baths have a facilitating effect on water consumption. Moreover, Pincetl et al. (2014) found that the **presence of a pool** is correlated with higher electricity consumption levels and they also mention (extensive) presence of **home appliances** and air-conditioning as potential explanations for increased electricity usage.

Resource characteristics

The characteristics of what is consumed can also facilitate or constrain consumption. Three such characteristics are indicated in the UM literature: the **price**, **availability** and **quality** of the resource. The effect of the resource **price** on consumption is analysed in five studies, with as common finding an inverse relationship between consumption and **price** (Athanasiadis et al., 2017a; Gingrich et al., 2012; Kim and Barles, 2012; Stergiouli and Hadjibiros, 2012). Sahely et al. (2003) only state that “fluctuations in the price of natural gas might have affected usage patterns”. Three publications indicate that greater water **availability** can facilitate consumption (Gorostiza et al., 2015; Renouf et al., 2018; Tello and Ostos, 2012). Mehta et al. (2013) provide an example where limited **availability** constraints consumption. In Bangalore the supply network did not keep up with the growing demand from a growing population, consequently the outer districts that experienced very fast population growth are least served by the water utility. The finding that these areas have the lowest average water use in terms of litres per capita per day actually thus reflect that water **availability**, rather than demand, is very low here (Mehta et al., 2013). Gorostiza et al. (2015) indicate that not only greater water **availability** but also improved **quality** of the water can explain the doubling of the water consumption in Madrid in 1900-1920, which both resulted from expansion and improvement of the supply network.

Consumer characteristics

Finally, the characteristics of consumers and their context influence consumer behaviour and in doing so influence consumption patterns. In general the role of consumer characteristics receives

little attention in the UM literature, but the literature does mention two factors related to personal characteristics – **income level** and **lifestyle** – one to social context - **household size** - and one to decision making – **behaviour**. The factor **income level** is the most commonly studied consumer characteristic. Six case studies found a relationship between higher consumption levels and higher **income levels** (Ariza-Montobbio et al., 2014; Athanassiadis et al., 2017b; Domene et al., 2005; Hall, 2011; Pincetl et al., 2014; Porse et al., 2016). The facilitating effect of a higher **income level** is also emphasized in the meta-study by Pincetl and Newell (2017) and in the review by Weisz and Steinberger (2010). The first study concludes that in the case of Los Angeles “affluence is the most important driver” of both electricity and water consumption (Pincetl and Newell, 2017). Based on their review, Weisz and Steinberger (2010) point out that it is not just the **income level** that is of importance but rather the high income **lifestyle** is the factor to blame for high energy use in urban areas. Also Hall (2011) indicates that such a **lifestyle** can facilitate consumption: wealthier neighbourhoods in Syracuse have a higher energy use at home per residence and per capita and use more energy for their vehicles because more people own a SUV. Ariza-Montobbio et al. (2014) point in the direction of a ‘lifestyle characterized by consumerism in low-density urban sprawl’, to explain the higher average electricity consumption in suburban towns. In these areas, they found higher **income levels** and a smaller **household size**. According to Weisz and Steinberger (2010), earlier studies also found a negative correlation between **household size** and per capita household energy use. Finally, Renouf et al. (2018) mention the relationship between **behaviour** and water consumption. They stress that lower water usage in Brisbane, compared to Melbourne and Perth, can in part be explained by **behaviour** change embedded in a preceding period of drought when water use restrictions were enforced.

4.4.3 Interconnectedness of factors

The literature reveals not just individual drivers and facilitators/constraints that affect consumption, but also discloses examples of interconnected factors that jointly influence consumption. Examples of the relationships between drivers demonstrate that the interconnectedness of these factors can be reduced to (a combination of) three types of relationships, namely (1) **simultaneous developments**, (2) **effect chains** and (3) **response mechanisms** (table 4.4). These relationships differ based on at what time drivers occur relative to one another. Whereas some examples were found of the **simultaneous** presence of two drivers (#1, table 4.4), most examples describe how drivers happen in succession (#2 and #3, table 4.4). Some of these successions are a relatively straightforward **effect chain** of two drivers. For instance, after the end of the Greek civil war (driver A) a time of population growth (driver B) in Athens followed and subsequently water consumption increased (Stergiouli and Hadjibiros 2012). Other interconnections are more

Table 4.4: Six different types of relationships identified between factors

Type of relationship	Schematic representation of relationship	Examples
1. Simultaneous developments Two drivers, A and B, are present at the same time ($t=1$), with both a similar increasing or decreasing effect on consumption.		In times of both increasing population size (A) and economic development (B), an increase of total consumption occurs. (Gingrich et al. 2012; Tello and Ostos 2012)
2. Effect chain Driver A ($t=1$), triggers a change in context B that subsequently manifests as a driver itself (at $t=2$) and affects consumption.		A crisis (A) triggers demograohic change (B), which leads to an increase or decrease in total consumption. (Gorostiza et al. 2015; Stergiouli and Hadjibiros 2012)
3. Response mechanism Driver A ($t=1$) triggers a deliberate response that aims to steer away from undesirable resource consumption patterns that may result from driver A. The response ($t=2$) can either be: (I) interventions in context B that subsequently manifests as a driver, or (II) adjustments to urban or resource characteristics (F/C).		Political interventions (B) and adjustments to the resource price (F/C) in response to a crisis or drought (A). (Gorostiza et al. 2015; Kalmykova et al. 2016; Kim and Barles 2012; Pincetl et al. 2014; Renouf et al. 2018; Stergiouli and Hadjibiros 2012; Swaney et al. 2012)
4. Prerequisite condition Driver A is prerequisite to be able to remove/adjust characteristics that act as a constraining factor (C). Hence, after this change in context A and subsequent adjustments from constraining to facilitating factors (F), consumption increases.		Technological inventions (A) that enable the construction of higher pressure pipelines, a prerequisite for expansion of the supply system (C->F). After expansion, total water consumption increases. (Swaney et al. 2012)
5. Curtailing condition After a change in context (driver A), urban/consumer/resource characteristics that were not a constraint before (F), now become a limiting factor (C) and consumption stabilizes or decreases as a result.		If population size increases (A) but expansion of the water supply network lags behind on this, water availability and the network size become a constraint (F->C). (Mehta et al. 2013; Tello and Ostos 2012)
6. Interlinked characteristics Different facilitators and constraints (F/C) are interlinked and thus jointly influence consumption.		Differences in consumption between poorer and wealthier neighbourhoods can be related to dissimilar building age and size (F/C) and income-levels (F/C). (Pincetl & Newell 2017; Porse et al. 2016)
Note These relationships and examples thereof are highly simplified representations of reality and should be interpreted accordingly.	Legend 	

complex, such as **response mechanisms** that cross various spatial scales. One such example is how the world-wide oil crisis in the 1970s (driver A) brought about political responses at national and city level, such as planning and policy interventions (driver B) (Kalmykova et al., 2016; Kim and Barles, 2012). So, drivers can occur both simultaneously and in succession, and one driver can both trigger another driver unintentionally and as intentional response.

Furthermore, three types of relationships between drivers and facilitators/constraints were identified. A **prerequisite** and **curtailing condition** (#4 and 5, table 4.4) both signify how a driver can unintentionally initiate changes in urban, resource and/or consumer characteristics. In addition, a **response mechanism** (#3, table 4.4) does not necessarily only comprise two drivers, but it can also involve deliberate changes in facilitating/constraining urban or resource characteristics. An example of this kind of **response mechanism** is supply network expansion (F/C) in response to increasing population size (driver A) (Swaney et al. 2012; Tello and Ostos 2012; Barles 2007; Gorostiza et al. 2015). When there is no such accurate response, and the size of the supply network does not keep up with the growing demand from a growing population (driver A), resource availability can become a constraint to consumption. Mehta et al. (2013) illustrate such a **curtailing condition** (#5, table 4.4) in the case of water consumption Bangalore. By contrast, in case of a **prerequisite condition** (#4, table 4.4) a driver can work as an enabler: making it possible to change constraining factors into facilitating ones. For example, technological inventions such as trains and railways, played an enabling role in the energy transition from fuel wood to coal. These inventions (driver A) were a prerequisite to overcome the constraints of the former supply network, which was based on roads and waterways; railway routes enabled access to energy supply areas that could not be reached until then (Gingrich et al., 2012; Kim and Barles, 2012).

Finally, the literature provides various examples of **interlinked urban, resource and/or consumer characteristics** (#6, table 4.4). This type of relationship implies that different facilitating/constraining factors are connected and present simultaneously, making it difficult to discriminate what the effect of each individual factor is. Examples of all sorts of **interlinked characteristics** were found in the literature, with the exception of interlinked spatial and resource characteristics (table 4.5). Most examples of interlinked facilitators/constraints comprised interconnected spatial and consumer characteristics.

Table 4.5: Examples of interlinked characteristics

	Infrastructural characteristics	Consumer characteristics
Spatial characteristics	<p>In Los Angeles, buildings built before 1950 have the highest median annual consumption per square-foot, but buildings built 1980-2000 consume more energy than those built between the 50s and 80s (Porse et al., 2016). Pincetl et al. (2014) indicate that this is probably the result of other characteristics at building level such as building size and presence of appliances.</p> <p>Domene et al. (2005) point out that the suburban housing typology in the Barcelona Metropolitan Region often also comes with gardens and swimming pools and that these factors enhance outdoor water consumption.</p>	<p>Ariza-Montobbio et al. (2014) mention as explanation for the higher average consumption of electricity per household in suburban towns the spatial factors density, building type and size and the characteristics of the consumers living there, namely income level, lifestyle, and household size.</p> <p>Likewise, in their analysis of energy consumption in Los Angeles, Porse et al., (2016) stress that population density is correlated with income level. Porse et al. (2016) and Pincetl and Newell (2017) also indicate that spatial variation in energy consumption in L.A. is not only linked to the income level of the different neighbourhoods, but also to the differences in building size and age between poorer and wealthier neighbourhoods. Also Weisz and Steinberger (2010) indicate that high income is correlated with higher per capita floor space.</p> <p>Pincetl and Newell (2017) and Domene et al. (2005) indicate that houses in comparatively wealthy areas have a different garden typology, with a higher water demand, than lower income households.</p>
	<p>Infrastructural characteristics</p> <p>-</p>	<p>According to Ariza-Montobbio et al. (2014), a higher proportion single-person household leads to an increasing number of appliances, which contributes to the higher electricity consumption with smaller household size.</p>
Resource characteristics	<p>Kim and Barles (2012) and Gingrich et al. (2012) discuss how the shift in supply routes from river to railway reduced transport costs in 19th century Europe, making coal more affordable</p>	<p>Pincetl et al. (2014) found that lower-income residents who pay less for water than the next tier conserve more water than those paying more for their water.</p>

4.5 Discussion

4.5.1 Robustness of the synthesis

This systematic literature review shows that the evidence-base of the UM field that analyses the factors influencing urban water and/or energy consumption is still thin. More case studies are needed to deepen our understanding of those factors. As our review revealed that this body of UM literature consists primarily of research on mature cities in the global north and in temperate climates (see figure 4.3), future empirical work with case studies in other contexts is needed. The overview of factors (table 4.3) and their effects presented here should thus be interpreted with caution; this paper provides neither a complete indication of factors of influence nor a conclusive indication of their effects. Rather, this paper gives an overview of the factors and effects that the existing UM literature addresses. As such it serves as a starting point for future theoretical and empirical work. The overview allows for informed decisions on which factors to study and at the same time recognise upfront which other factors might be at play. Future case studies should improve the overview presented here by also studying potential factors of influence that hitherto have not been researched in the UM field. To identify these factors, as well as the needs of consumers, the work

of the various disciplines that aim to understand the roots of consumption (Poças Ribeiro et al., 2019) may prove valuable. Likewise, it is relevant to examine the explanatory variables used in water and energy demand models, for example those presented for water in the review by House-Peters and Chang (2011). Useful input could also be provided by the body of research investigating how urban form affects urban energy consumption, especially for future case studies aiming to further understand the facilitating and constraining role of spatial characteristics (Seto et al., 2014; Wiedenhofer et al., 2013). Future research can thus not only strengthen the evidence for the factors presented here, but it can also provide insight in additional factors of influence and build a more comprehensive overview of factors.

4.5.2 Unification in terminology and methodology

Aligning future research is essential to build such a comprehensive overview. Unification in terms of terminology and methodology will facilitate comparison of findings from different case studies. The observed lack of consistency among empirical studies is a known challenge within the UM field (Beloin-Saint-Pierre et al., 2017). In general, the reviewed work lacks clear – and widely accepted and used – definitions and consistent terminology. Moreover, the work varies in type of supporting evidence provided. In part, this is due to the heterogeneous sample; the primary studies included in the review are diverse in research design and spatiotemporal resolution of analysis (see figure 4.4). Yet, we would argue that this heterogeneity should *not* be a reason to disregard certain research designs. After all, the review shows that different types of research provide complementary evidence on drivers and facilitators/constraints of consumption. Nevertheless, efforts are needed to unify how factors of influence are measured. A promising development in this regard is that multi-year flow analyses, which have been criticized for not using indicators to support their findings (Pincetl et al., 2012), are developing into trend analyses that use indicators to explain temporal differences. Another, next step would be to develop a common indicator set to unify the measurement of factors of influence, in terms of indicators and their units of measurement – building upon existing work by e.g. Kennedy et al. 2014 and Minx et al. 2011. Such an indicator set should, for example, clarify whether building size refers to the size of the building footprint or to the combined gross or net floor area on all storeys. Likewise, it should indicate whether to express the factor ‘climate’ with the ‘average temperature of the warmest and coldest month in degrees Celcius’ (Minx et al., 2011) or using heating degree days (HDD) and cooling degree days (CDD), as proposed by (Kennedy et al., 2014). Together with the overview of factors and their effects, such an indicator set could be the basis for a unified approach to identifying correlations that facilitates comparability across case studies and research designs.

4.5.3 Data quality assessment

Our review not only reveals the need for more and aligned case studies, but it also highlights that more attention should be given to the quality and transparency of the data set used in these studies. During the quality assessment step in the review process 19% of the publications were excluded because they were unclear about the resolution of data used, another 14% were excluded because water and energy consumption figures relied on downscaled data. Also other recent reviews of the UM literature highlight these data quality issues. According to Beloin-Saint-Pierre et al. (2017) about 9% of their primary studies “did not offer enough info to identify category of data used” and they state that as much as 65% of overall UM studies relies on downscaled data. Li and Kwan (2018) stress that “coherence and quality assurance call for more serious attention”. That said, overcoming the data gaps that exist when it comes to high-resolution case studies is a common struggle within the field that cannot be solved overnight (Porse et al., 2016; Voskamp et al., 2018). The first step to advance the field in this regard should thus be to increase transparency of the type of data used. Patricio et al. (2015) and Hoekman and von Blottnitz (2017) are valuable precedents in this regard, formulating assessment frameworks to assess the resolution, accuracy and reliability of the data underlying their case studies.

4.5.4 The potential of UM research to advance our understanding of cities

It still remains problematic to determine the precise causes of particular resource use patterns (Hoekman and von Blottnitz, 2017). One of the challenges is that analysing the relationship between consumption and a single factor implies identifying *correlations*, rather than identifying *cause-effect relationships*. Moreover, our findings raise the question at what level of analysis, and to what extent, consumption patterns can be attributed to individual factors present. Although our review revealed generally a prevalent effect direction for a given factor (i.e. increasing or decreasing consumption), it foremost showed no universal ‘factor-consumption relationships’. Our synthesis shows ‘factor-consumption relationships’ that are subject to exceptions - cases where factors show a negative instead of commonly found positive correlation with consumption, or vice versa - as well as relationships that vary greatly in intensity or those that are inconsistent over different scale levels (see e.g. Athanassiadis et al. 2017b). These exceptions support the notion that consumption patterns cannot be attributed to individual factors present, and that the influence of the interconnections between factors (see table 4) on the direction and magnitude of effects should be considered. Hence, to get more insight into the causes of consumption, further research is needed aimed at understanding the interconnectedness between factors and how these interconnections affect

‘factor-consumption relationships’. In this regard, we think it is especially relevant to connect with urban ecological research that aims to understand the interactions, relationships, and feedbacks of system components (McPhearson et al., 2016b). We deem this not only essential in the pursuit to better understand the effect of the interconnectedness of factors, but also agree with Bai (2016) that UM research needs to connect consciously with the theory and conceptual approaches of urban ecological research to realize its full potential in advancing our understanding of cities.

Although UM research relies upon several of the principles for conceptualizing urban areas as complex social-ecological-technological systems ²⁴ (McPhearson et al., 2016b), hitherto there is a general absence of clear and explicit conceptual approaches as starting point for these studies. Studying cities as social-ecological-technical systems offers a conceptual basis to synthesize insights from different disciplines (Bai et al., 2016) and UM research can have a valuable contribution to this common understanding of cities, complementary to urban ecological research and complex adaptive systems science (McPhearson et al., 2016b). Bai (2016) indicates that this contribution lies, among others, in improving our understanding of (I) the influence of spatial heterogeneity within cities and (II) the processes and mechanisms behind temporal differences and variation among different cities. Indeed, our findings demonstrate this potential of UM research. We found that spatial patterns house other, interlinked factors that jointly facilitate or constrain consumers in their resource consuming activities (see table 4.5). Likewise, the drivers and their interactions with facilitators/constraints that we identified (see table 4.4), reveal some of the processes and mechanisms behind temporal and intercity variation.

4.6 Conclusions

This systematic review demonstrates that a growing number of UM publications aim to provide insight in the factors that underlie spatiotemporal variability in urban water and energy consumption patterns. The diversification of this body of literature in terms of study design contributes to a more complete understanding of the factors of influence, because each design has a unique spatiotemporal resolution of analysis and thereby provides insight in specific sorts of factors. Overall, our review revealed twenty-one *facilitators/constraints* and fourteen *drivers* that affect urban water and/or energy consumption. We conclude that case-specific consumption patterns cannot be attributed solely to the effect of individual factors present, because these factors are interconnected in time and space. These interconnections can potentially influence the direction and magnitude of effects and thereby contribute to case-specific variability in consumption patterns. It is key to connect with

²⁴ See footnote 20, page 89

related disciplines to deepen our understanding of these interconnections among urban system components and their effects on UM. A common systems approach to studying urban systems can inform and advance UM research, whilst also providing the opportunity for UM research to make a valuable contribution to understanding the systemic characteristics of cities. Our findings confirm that UM research has the potential to provide insight into the influence of spatial heterogeneity on urban water and energy consumption patterns, as well as to reveal the mechanisms and interlinked processes that underlie the spatiotemporal variability in consumption. More case studies can strengthen the evidence for the factors presented here, and contribute to building a more comprehensive overview of factors by providing insight in additional factors of influence. It is essential to align these studies in terms of a common terminology, transparent quality assessment and a unified approach to measuring and expressing factors of influence.

4.7. Outlook

We acknowledge that a thorough understanding of the interconnectedness of urban system components and its effects on UM is a long-term effort that requires tailoring UM research designs in the near future. We suggest that research on UM profiles on the short term can inform our understanding of the characteristics and behaviour of cities as social-ecological-technological systems in the long-term. Specifically, we suggest identifying UM profiles based on spatial patterns that represent a specific combination of interlinked and nested facilitators/constraints that have a combined influence on consumption patterns (see figure 4.5). Various primary studies indicated this nested character of facilitators/constraints in spatial patterns, including examples from the suburban neighbourhoods in Barcelona metropolitan region (Ariza-Montobbio et al., 2014; Domene et al., 2005) and the different neighbourhoods in the metropolitan area of Los Angeles (Pincetl and Newell, 2017; Porse et al., 2016). Likewise, Thomson and Newman (2018), recently demonstrated that different parts of a city - the automobile, transit and walking urban fabric - differ in terms of their UM. They suggest that the UM of these areas is determined by their distinct urban form and affiliated characteristics that are typical for the time of development, including density, land use, spatial layout and transportation system. In addition to such research on intra-city variation, developing a typology of cities based on (dis)similar consumption patterns can be valuable. It can provide insight into characteristics that are of distinctive importance for the UM profile at city level. So far, UM profiles at city level have been identified based on level of economic development and economic specialisation (Ariza-Montobbio et al., 2014; Currie and Musango, 2017; Rosado et al., 2016). Other suggested distinctive characteristics include city size and urbanization dynamics

depending on a city's level of maturity (Seto et al. 2014; Weisz and Steinberger 2010; Kennedy et al. 2007). Gaining more insight into the relative importance and combined effect of factors is an essential first step to unravel the interlinkages between factors within an UM profile and gain deeper understanding of the cause-effect relationships that underlie specific consumption patterns.

Figure 4.5: An Urban Metabolism Profile consists of nested facilitators/constraints, with a combined influence on consumption

Finally, establishing UM profiles can be a vital step in tailoring UM research towards informing sustainable resource management. After all, different UM profiles may require different interventions to steer towards more sustainable consumption patterns. Therefore, it is not only relevant to investigate how prevailing system characteristics and societal organization are linked to the *current* UM of a city, representing so-called 'social-ecological regimes' (Barles, 2015; Haberl et al., 2004). Rather, it is valuable to formulate scenarios of a *desirable* UM and the corresponding context and system characteristics, as well as the plans that aim to steer towards this scenario. Detailing such plans would entail describing what kind of changes in context, i.e. drivers, can be anticipated and identifying which ones are (un)desirable. This allows for identifying the interventions that can help steer these changes towards the desirable scenario, either by targeting those drivers directly or indirectly, through altering facilitating or constraining factors. These interventions are intrinsically linked to different stakeholders: local governments, for example, can formulate policies; utilities can make decisions that affect infrastructure and resource characteristics; and planning and design professionals can suggest altering spatial characteristics. In this regard, it might be relevant to discriminate factors of influence into endogenous ones that are within the sphere of influence of a stakeholder and those that are not, the exogenous ones. This may give resource managers an idea with whom to collaborate to target factors that are outside their own sphere of influence and to account for factors that should be considered a boundary condition, such as lifestyle and income of a consumer. Ideally, when the interlinkages and embeddedness of the factors in a UM profile are acknowledged, this will give an idea which stakeholder is able to contribute in what way to sustainable resource management in a specific context.

Abstract

To design effective strategies for sustainable urban resource management, it is essential to understand which urban characteristics underlie consumption patterns. We used multiple linear regression analyses to examine sixteen factors on their explanatory power for spatial variation in residential electricity, gas and water consumption in Amsterdam. Four models per resource were used, based on distinct spatial units aggregating high-resolution data, i.e. neighbourhoods, districts, 1ha and 2.5 ha square units. We found twelve explanatory variables for spatial variability in consumption in total and nine or ten per resource. The number and relative importance of explanatory variables varies with the spatial units used. Overall, neighbourhood models explain variance in consumption data best (adjusted $R^2=0.88, 0.86, 0.74$). *Income level* and *building type* stand out for having high relative importance (top 4) in all four models for two of the three resources; *migration history* shows an important correlation with water consumption, which was not described hitherto. We conclude that explanatory variables for resource consumption are sensitive to size and shape of spatial units used. Accurate and high resolution data are key for providing a comprehensive and accurate insight in explanatory variables for consumption. Such insights support urban planners and designers in formulating context-specific interventions.

5.

Spatial, infrastructural and consumer characteristics underlying spatial variability in residential energy and water consumption

A high-resolution case study of Amsterdam

A slightly modified version of this chapter is under review as:

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Spatial, infrastructural and consumer characteristics underlying spatial variability in residential energy and water consumption in Amsterdam

Sustainable Cities and Societies

5.1 Introduction

With more than half of the world's population dwelling in cities (UN, 2019), urban areas are facing unprecedented challenges regarding efficient resource consumption and related pollution issues (Agudelo-Vera et al., 2011; Pulido Barrera et al., 2018). At the same time, climate change is expected to further increase urban resource demands, including increased seasonal water demand and demands for building heating and cooling (Ciancio et al. 2020; Rasifaghihi, Li, & Haghighat, 2020). These impacts are not only expected to differ among cities, given their different geographic locations and climate conditions, but also within cities due to microclimate differences (Chen et al., 2020a). Hence, urbanization, climate change and the interlinked processes of change pose a complex challenge to urban planning and decision making (McPhearson et al., 2016a).

To formulate sustainability strategies and affiliated interventions on consumption reduction, urban planners and designers need detailed insight into urban resource flows (Kennedy, Pincetl, & Bunje, 2011; Pulido Barrera et al., 2018; Voskamp et al., 2018). To inform such strategies and interventions, it is particularly essential to comprehend not only where resource consumption takes place, but also how the specific conditions and urban characteristics at hand affect this consumption (Bettignies et al., 2019; Castán Broto et al., 2012; Cui, 2018; Jayarathna et al., 2017). After all, cities are typically characterised by the heterogeneity of their demographic, socio-economic, environmental and cultural characteristics that are forming complex mechanisms which underlie differences within and amongst cities (Li and Kwan, 2018; Pickett et al., 2016). Scholars agree that it is essential to acquire better understanding of the factors and mechanisms underlying urban resource demands (Cui, 2018; Rosales Carreón & Worrell, 2018; Villarín, 2019; Voskamp et al. 2020; Zhang, Yang, & Yu, 2015). A fine level of spatial detail must be adopted in studies aiming to provide this understanding, for only then can the spatial variation of urban and resource characteristics within the city be captured (Beloin-Saint-Pierre et al., 2017; Li & Kwan, 2018; Pincetl et al., 2012; Pistoni & Bonin, 2017).

Hitherto, various factors have been described to underlie variability in residential energy and water demand. Studies have substantiated correlations between consumption and climate and weather conditions (Meng et al., 2020; Rasifaghihi et al., 2020), demographic and economic factors (Bettignies et al., 2019) and urban and architectural morphological characteristics (Chen et al., 2020b; Fox et al., 2009; You and Kim, 2018). Others revealed a combination of climate, socio-economic and morphological characteristics as explanatory variables for energy (Chen et al., 2020a; Kennedy et al., 2015; Wiedenhofer, Lenzen, & Steinberger, 2013) and water consumption (Chang et al., 2017; Jayarathna et al., 2017; Stoker & Rothfeder, 2014; Villarín, 2019). To date, however, few

studies consider a long-list of potential factors of influence. They account only for one or a small number of independent variables instead, with *household size* and *income level* being frequently studied (Bich-Ngoc and Teller, 2018; Wiedenhofer et al., 2013). Still, it is known that consumption patterns cannot be explained by individual factors but rather by a large number of interconnected factors that have direct and indirect effects (Bich-Ngoc & Teller, 2018; Voskamp et al., 2020; You & Kim, 2018). Moreover, studies that consider both water and energy demand are rare (e.g. Pincetl et al., 2014) and those assessing correlations at different levels of spatial resolution too (e.g. Chang et al., 2017; Ghavidelfar, Shamseldin, & Melville, 2017; Kennedy et al., 2015). Studies that look into spatial variability of consumption using more detailed data aggregation levels than city level and that rely upon metered data are still uncommon (Bettignies et al., 2019; Bich-Ngoc & Teller, 2018; Voskamp et al., 2020). Yet, multi-level, high resolution case studies can provide insight in the scale- and city-dependent behaviour of explanatory variables for consumption, about which still little is known (Bettignies et al., 2019; Chang 2017).

In this study we address the need for high resolution studies that provide insight in the factors underlying spatial variability in energy and water consumption at different spatial scales. We use multiple linear regression analysis to examine a large set of factors as explanatory variables for the spatial variation in residential energy (electricity, natural gas) and water consumption within the city of Amsterdam. We examined the relative importance of the explanatory variables for each resource in four multiple linear regression models, each relying upon another spatial data aggregation level.

5.2 Theory

This research builds upon a systematic review of the factors underlying spatial and temporal variations in energy and water consumption to ensure a comprehensive consideration of potential explanatory variables for spatial variability in consumption (Voskamp et al., 2020). The authors reveal not only a long-list of factors, but they also conceptualize their coherence and categorize them in line with the work of Dijst et al. (2018) and Poças Ribeiro et al. (2019). Three main categories of factors are differentiated: (I) the *needs* of consumers, (II) *facilitators/constraints* that increase or decrease the probability or degree to which resource consuming activities are triggered, comprising consumer, resource, spatial and infrastructural characteristics and (III) *drivers*, which encompass large scale developments in societal context. For more theoretical background on these three sorts of factors and their effect on consumption, we refer to Dijst et al. (2018), Poças Ribeiro et al. (2019) and Voskamp et al. (2020). Of these sorts of factors, only spatial, infrastructural

and consumer characteristics (*facilitators/constraints*) have the feasibility to explain spatial variation in residential energy and water consumption patterns within a city. *Drivers* and resource characteristics (*facilitator/constraints*) can be assumed homogeneous at city-level, and consumer *needs* are disregarded because no spatially explicit data are available on these type of traits of individual consumers, such as individual aspirations.

Accordingly, spatial, infrastructural and consumer characteristics are assessed in this study as potential explanatory variables for spatial variation in residential energy and water consumption, given their potentially facilitating or constraining effect on consumption (table 5.1). The factors listed in table 5.1 comprise those listed in the aforementioned review and additional spatial, infrastructural and consumer characteristics derived from other reviews and case studies. Voskamp et al. (2020) namely used strict inclusion criteria for their review of urban metabolism (UM) literature, excluding for example studies based on survey data, because critical data quality assessment is central to their systematic approach to reviewing literature. So, although their categorization is comprehensive, the authors stress that other fields of literature should be consulted to complement their list of factors and to also assess these factors on their influence in future case studies. We selected the following additional factors for our case study: *property value*, *home ownership*, *rental housing type*, *education level*, *age*, and *migration history* (Baiocchi et al., 2015; Bich-Ngoc and Teller, 2018; Chang et al., 2017; House-Peters and Chang, 2011; Lenzen et al., 2004; Porse et al., 2016; Wiedenhofer et al., 2013).

5.3 Methods and materials

5.3.1 Study area and levels of investigation

This research was conducted using data of Amsterdam municipality, the capital city of The Netherlands. We investigated the explanatory variables for spatial variation in water and energy consumption in this study area using four spatial aggregation levels to identify whether results are affected by the resolution of observation. This approach also enabled us to identify bias resulting from the Modifiable Areal Unit Problem (MAUP), which indicates that variation in results occurs when the same analysis is applied to the same data but using different aggregation units (Openshaw, 1984)²⁵. We considered two units based on administrative divisions within the city, neighbourhoods and districts, and two based on grids, 100m and 500m squares (figure 5.1). These spatial units are in correspondence with the data aggregation levels used by the Dutch Bureau of Statistics to publish

²⁴ For more details on this approach to MAUP, see for example Nelson & Brewer (2017).

Table 5.1: Overview of potential explanatory variables for spatial variability in energy and water consumption

Type of urban characteristic	Factor	Potential facilitating / constraining effect	Type of correlation		
			Electricity	Natural gas	Water
Spatial	Population density	Lower consumption per household with a higher population density	-	-	-
	Amount of tree canopy cover	Lower energy usage for heating and cooling with a higher presence of productive tree canopy cover	-	-	n.d.
	Garden type	Higher water consumption with larger gardens and higher presence of grass	n.d.	n.d.	+
	Building size	Higher energy and water consumption with larger building size	+	+	+
	Building type	Lower usage with a higher share of multiple family buildings (e.g. apartment buildings), at the expense of the share of single family dwellings	-	-	-
	Building age	Lower natural gas usage and higher electricity and water usage with more recent building year	+	-	+
	Property value	Higher water consumption with higher tax assessed values	n.d.	n.d.	+
	Home ownership	Higher energy consumption with a higher share of owner-occupied houses, at the expense of the share of rental houses	+	+	n.d.
Infrastructural	Rental housing type	Different energy usage levels with a higher share of rental housing owned by housing associations			n.d.
	Presence of supply network	Higher electricity consumption and lower natural gas consumption with electric heating or a district heating network present	+	-	n.d.
	Presence of a pool	Higher electricity and water consumption with a private swimming pool present	+	n.d.	+
	Home appliances	Higher electricity consumption with more home appliances (e.g. air conditioning) present	+	n.d.	n.d.
Consumer (personal)	Sanitary fittings	Lower water consumption with high efficiency fittings (e.g. low-flow taps and showers) present	n.d.	n.d.	-
	Income level	Higher consumption with a higher income level	+	+	+
	Lifestyle	Higher electricity consumption with a high-income lifestyle	+	n.d.	n.d.
	Education level	Different energy and water consumption levels with a different education level			
Consumer (social and cultural context)	Age	Different energy and water consumption levels with a different age structure in the population			
	Migration history	Different consumption levels with a different ethnic community, indicated by their migration history			
	Household size	Lower per capita and higher household consumption levels with larger household size	+	+	+

Note: '+' indicates that literature describes a positive relationship, meaning that an increase in the factor is correlated with a higher consumption level; '-' indicates that literature describes a negative relationship meaning that an increase in the factor is correlated with a decrease in consumption; 'n.d.' indicates that this relationship is not described; and when the cell is blank, literature does not present conclusive supporting evidence of the type of correlation. References for correlations in Baiocchi et al. 2015; Bich-Ngoc & Teller, 2018; Chang et al., 2017; House-Peters & Chang, 2011; Lenzen, Dey, & Foran, 2004; Porse et al., 2016; Voskamp et al., 2020; Wiedenhofer et al., 2013.

data (CBS, 2016a, 2016b). Overall, Amsterdam municipality consists of 480 neighbourhoods, with an average size of 21ha (range: 2 - 1012ha), 99 districts, with an average size of 198ha (range: 17 - 2899 ha), 6711 squares of 1ha and 993 squares of 2.5ha (figure 5.1).

Figure 5.1: The study area Amsterdam municipality and its location in The Netherlands (top) and the four spatial aggregation levels adopted in this study illustrated for the same surface area in Amsterdam (bottom)

5.3.2 Data collection and preparation

Open datasets were the main source of data for the residential consumption data and data representing the potential explanatory variables. Electricity and natural gas consumption data for 2016 are available as open data through the Dutch Central Bureau of Statistics, whilst the water usage data were provided by the drinking water provider Waternet for 2014 (Supplementary material table S4.1). Acquired consumption data consists of aggregated yearly household meter readings, aggregated by the four levels described in 5.3.1. The water consumption dataset partially contains estimates by Waternet because 30% of the households in Amsterdam had no water meter at the time. We acquired data for the nineteen factors listed in table 5.1 from various Dutch open

data sets on each data aggregation level. No data were obtained for *presence of a pool*, *home appliances* and *sanitary fittings*. Therefore, these factors were not considered in our analysis. For the remaining sixteen factors, we used the available data to formulate a long-list of variables that could represent these factors, including 59 variables for the administrative units and 29 and 33 for the 1ha and 2.5ha grids (Supplementary material table S4.2).

5.3.3 Evaluation of collinearity among explanatory factors

Subsequently we evaluated collinearity within the long-list of variables, to select appropriate variables for all factors and to decide whether different factors must be observed together in the regression analysis. Collinearity is present when two or more of the independent variables that ought to explain a dependent variable are highly correlated to each other (Dormann et al., 2013). This can be problematic, as correlated independent variables can interfere with each other, resulting in incorrect selection of significant variables for the multiple linear regression. We used the Pearson coefficient (r) to detect the degree of linear relationship between two independent variables, with $r = 0$ signifying no relationship and $r = 1$ a perfect correlation. We choose a threshold of $r = 0.75$ for collinearity. If collinearity was present, we eliminated the variable that has the highest correlation with all other variables. After the collinearity evaluation, we also checked whether the other assumptions of multiple linear regression²⁶ were not severely distorted as this could lead to bias in relationship estimation and unreliable significance tests (Williams et al., 2013).

5.3.4 Multiple linear regression analyses

We developed a multiple linear regression model at each of the four spatial aggregation levels for all three resources, resulting in twelve models in R (R Core Team, 2017). We performed backward stepwise elimination with a threshold significance value of $p = 0.05$ to identify significant explanatory variables. This procedure eliminates the least significant independent variables from the model in a stepwise manner, until all independent variables meet the threshold value (Hastie et al., 2009). We then compared the results per resource to check for potential MAUP effects. If we identified major differences in regression results across the models, such as a positive relationship using one spatial aggregation level and a negative using another, we considered the relationship biased. After this evaluation, we created multiple regression models at each level of spatial aggregation with the

²⁶ To test the assumption for multiple linear regression (Poole and O'Farrell, 1971), in addition to collinearity evaluation, we created scatterplots of the independent variables against the dependent variable to evaluate whether a linear relationship between the dependent and independent variables could be assumed. To test for homoscedasticity, meaning that the random disturbance is the same across all values of the independent variable; the residuals versus fitted values and scale-location were plotted. For the assumption of multivariate normality, a q-q plot was created and autocorrelation in the residuals was tested by inspecting the residual plot.

variables that were found significant and un-biased. We calculated for each independent variable in all models its relative importance (*relaimpo* package v2.2-3, Groemping & Lehrkamp, 2018), expressing how much the variable contributes to the overall model (Grömping, 2006).

5.4 Results

5.4.1 Findings across models

Our research gives an overview of explanatory variables for residential electricity, natural gas and water consumption in Amsterdam, using four different spatial data aggregation levels (Table 5.2). A comparison of the model performance (second row, table 5.2a, b, c) shows that the electricity models have the highest fit (adjusted $R^2 = 0.58 < 0.88$) and the water models the lowest (adjusted $R^2 = 0.46 < 0.74$). The 100m-grid natural gas model has the lowest fit of all models (adjusted $R^2 = 0.42$). Findings furthermore indicate that the models using administrative divisions show a better fit than those using grids. The variance in electricity and water consumption is best explained with the neighbourhood models, (adjusted $R^2 = 0.88$ and 0.74), whilst for natural gas the district model outperforms the neighbourhood model (adjusted R^2 values 0.90 versus 0.86). In the electricity findings, the 500m-grid model stands out for having a comparable fit to the districts model.

Overall, twelve independent variables are found to be correlated with residential energy and water consumption in Amsterdam, having significance at the 95% confidence level. The results of the multiple linear regression analyses (table 5.2), show that five of these factors are explanatory variables for the consumption of all three resources: *income level*, *household size*, *age*, *building type* and *garden type*. In addition to these, *property value* can be considered a factor of importance for residential energy and water consumption in Amsterdam. This factor was not considered as variable in the models, and thus does not show in table 5.2, because it was found to be strongly collinear with average income level (depending on indicator variables, $r = 0.817 < 0.919$) (table 5.3)²⁷. We also find that electricity and water consumption have the explanatory variables *building size*, *rental housing type* and *migration history* in common. The high collinearity of *migration history* with *education level* ($r = 0.777$) (table 5.3) excluded *education level* from the regression models; this does however also imply a relationship between education level and electricity and water consumption. *Population density* shows as explanatory variable for electricity and natural gas consumption, *building age* for natural gas and water consumption and *home ownership* is a unique explanatory variable for natural gas consumption.

²⁷ Average property value was employed to represent the factor income level in this study, because data was present for all four spatial units, whereas this was not the case for the indicator variables for income level.

Table 5.2: Explanatory variables for spatial variability in residential energy and water consumption in Amsterdam; a. Results for electricity consumption; b. Results for natural gas consumption; c. Results for water consumption

a.

Electricity

Adjusted R² per model for each spatial unit

Factor	Indicator variable	Correlation
Building size	Percentage of houses with living space area above 80 m ²	Positive
Income level	Property value	Positive
Building type	Percentage of multiple family homes	Negative
Household size	Household size	Positive
Rental housing type	Housing associations	Negative
Age	Percentage of people between 25 and 44 years old	Negative
Population density	Population density	Negative
Garden type	Garden size	Positive
Migration history	Percentage of people with non-western migration history ¹	Positive
Presence of supply network	Percentage of houses connected to district heating	Positive

b.

Natural gas

Adjusted R² per model for each spatial unit

Factor	Indicator variable	Correlation
Presence of supply network	Percentage of houses connected to district heating	Negative
Income level	Property value	Positive
Garden type	Garden size	Positive
Building age	Percentage of houses with building year after 2000 ²	Negative
Building type	Percentage of multiple family homes	Negative
Age	Percentage of people between 25 and 64 years old	Negative
Household size	Household size	Positive
Population density	Population density	Negative
Home ownership	Percentage of owner-occupied housing	Negative

c.

Water

Adjusted R² per model for each spatial unit

Factor	Indicator variable	Correlation
Household size	Household size	Positive
Migration history	Percentage of people with non-western migration history ¹	Positive
Building type	Percentage of multiple family homes	Negative
Building size	Percentage of houses with living space area above 80 m ²	Positive
Age	Percentage of people between 25 and 44 years old	Negative
Rental housing type	Percentage of rental housing owned by housing associations	Negative
Building age	Percentage of houses with building year after 2000 ²	Negative
Income level	Property value	Positive
Garden type	Garden size	Positive

¹ Non-western migration history comprises first and second generation migration from Africa, Latin-America Asia and Turkey (CBS 2014, 2016a,b);

² For the grids this is a building year after 2005.

Neighbourhoods		Districts		100m-grid		500m-grid	
0.88		0.80		0.58		0.78	
Rank	Relative importance	Rank	Relative importance	Rank	Relative importance	Rank	Relative importance
1	0.22	Not significant		NA		NA	
2	0.16	3	0.17	2	0.17	2	0.16
3	0.15	1	0.40	3	0.16	1	0.24
4	0.14	Not significant		1	0.37	3	0.16
5	0.10	4	0.14	4	0.10	5	0.13
6	0.07	Not significant		5	0.10	4	0.14
7	0.07	2	0.21	8	0.02	6	0.08
8	0.05	Not significant		7	0.03	8	0.04
9	0.03	6	0.04	6	0.05	7	0.05
10	0.02	5	0.05	NA		NA	

Neighbourhoods		Districts		100m-grid		500m-grid	
0.86		0.90		0.42		0.65	
Rank	Relative importance	Rank	Relative importance	Rank	Relative importance	Rank	Relative importance
1	0.33	1	0.27	NA		NA	
2	0.29	4	0.15	2	0.34	3	0.22
3	0.11	5	0.05	3	0.06	4	0.08
4	0.11	1	0.27	1	0.53	1	0.37
5	0.09	Not significant		7	0.01	2	0.27
6	0.04	6	0.04	5	0.02	6	0.02
7	0.03	7	0.04	8	0.01	5	0.04
Not significant		Not significant		4	0.03	Not significant	
Not significant		3	0.17	6	0.01	Not significant	

Neighbourhoods		Districts		100m-grid		500m-grid	
0.74		0.68		0.57		0.46	
Rank	Relative importance	Rank	Relative importance	Rank	Relative importance	Rank	Relative importance
1	0.30	Not significant		2	0.36	Not significant	
2	0.23	1	0.32	1	0.41	3	0.18
3	0.17	3	0.22	3	0.07	1	0.40
4	0.13	Not significant		NA		NA	
5	0.12	2	0.27	5	0.04	2	0.25
6	0.04	5	0.06	6	0.04	5	0.04
7	0.01	6	0.06	7	0.01	6	0.03
Not significant		Not significant		4	0.05	7	0.01
Not significant		4	0.07	Not significant		4	0.10

Note that 'NA' means that this factor could not be assessed with that particular model, owing to data availability

Table 5.3: Cross-correlations between the twelve explanatory variables found and the factors collinear to those

Note: Green indicates a positive correlation and purple a negative one; the size and shade of the circle show the strength of the correlation.

Values $0.75 < 1$ indicate collinearity; collinear factors were excluded from our regression analyses.

5.4.2 Explanatory variables for residential electricity consumption

Using four multi linear regression models, we found a total of ten explanatory variables for electricity consumption in Amsterdam (table 5.2a). *Income level*, *building type*, *rental housing type*, *population density* and *migration history* are found significant for all four models. The factors *income level*, *building type* and *household size* are of high importance for all four models, ranking in the top 3 for all models (table 5.2a). A higher *income level* is positively correlated with electricity consumption, whereas the presence of more *multiple family homes* has a negative correlation. Although *building size* ranks first for neighbourhoods, this factor is not significant for districts and could not be assessed for the grid models. *Household size* is not found significant for the district model, albeit a significant explanatory variable in the other electricity models. In the 100-m grid model *household size* is the most important explanatory variable. Likewise, *percentage of people between 25 and 44 years old* and *garden size* are not significant for the district model, whereas they are significant in the other three models. Finally, *population density* has a high relative importance in the districts model (0.21), whilst it has considerably lower importance in the other three models.

5.4.3 Explanatory variables for residential natural gas consumption

We found nine explanatory variables for residential consumption of natural gas in Amsterdam (table 5.2b). Five of these are significant with all spatial units used: *income level*, *garden type*, *building age*, *age*, and *household size*. *Building age* is the most important variable in all models except the neighbourhoods model, indicating that lower residential gas consumption levels are found in areas that have a higher *share of dwellings built after 2000*. For the districts model, this variable is of equal importance to *presence of district heating* (relative importance 0.27); no data was available for the grids. At neighbourhood level, the share of homes connected to *district heating* is found to have an even stronger negative correlation with natural gas consumption (relative importance 0.33, ranking first). *Income level* exhibits an important, positive relationship with natural gas consumption in all models and a similar, but less important correlation is found for *garden type*. Whereas *percentage of multiple family homes* is not significant for the districts model, it is significant for the other three natural gas models and is even of high importance for the 500m-grid model (0.27). The *share of owner-occupied houses*, on the other hand, ranks only high (number 3) in the district model. Finally, *population density* is only significant for the 100m-grid model.

5.4.4 Explanatory variables for residential water consumption

We found also nine explanatory variables for Amsterdam's residential water consumption, including five that are significant for all models: *migration history*, *building type*, *age*, *rental housing type* and *building age* (table 5.2c). A higher *share of people with a non-western migration history* and a lower *share of multiple family homes* are consistently correlated with higher water consumption levels. Both *migration history* and *building type* consistently rank in the top 3. Meanwhile, the *share of people between the age of 25 and 44* negatively correlated with residential water consumption for all models. This was the second most important variable for the district and 500-m grid models with a relative importance of 0.27 and 0.25. Although average *household size* in an area is an explanatory variable with very high importance for the neighbourhoods and 100m-grid water models, ranking first and second respectively, this factor is not found significant for the other two models. *Building size* could only be assessed for the models using administrative units, and is found only significant for the neighbourhoods model. Finally, *income level* and the average *garden size* are both found significantly correlated to residential water consumption for two of the four models.

5.5 Discussion

5.5.1 Findings across spatial units used

Our findings show that spatial variability in energy and water consumption levels is better explained by the models using administrative units than by the grid models. Overall the model fit is highest for the neighbourhood models and lowest for the 100-m grid models (table 5.2). Partly these differences in performance reflect that less data was available for the grid models and that data availability has affected the 100-meter grid models most, owing to privacy restrictions. The performance of the grid models is probably especially affected by the lack of data on *building size* and *presence of supply network* aggregated in square units, considering that these factors have very high importance in the neighbourhood models. Another explanation for the differences in model fit is the different geometry and size of the spatial units used in the models. Neighbourhoods and districts have been shaped historically and follow urban form and natural boundaries like water or roads, whereas the generally smaller square units that ignore these “natural” boundaries. Hence, the square units aggregate data with relatively higher variance in spatial and infrastructural characteristics. This effect of unit shape especially shows when comparing 500m-grid and neighbourhood results, as these models had comparable percentages of observations with missing values. The 500m-grid models have an adjusted R^2 of 0.78, 0.65 and 0.46, whereas this is 0.88, 0.86 and 0.74 for the neighbourhood models. It is recommended for future studies to explore further whether models using homogenous aggregates of spatial and infrastructural characteristics explain variance in consumption levels better. This would be a valuable insight, because urban form based units resonate with the urban planning and design field.

Our results confirm earlier research showing that explanatory variables for resource consumption are sensitive to the spatial units used. So far this was shown only in studies comparing two different levels of spatial resolution, in the case of water for census area versus household or census block level (Chang et al., 2017; Ghavidelfar et al., 2017) and in the case of energy for city versus census area level (Bettignies et al., 2019; Kennedy et al., 2015). By considering four levels of spatial aggregation, we show that it matters at which level of detail within the city spatial variation of urban and resource characteristics is studied. Our results show that the number and relative importance of explanatory variables varies with the spatial units used. Findings are particularly distinctive for the three districts models, which make use of the largest spatial units and thus represent the lowest spatial resolution in this study (see figure 5.1). It is for example striking that *household size* is not significant for the electricity and water district models. This factor ranks high for the other electricity and water models and the effect of *household size* on water and energy consumption is

substantiated in many studies (e.g. House-Peters & Chang, 2011; Lenzen, Dey, & Foran, 2004; Weisz & Steinberger, 2010). It also stands out that *home ownership* was found to have a much greater importance for the natural gas district model than the other models; the same applies to *population density* for explaining electricity consumption. Kennedy et al. (2015) suggest that *population density* is a relevant factor to explain variation in electricity consumption at a lower resolution of analysis, such as at district or city level, whilst other factors are appropriate explanatory variables at a more detailed level instead. Indeed, our results seem to show the significance of explanatory variables for consumption is dependent on the spatial unit used. To get a better understanding of the scaling impact, we recommend future high-resolution studies to also use different spatial aggregation levels when assessing factor-consumption relationships. Thereby, the modifiable areal unit problem (MAUP) should be considered and units should be included that correspond with the field of decision-makers, planners and designers.

5.5.2 Generic and Amsterdam specific explanatory variables

The majority of factors mentioned in the literature were found to be significant explanatory variables, with effects that are in line with previous studies (table 5.4). If we compare our results with evidence from literature, our finding for *migration history* and *age* stand out. It is striking that *migration history* is found to be an explanatory variable of high importance for water consumption, although this factor is not often considered in residential water demand studies thus far and no clear connection between this factor and water consumption has been described (Bich-Ngoc and Teller, 2018; House-Peters and Chang, 2011). Given the collinearity between *migration history* and *education level* (table 5.3), the latter consumer characteristic could also be explanatory. However, also for *education level* there is no agreement in literature on its potential effect. Explanations for the influence of these two consumer characteristics may be found in differences in environmental awareness, behavioural aspects, practices and attitudes towards water use (Bich-Ngoc and Teller, 2018). It is also notable that we found a moderately negative correlation between the *share of people between 25 and 44 years old* and electricity and water consumption. Previous studies do not agree on the effect of consumer *age* on water consumption and little is described in the context of electricity consumption (Bich-Ngoc and Teller, 2018; Wiedenhofer et al., 2013). We assume our results reflect that less time spent at home results in lower consumption, considering that the abovementioned age group is of working age.

Also our findings for *building age*, *home ownership* and *lifestyle* are not in line with what is described in literature. Instead, these results seem to indicate that different cities have different

Table 5.4: Summary of the identified relationships, classified according to their relative importance

Type of urban characteristic	Factor	Explanatory variable	Relative importance and direction of correlation		
			Electricity	Natural gas	Water
Spatial	Population density	Number of people per km ²	Moderate negative	Low negative	
	Amount of tree canopy cover	Number of trees per 100m ²			
	Garden type	Average size of the garden per household (m ²)	Low positive	Moderate positive	Low positive
	Building size	Share of houses with a living space area above 80m ² (%)	High positive		Moderate positive
	Building type	Share of multiple family homes (%)	High negative	Moderate negative	High negative
	Building age	Share of houses with built after 2000 (%) ¹		High negative	Low negative
	Property value	<i>Collinear with income level</i>			
	Home ownership	Share of houses that is owner-occupied (%)		Low negative	
	Rental housing type	Share of rental houses owned by housing associations (%)	Moderate negative		Low negative
Infrastructural	Presence of supply network	Share of houses connected to district heating (%)	Low positive	High negative	
	Presence of a pool	<i>Not assessed due to lack of data</i>			
	Home appliances	<i>Not assessed due to lack of data</i>			
	Sanitary fittings	<i>Not assessed due to lack of data</i>			
Consumer (personal)	Income level	Average property value (€)	High positive	High positive	Low positive
	Lifestyle	Average number of passenger cars per household			
	Education level	<i>Collinear with migration history</i>			
	Age	Share of people between 25 and 44 years old (%) ²	Moderate negative	Low negative	Moderate negative
Consumer (social and cultural context)	Migration history	The share of people with a non-western migration history (%) ³	Low positive		High positive
	Household size	Average number of people in a household	High positive	Low positive	High positive

Note: the classification in this table follows from the number of models for which the factor was significant, the relative importance scores and model fit (adjusted R²) for each level (table 5.2).

¹ For the 100- and 500-meter grids this is the year 2005;

² For natural gas this is the share of people between 25 and 64 years old;

³ Western migration history is defined by the Dutch Bureau of Statistics as first and second generation migration from Europe (excluding Turkey), North-America, Oceania, Indonesia or Japan.

relationships between factors of influence and consumption, as found previously (Bettignies et al., 2019). For example, our findings do not confirm a relationship between *building age* and electricity consumption, as Pincetl et al. (2014) found for Los Angeles. Whereas in L.A. newer buildings have more electricity consuming appliances installed like air conditioning, air conditioning is uncommon in The Netherlands. Likewise, we did not confirm the positive correlation between *home ownership* and electricity consumption and gas consumption found for L.A. (Porse et al., 2016). Yet, it should be noted that in 2016 almost 70% of all houses in Amsterdam were rentals, and over 60% of those rental houses was owned by housing associations (CBS, 2016a). Indeed, our findings do show that in the case of Amsterdam it is relevant to distinguish *rental housing type*, with significantly lower electricity and water consumption levels in areas with a higher share of rental houses owned by housing associations. Contrary to earlier findings, *lifestyle* was also not found to be a variable of significance. However, *lifestyle* was assessed with the variable ‘*number of passenger cars per household*’. Earlier studies that mention car ownership as indicator for *lifestyle* are from North America and Australia (Hall, 2011; Wiedenhofer et al., 2013). In these contexts, cities have a distinctively different, generally more car-dependent urban form than Europe and *car ownership* may be a useful indicator to distinguish between automobile, transit and walking urban fabric, or urban and sub-urban lifestyle (Thomson and Newman, 2018; Weisz and Steinberger, 2010; Wiedenhofer et al., 2013). Our findings thus reflect that *car ownership* is not an appropriate indicator for Amsterdam, which has a dense cycling and public transit network. Further research should show to what extent our results are specific to Amsterdam, and to what extent they are applicable to other Northern European or Dutch cities.

5.5.3 High resolution data for accurate explanation of variation

In this research we used multiple linear regression to assess the significance of the explanatory factors for residential electricity, natural gas and water consumption. The assumptions for linear regression were met for most resources and spatial aggregation levels. However, the assumption that the random disturbance is the same across all values of the independent variable, i.e. homoscedasticity, was not fully met for the natural gas grid models. This is probably because data on the presence of district heating was not available for the grids, whilst this was found the most important factor for explaining spatial variation in natural gas consumption with the neighbourhood and district models. Consequently, the results show that these models have lower adjusted R^2 values and the relative importance of explanatory variables becomes skewed towards one (*building age*) or few variables (*building age, building type, income level*). A more nuanced picture of the relative importance of variables is seen in the neighbourhood and district models.

When comparing the adjusted R^2 values of all models, we find very high values for the energy models using administrative units and overall lowest performance for the water models. The high R^2 values for the energy district and neighbourhood models could indicate that these models are somewhat overfitted, which means that the models partly explain noise in the data rather than the actual variance. Future research that applies the same method to another city could be a valuable means for cross-validation these findings. The performance of the water models may be affected by the water consumption data used, which has a greater degree of uncertainty than the energy data because it partially relies on estimates (see 5.3.2). Another explanation for the lower fit of the water models could be that the aggregation of data in yearly consumption levels for the spatial units used, is less suitable for water than for energy consumption. In the case of water, the resolutions used may still be too coarse and thus mask variations of key variables, considering that previous research found that indoor and outdoor use have different explanatory variables (Chang et al., 2017; Ghavidelfar et al., 2017; House-Peters et al., 2010; Rasifaghihi et al., 2020). A higher temporal and spatial resolution may thus be required for better performance of the water models. Higher resolutions can reveal seasonal variation, outdoor water use, and more accurately show spatial variation in explanatory variables – e.g. indicating garden presence per block instead of average *garden size* at neighbourhood level. The performance of our models thus underlines the importance of using accurate, high resolution data for these types of regression studies and indicate that the optimal resolution of study may differ with the resource of interest.

The importance of using accurate, high resolution data is also seen in the findings for *building size*, *garden type*, and *amount of tree canopy cover*. The data used for these variables may not represent the factor accurately enough. Contrary to our initial hypothesis, *building size* was not found to be a significant explanatory variable for natural gas consumption. However, this finding could also show that there was insufficient differentiation in the data used – houses were only discriminated into those having a living space smaller than 80m² or larger than 80m². The factor *garden type* was assessed using ‘*average m² of garden per household*’, which does not provide insight into garden characteristics affecting outdoor water use such as impervious surface cover or presence of irrigation-dependent vegetation (Chang et al., 2017). Similarly, the dataset for trees does not provide any information about the size of the tree canopy but merely on the number of trees under management by the municipality. To better assess the factors *garden type* and *amount of tree canopy cover*, remote sensing images may prove a useful data source. Chen et al. (2020), Chang et al. (2017) and Pincetl et al. (2014) show that such images can be used to derive the normalized difference vegetation index (NDVI) and assess the correlation of amount of green space coverage with water and energy demand.

5.5.4 Mechanisms underlying urban energy and water consumption

Our results show that energy and water consumption have a substantial overlap in terms of key explanatory factors for spatial variation at intra-city level. All but one of the variables that were found to have explanatory value are of significance for two or all three resources. Factors shared by three resources and with relative high importance are *income level*, *household size*, *building type*, and - with somewhat lower importance - *age* and *garden type* (table 5.4). *Building size*, *building age*, *presence of supply network* and *migration history* stand out because they are shared by two resources and are of relative high importance for at least one of these. Our collinearity evaluation shows that cross-correlations between these variables are present (table 5.3). For example, *income level* is correlated with *building size* ($r = 0.47$) and *migration history* ($r = -0.65$) and *building type* is correlated with *household size* ($r = -0.65$) and *the share of people of working age* ($r = -0.56$). We hypothesize that these interconnections reflect that consumer and spatial characteristics are generally present in specific combinations and that these “lifestyle clusters” each have characteristic consumption patterns. So, although the factor *lifestyle* was not found significant for any of the three resources, our results actually reflect that *lifestyle* is an overarching factor, captured by both consumer and spatial characteristics.

The notion of such clusters is also described by others, who identified similar connections between spatial and consumer characteristics as the ones that we found in Amsterdam. Wiedenhofer et al., (2013) and Baiocchi et al. (2015), for example, both stress that energy consumption patterns can be linked to the clusters of urban characteristics present, that are defined by the factors *population density*, *building type*, *income level*, *household size*, and *age* (e.g. ‘affluent urban dwellers’). The presence of clusters and the interconnections between factors could also clarify some of the unexpected relationships found, such as the positive correlation between *garden type* and energy consumption. These findings could reflect that a larger average *garden size* is indicative for a lifestyle with a generally high energy consumption, i.e. of high-income households (*income level*), living in larger homes (*building size*) and individual dwellings (*building type*), with a larger average *garden size*. Models such as regression tree analysis or machine learning algorithms like Random Forest could help identify such clusters based on consumption patterns and underlying, interconnected consumer and spatial characteristics. Regardless of the specific clusters, the explanatory variables identified in this study can already provide guidance for decision makers, urban planners and urban designers when formulating urban development plans and circularity strategies. We show the importance of taking future resource demands into consideration when designing development plans, as urban form and the lifestyle of envisioned future residents underlies water and energy

consumption patterns. Our findings highlight the relevance of spatially explicit approaches and tailoring policies and strategies to certain groups of citizens or the owners of rental housing.

5.6 Conclusions

Our multiple linear regression analyses have revealed the factors underlying residential electricity, natural gas and water consumption in Amsterdam. We found twelve spatial, infrastructural and consumer characteristics that are significant explanatory variables for spatial variability in residential energy and water consumption. Explanatory variables with high importance for electricity, natural gas and water consumption are *income level*, *household size*, and *building type*. Important correlations not described hitherto are those between *migration history* and water consumption, and between the *share of people between 25 and 44 years old* and electricity and water consumption. We conclude that the explanatory variables for resource consumption are sensitive to the spatial resolution of observation. Especially the three districts models reveal the influence of the spatial unit used, as they have some distinct findings in the relative importance of explanatory variables compared to the neighbourhood and grid models. Our neighbourhood and district models perform considerably better than the grid models, partially because the shape of these units correspond to urban form and partially because some factors could not be assessed with the grid models. We thus also conclude that for regression analyses to provide comprehensive and accurate insight into explanatory variables for consumption it is crucial to use accurate and high resolution data of a long-list of potential factors of influence that is aligned with urban divisions. When data is missing, model performance is clearly affected and less variance in consumption levels is explained. Finally, explanatory variables for consumption are found to be cross-correlated. Insight in these interconnections is needed to understand the complex mechanisms underlying spatial variability in residential water and energy consumption. We recommend identifying in what specific combinations consumer, infrastructural and spatial characteristics are present and whether consumption patterns can be linked to the specific cluster present. Also, more multi-scale, high-resolution case studies are needed to identify optimal shape and size of spatial aggregation units for these sorts of regression analysis and to shed light on site and scale specific mechanisms underlying spatial variability in consumption. Such insights are valuable for urban planners and designers when formulating context-specific interventions for consumption reduction.

6.

General Discussion

6.1 Urban metabolism assessments for urban planning and design

Transitioning to a circular economy is nowadays at the agenda of many national and city governments. With a growing attention for the circular economy in the past decade, interest in urban metabolism (UM) also increased from a policy and design practice angle (Athanasiadis et al., 2018b). Assessments of UM, such as material flow analyses (MFA), can provide insight into how urban areas function with respect to resource flows. Such knowledge is essential to design evidence-based plans and strategies for the urban environment that aim to effectuate the transition towards a circular economy.

Scholars acknowledge the potential of MFA to inform resource-conscious urban planning and design (Galan and Perrotti, 2019; Kennedy et al., 2011; Moffatt and Kohler, 2008; Pistoni and Bonin, 2017). Yet, this potential is limited because these UM assessments do not reveal metabolic differences within a city, nor do they unveil city characteristics that shape these patterns (Athanasiadis et al., 2015; Yetano Roche et al., 2014; Zhang et al., 2015). Therefore this research: (I) examined how comprehensiveness and resolution of analysis affect the potential of UM assessments to provide insightful evidence of UM, and (II) investigated the factors and mechanisms that underlie spatiotemporal variability in resource flows and stocks, to advance understanding of the systemic characteristics of cities and their metabolism. Energy and water were chosen as main resources of interest.

This research thus aimed to make methodological contributions and generate substantive knowledge that enhance the potential of UM assessments as evidence base for resource-conscious urban planning and design. The main findings of this thesis, in terms of contributions to these two research objectives per chapter, are summarized in figure 6.1. Comprehensiveness of analysis was the main focus of the ‘grey-box MFA’ of Amsterdam (chapter 2), whereas chapter 3 investigated at which spatial and temporal resolution UM should be assessed. These two chapters thus primarily provide answers to research objective 1 (see figure 6.1). Research objective 2 is mainly addressed with the systematic review of UM literature (chapter 4) and the high resolution case study of Amsterdam (chapter 5).

Present chapter discusses the main contributions of this thesis, highlights the value of this research for urban planning and design practice, and provides recommendations for future research. This thesis relies upon a methodological approach that is novel for the UM field (6.2.1) and contributes to methodological alignment in UM assessments (6.2.2). This research furthermore advances understanding of the systemic character of cities (6.2.3). Findings are valuable for formulating

strategic visions for urban development (6.3.1), planning infrastructural networks (6.3.2), and commissioning and designing neighbourhood (re)development plans (6.3.3). To enhance usefulness of UM assessments in practice, knowledge transfer between science and practice should be detailed in the design of UM research projects (6.3.4). A transdisciplinary ‘*research through designing*’ approach is promising to explore how UM assessments can be used and integrated in the design process (6.4.1) and methodological attention should be given to spatially explicit UM assessments that focus on optimization potentials (6.4.2). Future UM research benefits from an interdisciplinary, place-based and multi-scale perspective, which a ‘*landscape – SETS*’ can provide (6.4.3). In conclusion, this research discloses the potential of UM assessments as evidence base for resource-conscious urban planning and design, and it provides understanding of the factors and mechanisms that underlie spatiotemporal variability in UM (6.5).

6.2 Contributions to the Urban Metabolism field

6.2.1 Novelty and limitations of the research approach

This thesis relies upon a methodological approach that is novel for the UM field in three regards. Firstly, a *research for design* approach was taken – contributing to the evidence base for resource-conscious planning and design. Secondly, it relies upon a transdisciplinary approach, not only combining insights and methods from different disciplines, but also insights from local stakeholders. Thirdly, this research uses a multi-scale approach, as it investigates the metabolism of Amsterdam on different spatial resolutions. Hitherto, UM research that aims to inform the design of sustainability solutions is still scarce, even though this potential of UM research is endorsed. Likewise, multi-scale, mixed-methods and transdisciplinary UM research is uncommon, although such approaches are considered promising methodological directions for the field (Cui, 2018; John et al., 2019; Li and Kwan, 2018).

Research for design

This thesis demonstrates that UM assessments can form a relevant evidence base for resource-conscious urban planning and design. Findings from chapter 3 support that evidence of UM is essential to inform resource-conscious interventions. Stakeholders need adequate information on water and energy supply and demand to inform interventions, but this information is generally not readily available. UM assessments are a potential evidence base to provide this information, provided that data is available and analyses can be performed on a sufficiently high resolution.

Research objective 1 Methodological contributions

Comprehensiveness and resolution of UM analysis

- To evaluate the sustainability of a city's metabolism, it is beneficial to: account for resource rather than material flows, disaggregate in- and output flows, discriminate throughput flows and reveal internal sourcing processes;

- Comprehensive assessment is instrumental to benchmarking among cities and interpreting the temporal evolution of UM.

Chapter 2: Comprehensive 'grey-box' MFA

- The typical resolution of MFAs, on city level and per year, is generally of insufficient detail to inform resource-conscious interventions. UM assessments at higher resolutions are desirable;

- The relevant resolution of analysis depends on the envisioned intervention and the resource flow of interest.

Chapter 3: Spatiotemporal resolution of analysis

- It is valuable to assess UM at different spatiotemporal resolutions as this results in complementary evidence on factors influencing consumption.

Chapter 4: Factors and mechanisms of influence

- Significance and relative importance of explanatory variables for energy and water consumption are sensitive to the spatial resolution of analysis;

- An assessment at multiple spatial resolutions is essential to reveal scale dependencies of factors of influence;

- A comprehensive list of explanatory factors is essential for providing adequate understanding of factors that underlie spatial variability in UM.

Chapter 5: Explanatory factors at high resolution

Research objective 2 Substantive knowledge

Factors and mechanisms influencing UM

- Natural resource availability and presence of a port can explain metabolic differences between cities.

- A broad range of factors underlie spatiotemporal variability in consumption:
I) drivers, i.e. changes in societal context that shape consumption patterns,
II) needs of individuals and communities,
III) consumer, resource and urban landscape characteristics that manifest themselves as facilitators/constraints of consumption;

- Factors of influence are interconnected in time and space; these interconnections contribute to case specific UM patterns.

- Energy and water consumption have a substantial overlap in terms of key explanatory factors for spatial variation at intra-city level;

- Factors with relative high importance - such as *income level, household size, building type, migration history* - are cross-correlated, which substantiates that facilitators/constraints are interlinked;

- Correlations between consumption levels and explanatory factors are site and scale specific.

Figure 6.1: Overview of the main findings of chapter 2 – 5 in relation to the overarching research objectives of this thesis

Moreover, this research shows that a comprehensive MFA discloses key flows and processes for output minimization and multi-sourcing (chapter 2). A city-level UM assessment can accordingly support stakeholders with valuable knowledge for taking steps towards a circular metabolism. This thesis furthermore demonstrates the value of UM assessments for demand minimization. It is shown that UM assessments provide insight into a variety of factors influencing resource demand - with different research designs providing complementary understanding of these factors (chapter 4). Understanding these factors and mechanisms of influence is essential to design effective demand minimization strategies and interventions. A contribution to this evidence base is made with an overview of factors and mechanisms influencing energy and water demand (chapter 4) and with empirical evidence obtained in assessments of Amsterdam's metabolism (chapter 2 and 5).

The contributions of the 'research for design' approach are confined to methodological and substantive insights regarding the potential of UM assessments to provide knowledge of a city's *current* metabolism. Taking MFA as point of departure, implied a focus on the potential of a baseline assessment of UM as evidence base for resource-conscious urban planning and design. However, designing optimization strategies and interventions requires additional evidence, including evidence of place-specific, realistic targets for a *future* metabolism. Future UM *research for design* should therefore focus on methodological developments towards spatially explicit UM assessments that reveal optimization potentials.

Transdisciplinary research

This thesis shows that a mixed-methods, inter- and transdisciplinary approach in UM research is crucial to gain a more inclusive insight in UM. This approach also proved instrumental to identifying specific stakeholder needs and practical constraints that need to be accounted for in UM assessment frameworks, as stressed previously (Dijst et al., 2018; Wei et al., 2015; Zhang et al., 2015). The first chapters of this thesis (chapter 2,3) demonstrate that it is valuable to involve stakeholders in UM research. In chapter 2, an MFA is combined with stakeholder workshops. This research shows that such workshops do not only leverage access to data, but are also useful to gain insight into case-specific flows and processes of importance that should be accounted for in an UM assessment. The mixed-method design thus safeguarded the integration of stakeholder knowledge, which demonstrated valuable to assessing and understanding Amsterdam's metabolism. Acquiring stakeholder input in a structured way showed furthermore instrumental to identify stakeholder preferences/requirements for UM assessment methods and barriers to UM evidence uptake (chapter 3).

This thesis also illustrates that it is valuable to integrate methods and expertise from different disciplines in UM research. Chapter 4 shows that different spatiotemporal scopes and methodological approaches in UM research, which partially reflect different disciplinary perspectives on UM, provide complementary insights in UM and the factors influencing it. Chapter 5 shows that it is also valuable to collaborate with disciplines further from UM research, such as geo-information science. Expertise with regard to georeferenced data and methods is indispensable for research that investigates the spatial dimension of UM, which is an essential angle to take in future UM research.

Despite the above-mentioned contributions of the chosen research approach, this research has not fully utilized the value of transdisciplinary research. Given the overall project setup, there was greater involvement of stakeholders in the first part of the research. Also, involved stakeholders were primarily from the public sector, with few representatives from the private sector. Citizens were not involved whilst chapter 4 reveals that their characteristics, needs and activities play a determining role in UM. Most importantly, only a few practising designers were involved and their involvement was primarily limited to consultation. UM research would benefit from more insight from this practitioner side, such as UM-related questions that arise in design processes.

Multi-scale, embedded case study

This thesis shows that a multi-scale approach is essential for an in-depth understanding of a city's metabolisms and the mechanisms underlying variability in these flows. This thesis shows that valuable insights of influential city-characteristics can be obtained with a city-wide MFA (chapter 2), whilst high-resolution analyses at intra city level can provide additional insights in factors underlying spatial variability in consumption (chapter 5). Moreover, the multi-scale approach of chapter 5 reveals that a multi-scale approach can shed light on site and scale specific effects. Nevertheless, this research is limited by focussing only on the city of Amsterdam. It is essential to further contextualize findings and evaluate whether they are specific to Amsterdam, or also more generically applicable. Comparing findings with those obtained in studies of other cities proved an adequate means to interpret case-study results (chapter 2,5). Moreover, recent research shows that the MFA case study results (chapter 2) are useful to develop a more generic metabolic understanding across Europe (Bianchi et al., 2020), medium-sized cities (Bahers et al., 2018), and port-cities (Bahers et al., 2020; Tanguy et al., 2020). Additional comparative research, at multiple temporal and spatial scales, is needed to acquire a more in-depth understanding of generic and context-specific aspects of UM.

6.2.2 Methodological alignment of UM assessments

It is widely acknowledged that the lack of a uniform UM assessment methodology, data availability and consistent data classification are main challenges in the UM field (Cui, 2018; Dijst et al., 2018; Li and Kwan, 2018; Yetano Roche et al., 2014; Zhang et al., 2015). Accordingly, aforementioned reviews express that urgent methodological advancements for the UM field lie in methodological alignment, streamlining indicator use, consistent data classification and quality assurance of data. This thesis not only confirms that abovementioned issues affect UM research, but also makes contributions towards tackling these challenges and aligning future UM assessments.

This thesis shows that urban MFAs, even when taking the Eurostat method as starting point, differ greatly because they all adapt the original accounting methodology (chapter 2). This lack of methodological uniformity in urban MFAs impedes comparing case studies. According to Athanassiadis et al. (2018a), because these different methodological approaches “can result in case studies having very different levels of disaggregation, precision and comprehensiveness”. Nevertheless, this research reveals that the different methodological advancements that individual case studies propose are compatible. Integrating these advancements in an modified version of the Eurostat MFA is thus a step towards methodological alignment in city-level MFAs. A contribution towards alignment in UM assessments is also made with the overview of factors influencing energy and water consumption that is presented in chapter 4. The overview facilitates comparability in research designs of studies that are specifically designed to research correlations between consumption figures and factors explaining them. It enables researchers to make an informed decision as to which factors to assess in their case and to compare case study results, in view of factors (un)accounted for. Also the complementary long-list of potential indicator variables (chapter 5) can prove valuable for a unified approach to identifying correlations that facilitates comparability across case studies. Next steps lie in assessing general applicability of these indicator variables and alignment with existing international datasets and indicator sets (e.g. Kennedy et al., 2014; Minx et al., 2011).

This thesis also provides insights that are relevant to ongoing discussions in the field about data availability and data quality assurance (Beloin-Saint-Pierre et al., 2017; Li and Kwan, 2018; Pincetl et al., 2012; Yetano Roche et al., 2014). It is shown that high-resolution, measurement data is indeed scarce – revealing data gaps for Amsterdam (chapter 3) - and so are studies that rely on such data (chapter 4). It is also illustrated that availability of accurate data is crucial to enable comprehensive and high-resolution case study research and that the lack of such data affects results (chapter 2, 5). Additionally, this thesis shows that a call for high-resolution data

in itself is too generic. Chapter 3 provides a much needed perspective to this appeal, by revealing that efforts should actually be directed at answering “what are *desired* and *appropriate* spatial and temporal resolutions of analysis?”. Also, a focus on resolution in itself is too limited. Aspects such as data availability, accuracy and aggregation level should also be considered (chapter 3, 5). I thus align with Dijst et al. (2018) and Li and Kwan (2018) that UM research requires a more solid underpinning of the appropriate scale of research and that data quality assurance requires serious attention. Accordingly, transparent and strict data quality assessment was an important part of reviewing publications of UM assessments (chapter 4). Also, Amsterdam’s metabolism was assessed (chapter 2,5) using reliable, primarily open, high-resolution data. Nevertheless, additional steps must be taken with regards to data quality assurance in future UM research. Providing metadata in a standardized format should become common practice with UM assessments (see for example Hoekman and von Blottnitz 2017; Patricio et al. 2015), as it enables evaluation of the quality of underlying data and uncertainty analysis of UM assessment results.

6.2.3 *Advanced understanding of the systemic characteristics of cities*

Traditionally, the engineering UM field has an empirical focus. Explicit theoretical contributions are practically absent, barring few exceptions (e.g. Dijst et al. 2018). Also, a clear and common conceptualization of urban systems is missing except for the analogy of cities as organisms – whose appropriateness is being critiqued (Bai, 2016; Golubiewski, 2012; Newell and Cousins, 2015). Yet, it is acknowledged that the engineering field of UM research can contribute to an advanced understanding of the systemic character of cities by providing important insights into characteristics of the urban system (Bai, 2016). Scholars stress it is necessary to find a common language and conceptual framework that facilitate theoretical development and inter- and transdisciplinary UM research (Athanasiadis et al., 2018b; King et al., 2019; Pincetl et al., 2012; Zhang et al., 2015).

This thesis makes a contribution to understanding the systemic characteristics of cities and demonstrates that insights from empirical work can contribute to theoretical development in the UM field. Bai (2016) argues that empirical UM studies can provide insight into eight key characteristics of cities, including aspects of metabolic performance (characteristics #1-5, table 6.1), patterns and processes (#6-7) and mechanisms of influence (#8). These characteristics are listed and explained in the first column of table 6.1. This table shows that this thesis contributes to a better understanding of seven of these characteristics. Findings of chapter 2 contribute to aspects of metabolic performance, whilst chapter 4 and 5 contribute to understanding patterns, processes and mechanisms of influence. It is of particular importance that this thesis contributed with knowledge

Table 6.1: Contributions of this thesis to understanding the systemic characteristics of cities

Urban system characteristics	Research contributions	Chapter
1. Material and energy budget and pathway: the type, magnitude and pathways of flows, as well as their link with city characteristics and with impacts of these flows	A city's geographic location can explain the renewable energy performance of that city; The resource budget and flow pathways of port cities are strongly connected to their functional role: consumer-related consumption flows are dwarfed by throughput flows ascribable to the port	2
2. Material and energy intensity: the amount of resources used per area or per capita	Port cities are resource intensive; resource intensity is reflected in high direct material input (DMI) and domestic material consumption (DMC) per capita.	2
3. Material and energy efficiency: the amount of socio-economic services supported per unit of resource consumption	-	-
4. Rate of accumulation and retention: the accumulation, retention rate and flow speed of resources	Port cities have characteristic accumulation rates that can be traced back to port activities, i.e. long-term, bulk storage that extends across different years.	2
5. Self-sufficiency (vs. external dependency): the effective utilization of resources stocked or flowing through the city	Various local sourcing processes ensure effective utilization of local resource flows and stocks: -The local biophysical environment sustains a city with renewable energy, which is (still) a relatively small part of the overall energy budget, and stormwater and groundwater inflow into the sewer, which makes up a substantial proportion of the resource budget; - Waste is a valuable stock to source secondary resources, including various sorts of materials, electricity, heat and fuels.	2
6. Intra-system heterogeneity: the location of (potential) resources and the relationship between the structure of the city and its metabolism	Consumer, resource, spatial and infrastructural characteristics explain spatial variability in urban water and energy consumption at intra-city level, owing to their facilitating and constraining effects on consumption. In a city there are no universal relationships between consumption patterns and explanatory variables; significance and relative importance of these relationships depend on the spatial resolution of observation.	4 and 5
7. Temporal and intersystem variation: the processes of changing systems and the processes underlying intercity variation	Inter-city and temporal variation in UM reflect differences in the societal context in which the urban landscape is embedded; large scale developments in this context affect UM as <i>drivers</i> . This thesis describes 14 drivers and their effects on energy and water consumption. Also, consumer, resource, spatial and infrastructural factors can explain differences in consumption over time and between cities; these factors affect UM as they increase or decrease the probability or degree to which specific activities are triggered. This thesis describes 21 such <i>facilitators/ constraints</i> and their effects on energy and water consumption. The relationships between energy and water consumption patterns and their explanatory variables are not universal, these relationships are case-specific.	4 4 5
8. Regulating capacity: the mechanisms that shape and regulate metabolism	Interconnections between factors influencing UM affect the direction and magnitude of their effects, this results in case-specific variability in consumption patterns. This thesis describes six such relationships. Spatial, infrastructural and consumer characteristics are cross-correlated. Likely, these factors are present in specific combinations, "clusters", which form complex mechanisms that induce characteristic consumption patterns.	4 5

Note that '-' indicates that this thesis does not make a contribution on this aspect. Bai (2016) provides a more elaborate explanation of these eight characteristics, and the ways in which empirical UM studies provide insight into these aspects.

about ‘rate of accumulation and retention’, ‘self-sufficiency’ and ‘regulating capacity’, because there is fewer empirical evidence concerning these characteristics. Likewise, little is known about the interconnections between these eight system characteristics (Bai, 2016). This thesis makes two main contributions to understanding these interconnections: (I) a conceptual framework that categorizes different sorts of factors influencing urban resource consumption (chapter 4), and; (II) insight into the relationship between metabolic performance and patterns and mechanisms influencing UM, based on a review of UM literature (chapter 4) and case study research (chapter 2, 5).

Engineering UM research offers a complementary perspective to other disciplines working in the UM field and in urban research more generally (Bai, 2016; McPhearson et al., 2016b). As stressed in chapter 4, the social-ecological-technological systems (SETS)²⁸ framework is promising as a common conceptual ground, as it offers a systemic perspective that enables dialogue and integration between the different disciplines working in the urban field. Here I argue that a ‘landscape approach’ should complement this systemic SETS conceptualisation with the much needed spatial perspective (see 6.4.3). Such a ‘landscape – SETS’ approach can facilitate the connection with environmental design disciplines, whilst it can also make the abstract notion of SETS concrete and tangible. After all, landscapes – including those at great distances from our cities – are physical expressions of the integrated ecological, socio-economic and technological processes and structures that (have) shape(d) and sustain(ed) our past, present and future societies (textbox 6.1).

Textbox 6.1: Cities and their metabolism: SETS embedded in landscape

Urban areas have developed in close connection with the local landscape and the resources it could provide. It is no coincidence many cities worldwide are positioned in the world’s biodiversity hotspots in coastal areas (Elmqvist et al. 2013). Historically, settlements were located in floodplains and in low areas with high fertility, as this richness allows many species to thrive and thus secured resource supply. Hence, the physical structures of society have always been essentially rooted in the ecosystem services that our natural landscape provides and upon which our social-economic systems rely (Haberl et al., 2004). Yet, as our societies changed, the metabolism of our cities changed and so did the connections with the landscape in which they are embedded. Based on these changing relationships between society and the natural system, prevailing system characteristics, and metabolic characteristics, different “social-ecological regimes” can be appointed (Barles, 2015; Haberl et al., 2004). With transitions in regimes, such as from the agricultural towards the current industrial society, also came large-scale landscape transformations (De Jong and Stremke, 2020). In our industrial society, we rely more and more on large infrastructural and logistic systems for our supply (Agudelo-Vera et al. 2011). Accordingly, the metabolism has become “externalised” or “outsourced” – supply areas have become larger in size and at greater distance from the city – whilst having greater spatial impacts on our landscape (Bahers et al., 2020; Barles, 2015; Kim and Barles, 2012; Tanguy et al., 2020). These impacts differ with the type of resource, whether it concerns landscapes of resource extraction, conversion, storage or transport, and the pace and permanence of landscape transformation (Pasqualetti and Stremke, 2018). Nowadays cities have become small entities within the overall engineered, transboundary infrastructures that safeguard their functioning (Ramaswami et al., 2012). Hence, cities have become structures that are not only embedded in the landscape through ecosystems services, as social-ecological systems, but also in large-scale infrastructural systems as social-ecological-technological systems.

²⁸ See footnote 20, page 89.

6.3 Societal value and usefulness for practice

The current generation of policy makers, planners, designers and resource managers awaits the challenge to design and implement pathways and solutions for sustainable urban development. This thesis provides *descriptive* and *analytical* insights in support of this challenge, which can help planners and designer address questions like “*What is going on here?*” and “*Why is it like that?*” (Campbell, 2012). This research specifically provides useful insights for three fields of resource-conscious planning and design – and the specific practitioners involved in these fields: regional design, infrastructural design and urban design. *Regional design* refers to designing a desirable future for a city or metropolitan region in several decades time, thus having a broad spatial and temporal scope. These designs “have a strategic character and provide the framework for smaller scale decisions” (Kempenaar et al., 2016). Designers typically involved in these sorts of designs include urban planners and landscape architects, in collaboration with stakeholders such as local governmental and institutions that regulate land use (e.g. port authorities). *Infrastructural design* refers to designing infrastructural networks for resource supply and waste handling, which is primarily the field of civil engineering and urban planning, and stakeholders such as utilities. *Urban design* refers to designing new city developments or redesigning existing neighbourhoods and districts, including the integration of technologies at the building level (e.g. solar panels). Such projects are typically commissioned by city authorities and different kinds of designers can be part of the design process, including civil engineers, landscape architects, urban designers and architects.

6.3.1 Regional design

This thesis demonstrates that a comprehensive, city-wide MFA provides descriptive knowledge of UM that is valuable as UM baseline assessment for regional design (chapter 2). Such an assessment can be used to describe the ‘current state of affairs’ by revealing the most relevant impacts flows of a city. The proposed modifications to the urban Eurostat MFA make these MFA findings particularly useful as a baseline for formulating visions and strategies that aim to bring about a transition toward a more circular UM, and to benchmark progress towards these visions. This confirms the previously stated usefulness of city-wide MFAs for monitoring UM development, identifying strategic points of intervention and evaluating the impact of measures (González et al., 2013; John et al., 2019; Yetano Roche et al., 2014; Zhang et al., 2015). Yet, UM assessments at city-level in itself provide only partial answers to the question “*Why does the metabolism of this city look the way it does?*”. To answer this question, the results of chapter 4 may prove valuable. These findings indicate that

the societal context and facilitating/constraining city characteristics can be investigated to interpret the findings of an UM baseline assessment.

The overview of drivers and facilitators/constraints that are relevant at city level (chapter 4) is also useful for stakeholders involved in designing long-term visions and plans. At first glance, large scale changes in societal context (*drivers*) might seem to be part of ‘the toolbox’ of other stakeholders than environmental designers. Decision-makers, for example, can formulate an adequate response to *crises*, set *rules and regulations* and initiate large-scale *educational campaigns*. Yet, *drivers* are also a vital part of designing strategic plans and future visions at the city and metropolitan level. Such visions are not just images of the future spatial situation, rather, these visions reflect which future societal context is envisioned and which city characteristics are desirable and which not. A vision can for example reflect whether or not a city will accommodate *population growth* and what type of a city or region strives for – and whether or not that implies providing a location to all sorts of businesses, with their characteristic consumption profile and sustainability ambitions. Accordingly, these visions form a framework for decisions at different levels of intervention for a long period of time. It is thus valuable that this thesis outlines how societal context and city characteristics affect resource demands. This overview may support regional designers in evaluating choices regarding envisioned societal context on their effect on the future UM.

6.3.2 Infrastructural design

This thesis also shows that a comprehensive, ‘grey box’ MFA can provide useful evidence for stakeholders involved in infrastructural design. Such an UM assessment is in particular valuable for benchmarking and identifying key flows and processes for optimization. Owing to increasing transparency of the system, the MFA findings reveal key internal local sourcing processes, such as the sourcing of secondary resources from internal waste treatment processes. Insight in these processes can match the information needs at municipal level for designing resource recovery or reuse solutions that rely on these secondary resources (chapter 3). Likewise, findings of chapter 2 reveal the amount of heat obtained from biogas conversion, derived from wastewater sludge digestion at waste water treatment plants. Evidence on the amount of locally generated heat is useful for the design of interventions such as heat networks.

The overview of factors influencing consumption (chapter 4) can also prove relevant for stakeholders involved in infrastructural design. Developing scenarios is considered a useful approach for planners and engineers for choosing flexible design alternatives in infrastructural design (Spiller et al., 2015).

Scenarios can be used to evaluate what kind of infrastructure is flexible and robust to cope with different future situations and, given its ability to cope with future change, what are accordingly potential low- and high-risk investments. The overview of drivers can be used to formulate different urban development scenarios and to assess how these changes may result in different demands and related changes in system capacity. What kind of promising technological developments are currently gaining momentum and how to provide the flexibility to accommodate future inventions in the existing urban infrastructure? But also, what kind of economic, demographic and cultural changes may be anticipated and how do they affect future demands? What would be the effect of uncertain, but disruptive crisis events? Additionally, the results of chapter 4 indicate the possible interplay between drivers and design and management decisions: response mechanism, prerequisite condition and curtailing condition. Hence, these findings underline that questions are not just: what resources, of which quality, can be made available in the future, with what sort of supply infrastructure and for which price? But also, what are the right interventions in response to changes in societal context, which changes are a prerequisite condition and how may changes result in curtailing conditions?

6.3.3 *Urban design*

As mentioned in 6.3.1, strategic choices and ambitions at the city level are of utmost importance for the future metabolism as they set the boundary conditions for urban developments. This also applies to choices made in the design of master plans for neighbourhood or district (re)developments and the related commissioning process. Local governments can make a major contribution towards sustainable future consumption patterns by considering determinants of resource demand in the public master planning and commissioning. These factors can be accounted for as part of the design brief and/or as part of the evaluation of design proposals.

This thesis shows that specifications of a master plan for an urban (re)development, and the choices subsequently made in elaboration of these plans, can affect resource demands in both a direct and indirect way. Direct considerations for commissioning lie in the specification of spatial and infrastructural characteristics. This may include outlining characteristics such as density, stipulating a percentage of social housing rentals, and specifying whether specific infrastructure is to be integrated, for example a district heating network. These characteristics are not only found potential factors of influence (chapter 4), but these factors are also empirically validated as explanatory variables of significance for energy and water consumption in Amsterdam (chapter 5). Master plans and the commissioning process can affect future resource demands also in a more

indirect way, by outlining an envisioned atmosphere and/or market segment. In the elaboration of neighbourhood (re)development plans, designers will make design choices that fit this atmosphere and/or type of future residents. These are for example choices with regard to building type, size and garden size – spatial factors found to be of high importance for explaining consumption of residential energy and water consumption in Amsterdam (chapter 5). At the same time, these design choices affect property values and what kind of income groups, household compositions (e.g. families, couples or students), and related lifestyles are attracted by the plans. Chapter 5 shows that consumer characteristics are important explanatory variables for water and energy consumption and that explanations for demand are also to be found in lifestyle, which is reflected in the combination of spatial and consumer characteristics. The potential contribution to be made with urban design is considerable, given the urban development task at hand in the coming years. This contribution can be made by various urban design actors as the city characteristics that facilitate or constrain consumption are part of the working domain of a multitude of designers, including civil engineers, landscape architects, urbanists and architects.

6.3.4 Towards comprehensible and applicable evidence for practice

Additional work is needed to ensure applicability of this research in planning and design practice. The previous sections highlighted the value of this research as evidence base for resource-conscious planning and design, but this does not mean that this evidence can be directly applied in practice. Another essential step is to translate and communicate this evidence in an accessible and understandable way, so that it aligns with the language of planners and designers and is applicable in the design process (Brown and Corry, 2011). Future research should explore how descriptive and analytical insights from UM assessments can be translated in such a way that they enable judgment what action to take in which circumstances (Campbell, 2012). A promising approach could be to formulate UM planning and design guidelines: “evidence-based, universally applicable knowledge that guides urban design actions in a variety of site-specific spatial and functional circumstances, and that is considered useful by design practitioners” (Klemm et al., 2017) (see 6.4.1).

Nevertheless, effective knowledge transfer between research and practice is not straightforward (Hurley et al., 2016; Nisha and Nelson, 2012; Rijken et al., 2020; Stigt et al., 2014), and this challenge is also faced within the UM field (John et al., 2019; Perrotti, 2019; Yetano Roche et al., 2014). I deem it therefore not only important that transdisciplinary research becomes more common in the UM field, but also that research projects are designed bearing the conditions for effective knowledge transfer in mind. Accordingly, the UM field should not just call for transdisciplinary approaches, but

also start a dialogue how to ensure effective knowledge exchange between different disciplines and between academics and stakeholders in such projects. So far, there is little attention in the UM field how to foster knowledge exchange between science and practice to generate impactful knowledge, barring exceptions (e.g. Perrotti 2019). Whom to involve, when and why? What is a desirable level of collaboration, the related role of the people involved and their influence on the research output? How to ensure that different experts understand each other's different way of thinking and working? What type of process setup can facilitate this and what does this imply in terms of time investment and value created? Institutions that fund research projects that aim to generate 'science for impact', such as the Amsterdam Institute for Advanced Metropolitan Solutions (AMS), have a contribution to make in ensuring that a process setup facilitates the intended knowledge transfer.

6.4 Directions for future research

I recommend that for UM assessments to adequately inform urban planning and design, new approaches in UM research should be taken. These approaches should go beyond the current descriptive, analytical perspective of methods such as MFA. I discern three relevant angles to advance UM research and to further explore the potential of UM knowledge in general and UM assessment in particular for resource-conscious urban planning and design. These are the following:

- I. Transdisciplinary design research;
- II. Spatially explicit UM assessments that focus on optimization potentials;
- III. UM research from an integrated landscape – SETS approach.

6.4.1 *Transdisciplinary design research*

I recommend future transdisciplinary research aimed at making evidence from UM assessments more comprehensible for practitioners and better tailored to the design process. As Klemm et al. (2017) show, participatory design workshops can be a means to formulate guidelines that connect scientific knowledge that has been obtained in a 'research for design' approach with knowledge of practitioners. A guideline suggests a specific strategy or principle for a set of situations that are generalisable; they are thus neither completely universal, nor entirely specific, prescribed solutions. Guidelines are beneficial for the efficiency and outcome of a design process because it gives designers an idea of the possible solutions that fit a specific situation, thereby excluding less suitable

alternatives (Prominski, 2017). UM planning and design guidelines could for example complement the UM typologies discussed in chapter 4, giving guidance what are promising demand optimization strategies for various UM types. Scenario development can be used to develop guidelines with decision-makers, engineers and planners to support them with master planning at a strategic level. By comparing the desired future situation to the current situation (chapter 2), guidelines can be developed how to arrive at that situation and how to accommodate anticipated and unexpected drivers. Broersma and van den Dobbelsteen (2018) illustrates the potential of such an approach with the Urban Energy Transition Methodology. They show that scenario development can be used to arrive at energy transition guidelines for different neighbourhood types, and to formulate an integrated city roadmap that connects these guidelines with concrete targets, a timeline and preference location for interventions.

Design research that uses the act of designing as main research component, so-called ‘research through designing’ (Prominski, 2017), can also be a valuable means to further explore how UM quantifications can be used and integrated in the design process. The integration of UM evidence in the design process is addressed in few scientific publications so far (Galan and Perrotti, 2019; Marin and Meulder, 2018; Roggema, 2019), even though this integration requires attention. Choices regarding housing typology, garden typology and density, for example, will not just influence energy and water demand, but will also affect the local climate conditions, mobility, as well as social interaction and aspects like liveability, safety and security. The challenge of designing sustainable urban environments lies not just in those individual aspects, of which a more sustainable metabolism is one, but the more in the integration of these aspects. To bring all these interests, perspectives and insights regarding sustainability together, it is essential to include experts with different disciplinary backgrounds and practitioners from different fields (Luederitz et al., 2013). I recommend that designers should play a central role in such future transdisciplinary UM research endeavours, as do the methods they have at their disposal, such as spatial analysis, scenario development, mapping and 2D and 3D visualizations. Designing is in essence an integrative activity (Ahern, 2013) which can contribute by exploring the issues at hand and developing coherent solutions. Designing can also provide process-related contributions and for example influence perception, engage people and support consensus building (Kempenaar et al., 2016). The integrative, interdisciplinary character of design, as well as the balancing of interests that is inherent to the design process, the forward looking perspective anchored in a profound historical and systemic understanding of landscape, is of utmost value to explore how to set out sustainable urban pathways that are widely supported.

6.4.2 UM assessments that reveal optimization potential

I have shown that the inventory of flows and stocks that UM assessments such as MFA provide, can give leads for essential first steps towards circular UM (6.2.1). Yet, I argue that a different angle should be taken for UM assessments to inform resource-conscious interventions and strategies. As also stressed by other scholars, attention should be given in the UM field to what a desirable, future metabolism is and how to realize it (John et al., 2019; Rosales Carreón and Worrell, 2018; Yetano Roche et al., 2014). I argue that a promising direction for future research are spatially explicit and comprehensive UM assessments that disclose UM optimization potentials.

Rather than focussing on current inflows and outflows in UM assessments, emphasis is needed on optimisation potentials and the quality of (available) resources in a spatially explicit manner. For example, where is how much surface water present and what is the quality of that water? Which drinking water demands could this source substitute and what level of treatment would that require? In the field of energy-conscious planning and design methods already exist with such a focus. Energy potential mapping can provide insight in spatial distribution of energy sources and sinks and accordingly inform energy-conscious interventions and strategies (Fremouw et al., 2020). This methods comprises mapping the quantity, quality and location of energy demands and potentials within an area, including renewable sources and anthropogenic ones, such as heat generated with industrial processes (Broersma et al., 2013; Van den Dobbelsteen et al., 2011). Wielemaker et al. (2020) show that potential mapping is also relevant in the context of nutrient recovery. They reason that their maps of nitrogen, phosphorus and potassium hotspots in Amsterdam can be used to identify locations with high nutrient loads, which may be promising locations to implement nutrient recovery technologies.

I suggest that future UM assessments should take a comprehensive approach in mapping potentially re-usable output flows, harvestable renewable sources, as well as stocks and demands. What and where are the potentials to reduce resource demand, to substitute high-quality inputs with lower-quality ones, to upgrade the quality of flows and to mine urban stocks? A valuable first step in this direction are recent spatial approaches to MFA, especially those revealing the locations of stocks of urban resources, “urban mines” (Geldermans et al., 2019; Han et al., 2018). It is furthermore essential in these assessments to look beyond the built environment and also consider the green and blue infrastructure in cities. Not only because it houses sources, sinks, pathways and stocks of resources, but also because of its (potential) provision of ecosystem services which can play an important role in supporting a more sustainable urban metabolism (Perrotti and Stremke, 2020). Such a comprehensive approach to potential mapping is useful to formulate adequate and place-

specific strategies, but also to formulate feasible scenarios and realistic UM optimization targets that can be the basis for planning and design proposals.

6.4.3 UM research from an 'integrated landscape – SETS approach'

Finally, I deem it essential that a common conceptual ground is sought between the Industrial Ecological UM tradition, the other fields of UM research and environmental design disciplines. I argue that an integrated landscape-SETS approach is promising as common conceptual ground as it enables taking an integrated, interdisciplinary and multi-scale perspective. I have outlined (chapter 4) that the conceptualisation of cities as SETS is valuable to facilitate the dialogue between the different disciplines working in the urban field. Such a common conceptualisation in urban research is needed to advance our understanding of the mechanisms shaping our current society, which is essential to shift towards a new, sustainable society. At the same time, sustainability strategies also need to account for capacities and considerations of governing institutions (Barles, 2015; Ramaswami et al., 2012). Likewise, it is vital to account for technological and spatial constraints as well as qualitative stakeholder considerations, when formulating sustainability targets (Oudes and Stremke, 2018). What is desirable for heritage sites? How can UM optimization (see 6.4.2) affect provision of other ecosystem services (e.g. cultural ones)? I therefore argue that a 'landscape approach' should complement the systemic SETS conceptualisation to support research aiming to connect with environmental design disciplines and to inform sustainable urban development.

A landscape approach in UM research can complement a SETS approach in several ways. Whereas a SETS approach facilitates a conceptual, multi-scale spatial perspective that connects the city with the larger territories and infrastructure it is embedded in, a landscape approach can offer a place-based focus. The unique spatial identity of a particular place also reflects the mechanisms that have shaped and are shaping a city and its metabolism (see textbox 6.1) – and thus also facilitate concretizing a multi-scale temporal perspective. As shown in chapter 3, such a multi-scale, spatiotemporal approach is essential to provide useful evidence for planning and design. Additionally, a landscape approach is complementary to a SETS perspective in acknowledging the multifaceted character of landscapes – which is the challenge when designing sustainable urban landscapes, outlined above (6.4.1). Especially in an urban context – where space is scarce and highly demanded – multifunctionality is of utmost importance in development strategies. Accordingly, designing requires balancing different societal interests - economic, social, ecological, cultural - and considering all these interest in coherence with functionality, attractiveness and future value of the design to ensure spatial quality (Hooimeijer et al., 2001). Landscape is not only an integrative

concept that bridges the ecological, economic, socio-cultural and political dimension - and the disciplines working in these domains, but landscape approaches are also based on the recognition that landscapes are multifunctional by nature (Arts et al., 2017).

The challenge lies not only in the development of the integrated SETS-landscape approach as basis for conceptual and theoretical alignment, but also in reflections thereof in methodological approaches as concrete steps forward. Promising methodological developments for UM accounting in this regard include aforementioned spatial approaches to MFA (6.2.2), as well as ecosystem-service expanded MFAs (Perrotti and Stremke, 2020), multi-scale analyses that consider dependency on foreign territories (Tanguy et al., 2020) and MFAs that account for the overall water balance (Farooqui et al., 2016; Kenway et al., 2011; Renouf et al., 2018). To make real steps forwards in the direction of a common conceptual ground, efforts should be given to education, as this will provide the practitioners of the future with a systemic landscape perspective. Educating different disciplines with similar frameworks safeguards that the civil engineer, urbanist, landscape architect, urban ecologist, urban planner and policy advisor of the future speak a similar language that enables collaboration (Ramaswami et al., 2012). This should not be confused for educating all those professionals in similar fashion, rather it is about giving them shared frameworks and concepts in which they can place themselves and their disciplines adjacent to others. For these professionals from different disciplinary backgrounds to collaborate successfully on sustainability solutions, they need to be well-trained in their own discipline but also capable of looking beyond its boundaries and able to communicate beyond (Arts et al., 2017). Social-ecological-technological systems and their expression in landscape – which is the working domain of the aforementioned disciplines - can serve as such a common ground that enables the experts of the future to connect their different knowledge domains.

6.5 Conclusions

This thesis aimed to inform methodological development of UM assessments to enhance their usefulness for resource-conscious urban planning and design and to acquire an advanced understanding of the systemic characteristics of cities and their metabolism. I conclude that for UM assessments to provide insightful evidence of UM for resource-conscious urban planning and design, a city's metabolism and its underlying factors of influence should be assessed comprehensively and at several spatial and temporal resolutions. This thesis shows that a comprehensive, 'grey-box' MFA provides a deeper understanding of UM than a conventional MFA. Such a comprehensive assessment is instrumental to evaluating the sustainability of a city's UM and can inform urban

strategies that aim to enhance the sustainability of an urban area. Higher resolution assessments are needed to inform the implementation of interventions, as stakeholders need a more detailed insight in resource flow variability for this. To ensure that UM assessments generate meaningful results for resource-conscious urban planning and design, it is foremost essential to provide a solid underpinning of the chosen resolution(s) of UM assessment. Such a choice should not just be based on the specific case and design project at hand, but should also consider the resource flow(s) of interest and the required type of data and desired level of accuracy. Taking such a comprehensive, multi-scale approach is also essential to provide a systemic understanding of a city and its metabolism. This thesis namely shows that consumption patterns cannot be attributed solely to 'universal factor-consumption relationships'. Rather, the relationship between consumption patterns and factors is case and scale dependent, and consumption patterns are a reflection of place-specific interconnections between factors in time and space. Combining the methods and perspectives from different academic disciplines with stakeholder knowledge is essential to acquire an in-depth understanding of a city's metabolism. Moreover, a place-based and multi-scale perspective in UM research is essential to advance our understanding of (case-specific) consumption patterns and their underlying case- and scale-specific mechanisms of influence.

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Supplementary Material

S1. Supplementary material from chapter 2

S1.1 Data sources used for the MFA study of Amsterdam

Local extraction

Stormwater and groundwater inflow into sewer

- Estimates based on time series analysis wastewater inflow at Amsterdam's WWTPs (De Fooij, 2015).

Biomass

- Amsterdam specific figures on crop acreages in 2012 (Binternet, 2015);
- Dutch averages on yearly crop yields per hectare (CBS, 2015; KWIN 2010);
- Amsterdam specific figures on grape yield (Amsteltuin, 2015).

Renewable energy

- Wind energy: based on statistics installed capacity in Amsterdam in 2012 (Windstats, 2015);
- Solar energy (PV): based on statistics installed capacity in Amsterdam in 2012 (City of Amsterdam, 2015);
- Incineration of green waste: measured amount of energy generated by AEB Amsterdam in 2012 (AEB, 2015a) and Dutch averages on biogenic waste fraction (Agentschap NL, 2013);
- Biogas combustion: measured amount of biogas combusted by AEB Amsterdam in 2012 (AEB, 2015a) and general numbers on yearly electricity and heat production at Orgaworld Amsterdam (Groengas, 2011; Orgaworld, 2015, Warmtenetwerk, 2012);
- Geothermal energy: estimates based on Amsterdam specific 2013 data of licensed ATES capacity (City of Amsterdam, 2014a; OD NZKG, 2013);
- Biomass stoves and boilers: top-down extrapolations from national data for Amsterdam in 2012, provided by the Dutch Ministry of Infrastructure and the Environment (Klimaatmonitor, 2015);
- Cold extraction from surface water: measured amount of cold extracted in Amsterdam in 2012 (Nuon, 2015).
- Hydrogen: measured amount of hydrogen produced in Amsterdam by GVB (municipal public transport company) in 2012 (GVB, 2015).

Recovered materials& energy from waste

- Rubber products: general numbers on yearly amounts of rubber recycling within Amsterdam (Granuband, 2015);
- Metals and nonmetal minerals: measured amount of materials recovered at AEB Amsterdam in 2012 (AEB, 2015a);
- Fertilizer: general numbers on yearly fertilizer production at Orgaworld, Amsterdam (Orgaworld, 2015);
- Heat and electricity from waste incineration: measured amount of energy generated by AEB Amsterdam in 2012 (AEB, 2015a);
- Fuel pellets from industrial waste: yearly production by Icovia, Amsterdam in 2012 (Port of Amsterdam, 2012);
- Biodiesel: based on production by Simadan, Amsterdam in 2012 (Simadan, 2015);
- Green gas from sludge digestion: numbers on actual production by AEB (AEB, 2015b).

Imports and exports

Majority of flows are based a transport statistics database that comprises data at the level of Amsterdam Municipality (in tons) for 2012 from the Port of Amsterdam and CBS (National Bureau for Statistics) (Port of Amsterdam, 2015). Data of the shipment by sea ships, river barges and trains contained in this database are provided by shipping agents and all companies that transport goods by rail, whereas data on transport by trucks are based on extrapolations from samples. Transport by plane was not considered because the airport is located outside of the municipal boundaries.

Additional databases used

- Industry water and drinking water: import and export of were based on production and distribution figures of Waternet for 2012 (Waternet, 2015a). Because measurements on drinking water distribution were only available at the scale of the urban agglomeration, invoice data was used to determine what share of the regionally distributed water had to be allocated to the Amsterdam municipality (Waternet, 2015b);
- Waste water: measured amount of wastewater influent of Amsterdam's WWTPs in 2012 (Waternet, 2014);
- Sewage sludge: measurements on sewage sludge import, treatment and export by Waternet in Amsterdam in 2012 (Waternet, 2014);
- Fuels for traffic: energy consumption by traffic taking place within Amsterdam Municipality in 2012, based on kilometers traveled on different types of infrastructure, per type of vehicle and type of fuel (Klimaatmonitor, 2015; City of Amsterdam, 2014b)
- Municipal solid waste: statistics on waste treatment in Amsterdam in 2012 (City of Amsterdam, 2013);
- Renewable electricity: derived from energy consumption and production in Amsterdam in 2012 (Klimaatmonitor, 2015);
- Cold extraction from surface water and heat imported: measured amounts of cold and heat imported in Amsterdam in 2012 (Nuon, 2015);

Waste treatment

- Municipal waste: measured amount of waste collected and incinerated in Amsterdam in 2012 (AEB, 2015a), statistics on waste treatment in Amsterdam in 2012 (City of Amsterdam, 2013), report on waste treatment recyclables (AEB, 2012), monitoring reports on waste separation in Amsterdam in 2012 (CREM, 2013);
- Industrial waste incinerated: statistics on waste treatment in Amsterdam in 2012 (City of Amsterdam, 2013);
- Industrial waste anaerobically digested: general numbers on yearly processed waste at Orgaworld, Amsterdam (Orgaworld, 2015).

Flows to nature

- Emissions to air: calculations based on energy consumption in Amsterdam in 2012 (City of Amsterdam, 2014b);
- Emissions to water: measured amount of wastewater effluent of Amsterdam's WWTPs in 2012 (Waternet, 2014);
- Dissipative flows: estimates based on Dutch drinking water statistics and validated by dry weather flow calculations (De Fooij, 2015; Vewin, 2012).

S1.2 Data sources used for the renewable energy benchmark

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Vienna: (Stadt Wien, 2015; Viennaregion, 2015).

S1.3 References

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S2. Supplementary material from chapter 3

Elaborate description of methodology

For this research, the tool SIRUP - “*Space-time Information analysis for Resource-conscious Urban Planning*” - has been developed. SIRUP consists of a frame with pre-defined spatial and temporal scale levels. The scales of time are located on the x-axis and range from seconds to decades, whereas the spatial scale levels (y-axis) range from individual building to country level (figure S2.1). The SIRUP frame is tailored to visualize the spatiotemporal resolution of data, i.e., the level of detail of data in time and space, as well as the spatiotemporal extent of data, i.e., the period and geographical area that the data cover. In this research, SIRUP has been used to assess on which spatiotemporal resolution stakeholders need information on resource flows to inform urban planning and design decision-making aimed at developing resource-conscious strategies, and to evaluate whether the spatiotemporal resolution of existing data can provide the information needed or that there is a data gap. The unique aspect of the SIRUP approach is that it explicitly positions data analysis in a space-time frame. This has the advantage that data specifications are not abstract, but that they are linked to spatial and temporal scale levels (e.g. streets, neighbourhoods, days and week), which are part of the terminology used by urban planner and designers. Moreover, by presenting the results in the form of a space-time frame, data gaps are much easier to communicate with, amongst others, policy makers.

Figure S2.1: The SIRUP frame with fixed scale levels of space and time

The SIRUP tool is applied in four steps (figure S2.2):

- I. generate an inventory of UM interventions;
- II. determine the information needed for implementing each of these interventions;
- III. describe the spatiotemporal resolution of existing data relevant for the intervention;
- IV. identify whether the resolution of identified data can satisfy the stakeholders' intervention information needs.

Note that these steps can be executed in a workshop setting with stakeholders, but also as analysis steps with time lags in between. The four steps will now be described in more detail.

Figure S2.2: The four steps of the SIRUP tool

Note: The figure includes as subfigures a schematic representation of the potential outcome of the different steps. The green, red and blue circles/ellipses, rectangles and arrows represent respectively three different information needs, existing data sets and data gaps for a single intervention on the SIRUP frame (in grey).

Step I

The first step is to generate an inventory of UM interventions, whilst making stakeholders acquainted with the SIRUP space-time frame. In this research eleven stakeholders were interviewed, using semi-structured interviews, and thirteen stakeholders participated in a workshop. Participants were provided with a number of A4-format sheets of paper on which they had to describe a resource-conscious intervention that they envisioned to be implemented in Amsterdam. On a sheet,

participants had to fill in their name and the name of an intervention they envision and they had to provide a short description of the intervention. Participants were asked to specify in the SIRUP frame at the back-side of the paper (figure S2.1) at which spatial scale level the intervention would take place and which time frame they envisioned for implementation. In the workshop setting, participants received about 15 minutes to complete step I individually and they were free to choose how many interventions they described in this time.

Step II

In step II the *Space-time resolution of information needs* is defined. Participants received the SIRUP frame in A3-format and were asked to specify the information needed for an intervention that they mentioned in step I and to indicate the required spatial and temporal resolution of this information (figure S2.3). During the workshop, step II was performed in a group setting of four participants plus one facilitator. Sixty minutes were spent sharing and discussing the information needs of four interventions in total (one intervention per participant). The participants could decide for themselves which intervention from step I they wanted to discuss in step II. In this research, the interviewer or workshop facilitator had to ensure that participants described the information needs related to resource flows necessary to enable the intervention. Although not included in this study, it is also possible to include other sorts of information that is needed for implementing the intervention (e.g. demographic information) and to specify on which resolution this information is needed.

Figure S2.3. A schematic representation of the potential outcome of step II for a single intervention: the SIRUP frame (in grey) with three information needs (in blue, red, green) of diverging resolution.

During step 1 and 2, SIRUP was used in pen-and-paper format because this format allows for greater flexibility than a digital setting (Vervoort et al., 2014). After the workshop and interviews, all contributions were digitalized and labelled to enable the selection of interventions and information needs that are within the scope of the research. The interventions were classified according to the type of intervention and the resource flow(s) for which information is needed. The interventions were classified according to six different categories of types of interventions and four categories of resource flows (table S2.1). The interventions that were classified as spatial or technical and that required information on energy and/or water flows were selected for further analysis (bold in table S2.1). The information needs of the selected interventions were clustered into one SIRUP frame to facilitate interpretation of findings.

Table S2.1: Classification of the interventions.

Types of intervention	Resource flows
Awareness raising	Energy
Financial incentive	Inorganic materials
Information service	Organic materials
Legislation	Water
Supply chain management	
Spatial	
Technological	

Note: The classes indicated in bold were selected for this research.

Step III

In the third step, *Inventory of existing data*, an inventory is made of existing data that is relevant for the interventions and the spatiotemporal resolution of these data is described. In this research, a desk study was conducted to identify which data exist on Amsterdam's energy and water flows and to compose an overview of these data. Data portals, databases and reports were considered that contain open or restricted data on Amsterdam's energy and water flows. Expert consultation was used to identify relevant datasets and to obtain access to restricted datasets. For all datasets obtained, metadata was described using a format that was based on INSPIRE (Infrastructure for Spatial Information in the European Community) and ISO metadata standards to ensure compatibility with other datasets in the world. The mandatory elements of the metadata standard used were, amongst others, the level of detail of the data in the spatial dimension and in the time dimension, i.e., the spatial and temporal resolution of the data. Moreover, it was required to state the limitations and rules on accessing, use and publishing of the existing data to indicate whether the data is open or restricted (table S2.2). Based on the metadata-description on spatial and temporal resolution, the datasets were placed in the SIRUP frame (figure S2.4).

Figure S2.4. A schematic representation of the potential outcome of step III for a single intervention: the SIRUP frame (in grey) with three data sets (in blue, red, green) with data of diverging resolution.

Step IV

In the final step, *Data gap assessment*, the resolution of information needed and data existing is compared to detect whether the identified data can satisfy the stakeholders' information needs. First, it was evaluated for each intervention whether the attributes of each data set were relevant for the information needed. So, in case an intervention required information on drinking water temperature, it was evaluated for each data set whether it provided information on drinking water

Table S2.2: The Urban Pulse Metadata Standard used for describing existing data and its link with leading metadata standards

Urban Pulse Metadata Standard		INSPIRE equivalent	ISO (19115) equivalent
Identification	Title	1.1 Resource title	
	Code name	1.5 Unique resource identifier	
	Abstract	1.2 Resource abstract	
	Information url	1.4 Resource locator	
Keywords & Dates	Key phrase	3.1 Keyword value	
	Date of metadata	10.2 Metadata date	
	Date of publication	5.2 Date of publication	
	Date of creation	5.4 Date of creation	
	Date of last revision	5.3 Date of last revision	
Temporal & Spatial Extent	Update frequency		
	Geographical extent	4.1 Geographic bounding box	
Data type, format and representation	Temporal extent	5.1 Temporal extent	
	Geographical description		3.1.1.335 description - exDesc
	Resource type	1.3 Resource type	
	Distribution format		2.10.1.271 distributionFormat - distFormat
	Data value units		
	Spatial representation type		2.1.1.37 spatialRepresentationType - spatTpType
	Temporal representation type		
	Spatial reference system		2.7.2.196 RS_ReferenceSystem - RefSys
	Spatial resolution	6.2 Spatial resolution	
	Temporal reference system		2.7.2.196 RS_ReferenceSystem - RefSys
	Temporal resolution		
	Spatial data service type	2.2 Spatial data service type	
Access & Constraints	Flow data type		
	Resource language	1.7 Resource language	
	Access information		
	Access constraints	8. Constraint related to access and use	
	Use constraints	8. Constraint related to access and use	
Parties & Contact	Publish constraints		
	Data custodian	10.1 Metadata point of contact	
	Party on data resource	9.1&9.2 Responsible party (of a specific 'Responsible party role')	
	Party on data provider	9.1&9.2 Responsible party (of a specific 'Responsible party role')	
	Other parties	9.1 Responsible party (of any other role)	

Note: mandatory elements are indicated in bold.

temperature. Second, when a dataset was indeed relevant, the information needs for the intervention and the relevant data set(s) were combined in one SIRUP frame. Third, arrows were drawn from the data sets to the information needed to assess the presence and severity of data gaps (figure S2.5).

Because the resolution of both information needs and data sets could cover multiple spatial and/or temporal scales, depending on the size of respectively the circle/ellipse (information needs) or the rectangle (data set) in the SIRUP frame, arrows were drawn so as to show the smallest data gap. This choice entails that arrows were generally drawn from the lower left corner of the 'data set rectangle', which represents the highest spatiotemporal resolution of that data set, to the upper right corner of

Figure S2.5. A schematic representation of the potential outcome of step IV for a single intervention: the SIRUP frame (in grey) with three data gaps (in blue, red, green) of diverging size and dimension.

the ‘information need circle/ellipse’, which represents its lowest resolution. When the highest resolution of the existing data was higher than the lowest resolution of the information needed, but lower than the highest resolution of the information needed, the arrow was drawn from the highest resolution of the data set to the same level of resolution of the information needed. When the highest resolution of the existing data exceeded the highest resolution of the information needed, but the lowest resolution of the existing data was lower than the highest resolution of the information needed, the arrow was drawn from the data set at the level that was equal to the highest resolution of the information needed. In case that the lowest resolution of existing data was higher than the highest resolution of the information needed, the arrow was drawn from the lowest resolution of the data set to the highest resolution of the information needed.

Subsequently, the size and dimension of these ‘data gap arrows’ were analysed. An arrow can either indicate a two-dimensional data gap, implying that both the spatial and temporal resolution of existing data is insufficient, or it can indicate a one-dimensional data gap, where either the spatial or the temporal resolution of existing data is lower than required. A two-dimensional data gap is indicated by arrows pointing towards the lower left corner (↙). Arrows pointing downwards or to the lower right corner (↓, ↘) indicate a one dimensional data gap, in the spatial dimension only. The reason for this is that the arrows indicate that the temporal resolution is equal to or higher than needed. Because aggregation from higher temporal resolution to lower resolution is possible without an information loss, the required temporal resolution can be derived from this information. For example, hourly totals can be derived from data on minute level by summing all available minute data points. Arrows pointing to the left or higher left corner (←, ↖) represent a gap in the temporal dimension only, because the spatial resolution of the data is sufficient or higher than needed. When the spatiotemporal resolution of information needs are equal to the resolution of existing data, these exact matches are indicated by a circle (●) in the SIRUP frame. There is also a match when existing data has either the right resolution in one dimension and a higher resolution in the other or a higher resolution in both dimension, implying that data can be aggregated to get to the required resolution. These matches are indicated by arrows pointing up (↑), to the right (→), or diagonally in the upper right direction (↗).

Table S2.3: Overview existing data

ID	Database content	Link (if applicable)
1	This dataset describes water usage per adress in Amsterdam. Based on yearly measurements from max. 15 years (till 2013), a best estimation is calculated for a normal year per adress.	not applicable
2	This dataset contains measurements from watermeters at houses in the Amsterdam municipality for the year 2014	not applicable
3	This map describes water usage per neighbourhood in Amsterdam, based on yearly water usage measurements per adress	not applicable
4	This report describes monthly up to yearly totals of drinking water produced and distributed, including distribution area, by the drinking water treatment plants of Waternet	not applicable
5	This report describes the yearly totals for waste water quantity and quality measurements at all waste water treatment plants in the management area of Waternet	not applicable
6	This dataset contains the minute-based flow measurements at the five major pumping stations in the drinking water network of Amsterdam.	not applicable
7	This dataset contains the minute-based flow measurements at the drinking water treatment plant	not applicable
8	This dataset contains minute-based quantity and quality measurements at the two waste water treatment plants in Amsterdam	not applicable
9	This website provides, amongst others, maps on surface water measurements such as flow rate and water level measurements. Data are provided for every 10 minutes.	https://www.rijkswaterstaat.nl/kaarten
10	This website provide maps on Dutch climate statistics, including rainfall, on a daily up to seasonal basis.	https://www.knmi.nl/nederland-nu/klimatologie
11	This website provide maps related to several watermanagement issues in Amsterdam, including a map of groundwater quantity measurements that are performed four times a year	http://maps.waternet.nl
12	This report provides information on the quality of the groundwater in the Netherlands, based on measurments from 350 monitoring wells that are sampled once every year/once every 2 years/once every 4 years	http://www.rivm.nl/Documenten_en_publicaties/Wetenschappelijk/Rapporten/2010/augustus/De_kwaliteit_van_ondiep_en_middeldiep_grondwater_in_Nederland_in_het_jaar_2008_en_de_verandering_daarvan_in_1984_2008
13	This database contains data on energy consumption per sector, (renewable) energy sources, emissions etc. Data on municipal level (though often top-down extrapolations Dutch data), including benchmarking possibilities with other municipalities/regions	http://www.klimaatmonitor.databank.nl/
14	This dataset covers the energy usage of small energy users aggregated per postcode (6-digits level).	https://www.liander.nl/over-liander/innovatie/open-data/data
15	This website provides yearly totals for energy usage in Amsterdam, including an overview of the electricity demand by different sectors	http://www.energieinbeeld.nl
15	On this map the average energy consumption in terms of electricity and gas for each neighbourhood in Amsterdam is provided.	http://maps.amsterdam.nl/energie_gaselektra
16	On this website several maps can be viewed, amongst others on potential electricity by PVpanels for all rooftops in Amsterdam.	http://maps.amsterdam.nl/
17	This report describes the energy infrastructure, energy usage and the theoretical potential, actual potential and current usage of several energy sources in Amsterdam	https://www.amsterdam.nl/gemeente/organisatie/ruimte-economie/ruimte-duurzaamheid/ruimte-duurzaamheid/making-amsterdam/publications/sustainability-0/energy-atlas/
18	This source describes the average energy usage of a streetlight in Amsterdam per day	not applicable
19	This database contains statistics of monthly amounts of waste processed and energy (heat + electricity) produced by the two incinerators of Amsterdams waste-to-energy plant	not applicable

S3. Supplementary material from chapter 4

S3.1 Elaborate description of methodology

S3.1.1 Search strategy development and implementation

The first step of the review process was to develop and implement a search strategy to identify relevant publications. To identify these studies a Boolean search string was formulated and different variations of the search string were tested, based on different sets of inclusion and exclusion concepts and their synonyms, (see table S3.1).

Table S3.1: The elements of the search string

Search string elements	Inclusion concept 1:		Inclusion concept 2:		Exclusion terms	
	"Urban metabolism / ecology "		"Water / energy use "			
Synonyms	Urban	Metaboli*	Water	Use	Modelling	
	Metropol*	Ecology	Energy	Usage	Disease	
	Neighbourhood		Resource*	Consum*	Water quality	
	City		Material	Flow*	Species	Plant*
	Cities			Demand*		Bee*

Different variations of the search string were tested (examples given in textbox S3.1) to identify relevant terms to be included and excluded. Accordingly, the search string was refined until a sample was obtained that was deemed to have an appropriate balance between sensitivity and specificity given the scope and constraints of the research. This means that, judged on the results of the different search string test runs, the search identified a high proportion of relevant articles in existence and a minimum of irrelevant studies (Gough et al., 2012; Petticrew and Helen, 2005). The search strategy was implemented in the databases Scopus and Web of Science in January 2019 to include all print publications up to and including 2018. Articles in the sample that were Online First/Version publications, not yet printed in an issue, were excluded. The final search string, as implemented on 14 January 2019, yielded 441 results in Scopus and 201 results in Web of Science. After duplicate removal, 496 unique items remained for screening.

S3.1.2 Relevance assessment

The second step of the review process entailed screening the retrieved studies and deciding which ones had to be examined in detail. In order to make this decision, criteria were formulated that specified which studies were to be included and excluded in the review. A detailed overview of this process is provided in figure S3.1.

The 496 items that were obtained from the database search were firstly screened on title and abstract, appraised on four criteria and accordingly coded in the EPPI-Reviewer software (Thomas et al., 2010). The first three criteria of appraisal related to the relevance of the publication; items were coded 'exclude' if: (I) the *topic* of the item was not resource management, but for example, management of urban flora and fauna; (II) resource consumption was not the *scope* of the article, rather the item focussed on effectiveness of an intervention such as a particular technology for resource management; (III) the item did not focus on urban water and/or energy consumption or overall urban metabolism, but either on other *resources* or on other types of '*flows*' (production and emissions), such as food consumption, usage of building materials or greenhouse gas emissions²⁹.

Textbox S3.1: Final search string and search string test runs used for a specificity and sensitivity check

Final Search String

In Scopus: (TITLE-ABS-KEY ((urban OR metropol* OR neighbourhood OR city OR cities) W/3 (metaboli* OR ecology)) AND TITLE-ABS ((water OR energy OR resource* OR material) W/3 (use OR usage OR consum* OR flow* OR demand* OR suppl*)) AND ORIG-LOAD-DATE AFT 20161129 AND NOT TITLE-ABS-KEY (modelling OR "water quality" OR disease OR (species AND (plant* OR bee* OR bird*)))) AND (EXCLUDE (PUBYEAR , 2019))

In Web of Science: TS=((urban OR metropol* OR neighb*rhood) NEAR/3 (metaboli* OR ecology)) AND TS=((water OR energy OR resource* OR material) NEAR/3 (use OR usage OR consum* OR flow* OR demand* OR suppl*)) NOT TS=(modelling OR disease OR "water quality" OR (species AND (plant* OR bee* OR bird*)), Timespan=1945-2018

Examples of Search String Test Runs in Scopus, January 2019

- TITLE-ABS-KEY ((urban OR metropol* OR neighbourhood OR city OR cities) W/3 (metaboli* OR ecology)) AND EXCLUDE PUBYEAR (2019): **4,064 results**
- TITLE-ABS-KEY ((urban OR metropol* OR neighbourhood OR city OR cities) W/3 (metaboli*)) AND (EXCLUDE (PUBYEAR , 2019)): **1,068 results**
- TITLE-ABS-KEY ((urban OR metropol* OR neighbourhood OR city OR cities) W/3 (metaboli*)) AND TITLE-ABS-KEY (driv*) AND (EXCLUDE (PUBYEAR , 2019)): **89 results**
- TITLE-ABS-KEY ("urban metabolism") AND EXCLUDE PUBYEAR (2019): **538 results**
- TITLE-ABS-KEY ("urban metabolism" AND "driv*") AND EXCLUDE PUBYEAR (2019): **61 results**

²⁹ In the case of review studies, the criteria scope and resource flow related to the primary research studies that were included in the review. Reviews were included if they discussed urban metabolism case studies based on empirical research, for example material flow analyses, environmental history analyses and regression analyses.

Figure S3.1: The coding scheme with all exclusion criteria

The fourth criterion dealt with the quality of the study as it was about appraisal of the appropriateness of the study design. Study designs that were included were reviews and urban metabolism case studies based on empirical research, such as material flow analyses, environmental history analyses and regression analyses. Modelling, conceptual and theoretical papers were excluded. Based on this screening of title and abstract 163 items were included for screening on full text, of which 150 full reports could be obtained. For 81 of these items, screening of the abstract and title of these items did not provide sufficient information on the scope and study design to decide whether these articles should be included or not. Therefore these items, of which 75 could be obtained, were additionally screened on the introduction, methods and/or conclusion section and coded. Items were excluded based on their *scope*, if the full text proved not to be in the English *language*, or if the *evidence* presented was inappropriate. The latter entailed an appraisal of appropriateness of the study design (reviews and empirical case studies), as well as execution of the study. Case studies were excluded if screening revealed that no quantitative figures on water and/or energy consumption were given. The evidence presented in these publications was considered unsuitable to answering the research question. Through this second screening step, 23 items were included. Together with the 75 other items that were directly included based on screening of title and abstract, this resulted in a total of 98 included items.

The next step was screening all remaining items on full text, starting with categorizing those items into case studies and reviews. Both types of studies were coded 'exclude' when the screening of full text revealed that an item did not fulfil the before mentioned criteria language, topic, scope, resource flow, study design and evidence. Case studies were also excluded when they did provide insight in water or energy consumption yet lacked a discussion of the factors that could explain temporal and/or the spatial variation in this consumption. Case studies were also excluded when the analysis turned out to be on a scale level less detailed than the metropolitan level. Review studies were excluded when they did not discuss the factors influencing urban metabolism, nor discussed the interconnectedness of such factors.

Based on this screening on full text, 43 items remained, including four reviews and 39 case studies. Finally, reference list checking of the included review studies identified an additional six eligible studies, including two reviews and four case studies. This brought the total number of studies on 49.

S3.1.3 Quality assessment

After the relevance assessment, the next step was to evaluate whether the publications that remained items also met quality requirements on the basis of which they should also be *included* in the final sample. Accordingly, reviews were only included if they discuss how factors are related

to consumption, thus mentioning their effect. Case studies were evaluated on two characteristics of the quality of the data used. First, the main data source of the water and energy consumption figures have to be reliable, actual consumption data provided by utilities, statistical offices, governmental bodies or similar sources. Second, the resolution of the data used have to be at the level of analysis or more detailed. This implies that an analysis on city-level is only included if the underlying data is on city scale or more detailed, not if the analysis relies on downscaled regional or national data. The reasoning behind those two criteria is that actual consumption data on the scale of assessment are essential to reliably determine the relationship between the factors of influence and the spatiotemporal variations in consumption. Otherwise, the validity of the relationship found could be affected. For example, variations in urban water consumption that are calculated by downscaling national level data, reflect that factors have caused variations in consumption on a national level. However, that these variations occur on national level does not automatically imply that these factors have affected consumption on city level in a similar way. City level data are essential to investigate if this was indeed the case. Likewise, calculated consumption figures, instead of measured data, are unfit to determine the influence of factors on consumption. After all, analysing such figures is essentially checking the calculations made to determine these numbers, because these figures represent assumptions on the factors that influence consumption. Table S3.2 shows the scores of the different publications during this final step of quality assessment. After this step the final sample totalled thirty publications.

S3.1.4 Data extraction

During data extraction, two types of data were extracted from each item: (I) data on descriptive characteristics of the study and (II) data on the relationship between spatiotemporal variability of water and/or energy consumption and the factors that generate these geographical variations and changes over time, from now on referred to as ‘factors of influence – consumption relationships’. First, all studies were coded on descriptive variables because these contextual features of studies are relevant to describe the nature of this field of research and can reveal gaps in this body of literature (Gough et al., 2012). Describing the study characteristics of the was also considered relevant for the second research objective, because it can support interpretation of the findings and the synthesis (Gough et al., 2012). Accordingly the studies were coded on: (I) year of publication (II) name, country and continent of the embedded case(s) studied, (III) resource flow(s) studied; (IV) spatial scale of analysis; (V) temporal scale of analysis; (VI) research design.

Second, all thirty studies were uploaded in the reference management software Mendeley Desktop to extract data on ‘factors of influence – consumption relationships’(see table S3.3). In each study,

Table S3.2: Scores of the quality assessment: an evaluation of the data underlying consumption figures

Reference	Data resolution evaluation	Data sources consumption figures in article	Source is actual consumption data (statistical/utility)	Resolution source mentioned/clear	Resolution is at level of analysis or more detailed	Details data sources provided
Abdelalim et al., 2015						
Ariza-Montobbio et al., 2014						
Athanassiadis et al., 2017						
Athanassiadis et al., 2017						
Balogh et al., 2016						
Barles, 2007b						
Barles, 2009						
Beloin-Saint-Pierre et al., 2017	review					
Bristow & Kennedy, 2013						
Codohan and Kennedy, 2008						
Conke & Ferreira, 2015						
Cui & Wang, 2015						
Cui, 2018	review					
Delgado-Ramos, 2015						
Domene et al., 2005						
Facchini et al., 2017						
Gingrich et al., 2012						
Gorostiza et al., 2015						
Hall, 2011						
Kalmykova et al., 2015						
Kalmykova et al., 2016						
Kennedy et al., 2015						
Kenway et al., 2011	review					
Kim and Barles, 2012						
Lenzen et al., 2004						
Li et al., 2016						
March et al., 2015						
Marteleira et al., 2014						
Mehta et al., 2013						
Núñez et al., 2010						
Pincetl et al., 2012	review					
Pincetl et al., 2014						
Pincetl et al., 2016						
Pincetl et al., 2017	review/metastudy					
Porse et al., 2016						
Renouf et al., 2018						
Rosado et al., 2016						
Sahely et al., 2003						
Schulz, 2007						
Stergiouli & Hajib, 2012						
Swaney et al.2012						
Tello & Ostos, 2011						
Thomson&Newman, 2018						
Voskamp et al. 2017						
Wang et al., 2017						
Warren-Rhodes & Koenig, 2001						
Weisz and Steinberger, 2010	review					
Zhang & Yang, 2007						
Zhang et al., 2015	review					

Legend

Scores final evaluation

	Included
	Included, with remarks
	Not included: resolution underlying data unclear
	Not included: estimations or downscaled data

Scores evaluation four criteria

	Yes
	Overall yes, but with remarks
	Unclear or not mentioned
	No

data on temporal or spatial variations in consumption and explanations for these variations were labelled. Also text that described the link of a driver to other variables was labelled, because it was considered relevant for interpretation of the results and assessment of the applicability and generalisability of the findings (Popay et al., 2006). Moreover, the data on ‘factors of influence – consumption relationships’ was coded on the type of evidence presented. Coding on evidence type was deemed essential to support quality appraisal of the findings and qualification of synthesis results (Gough et al., 2012). So, coding on evidence type was done to appraise differences in evidence on ‘factors of influence – consumption relationships’ because the studies differ in terms of the nature of their findings due to their heterogeneity in research design. Table S3.3 provides an overview of the elements of data extraction.

Table S3.3: Elements of data extraction on ‘factor-consumption relationships’

Extracted data	Explanation
Factor	Variable(s) that is/are mentioned as explanation for spatial and/or temporal variability of urban water or energy consumption
Resource	The resource whose variability is influenced by the factor: water, energy or both
Effect, effect direction and size	Effect that the factor has on this spatiotemporal variability, i.e. the temporal and/or spatial variation in consumption described; and, if made explicit, the effect size or magnitude.
Linked variable(s)	If relevant; (an)other variable(s) that is indicated to be linked to variable of interest
Evidence type	Whether the findings on effect are supported by qualitative or quantitative data. If quantitative, details on the statistical correlation

S3.1.5 Data synthesis

After data extraction, findings were brought together using the four elements of a narrative synthesis as described by (Popay et al., 2006).

At first, a theoretical framework was developed (see section 3.2) to enable the interpretation of findings and the assessment of the wider applicability of those findings (Popay et al., 2006). Second, a preliminary synthesis was developed. The sample was organised into smaller sub-groups to make the synthesis process more manageable and because this can aid the process of analysis, identifying patterns across these groups, interpreting the findings and drawing conclusions about generalisability and transferability of findings (Gough et al., 2012; Popay et al., 2006). The included publications were grouped according to a combination of study design and scale of analysis. This exploration of relationships in the data informed the third element of the synthesis, a thorough exploration of the emerged patterns with particular interest in identifying elements that might explain differences in findings between studies (Popay et al., 2006). In order to identify these elements, the findings were categorized in line with the theoretical framework (see 3.2). For each

factor, the extracted data from all publications that listed that specific driver was listed, evaluated and compared to try to explain the differences in effect direction and size that were found. It was, for example, investigated whether the linked variables could explain differences in findings with respect to effect direction and size. The fourth and final element of data synthesis entailed assessing its robustness by critically reflection (Popay et al., 2006). Both the quality and quantity of the evidence base of the synthesis was reflected upon, informed by the appraisal of the type of evidence of the included studies (see 3.2) and by guiding questions such as “do results depend heavily on one or two studies in the absence of which they would change significantly?”(Gough et al., 2012). Also the clusters developed during the preliminary synthesis as well as the theoretical framework, informed this assessment of the generalisability of findings. This final step of the narrative synthesis is reported in section 3.5.1.

S3.2 Case study locations

Table S3.4: The cities researched in each case study and the location of these cities

Case study number and reference	City/cities of embedded case(s)	Continent	Climate zone ¹
1 Ariza-Montobbio et al., 2014	Barcelona (Catalonia)	Europe	Csa
2 Athanassiadis et al., 2017a	Brussels	Europe	Cfb
3 Athanassiadis et al., 2017b	Milan, London, Brussels, Glasgow, New York City, Los Angeles, San Francisco, Chicago, Buenos Aires, Cape Town	Europe, N-America, S-America, Africa	Cfa, Cfb, Cfb, Cfb, Dfb, Csa, Csb, Dfa, Csa, Cfa
4 Barles, 2007b	Paris	Europe	Cfb
5 Barles, 2009	Paris	Europe	Cfb
6 Domene et al., 2005	Barcelona	Europe	Csa
7 Gingrich et al., 2012	Vienna	Europe	Cfb
8 Gorostiza et al., 2015	Madrid	Europe	Cfa
9 Hall., 2011	Syracuse (state of New York)	North-America	Dfb
10 Kalmykova et al., 2015	Stockholm, Gothenburg, Malmo	Europe	Cfb
11 Kalmykova et al., 2016	Stockholm, Gothenburg, Malmo	Europe	Cfb
12 Kim and Barles, 2012	Paris	Europe	Cfb
13 Marteleira et al., 2014	Lisbon	Europe	Csa
14 Mehta et al., 2013	Bangalore	Asia	Aw
15 Núñez et al., 2010	Barcelona	Europe	Csa
16 Pincetl et al., 2014	Los Angeles	North-America	Csa
17 Pincetl et al., 2016	Los Angeles	North-America	Csa
18 Porse et al., 2016	Los Angeles	North-America	Csa
19 Renouf et al., 2018	Perth, Melbourne, Brisbane (SEQ)	Australia	Csa, Cfb, Cfa
20 Rosado et al., 2016	Stockholm, Gothenburg, Malmo	Europe	Cfb
21 Sahely et al., 2003	Toronto	North-America	Dfb
22 Schulz, 2007	Singapore	Asia	Af
23 Stergiouli & Hajib, 2012	Athens	Europe	Cfa
24 Swaney et al.2012	New York City	North-America	Dfb
25 Tello & Ostos, 2011	Barcelona	Europe	Csa
26 Voskamp et al. 2017	Amsterdam	Europe	Cfb
27 Wang et al., 2017	Beijing, Tianjin and Tangshan	Asia	Dwa
28 Warren-Rhodes & Koenig, 2001	Hong Kong	Asia	Cwa

¹ According to Köppen–Geiger climate classification; A: tropical; B: dry; C: temperate; D: continental; E: polar

base map from: https://commons.wikimedia.org/wiki/File:World_Map_Blank_-_with_blue_sea.svg

Figure S3.2: The locations of the cities researched in the case studies

Each dot represents a city, numbers refer to the reference numbers listed in table S3.4

S4. Supplementary material from chapter 5

S4.1 Datasets used

Table S4.1: Datasets used for the dependent consumption variables

Resource	Indicator for neighbourhoods and districts	Source	Indicator for 100- and 500-meter squares	Source
Electricity	Average annual electricity usage in KWh per household	CBS (2016a)	Average annual electricity usage in KWh per household	CBS (2016b)
Natural gas	Average annual natural gas usage in m ³ per household	CBS (2016a)	Average annual natural gas usage in m ³ per household	CBS (2016b)
Water	Average annual water usage in dam ³ per household	Waternet (2014)	Average annual water usage in dam ³ per household	Waternet (2014)

Table S4.2: Datasets used for the independent variables

Category	Factor	Indicator for neighbourhoods and districts	Source
Spatial	Population density	Population density	CBS (2016a)
		Density of addresses	CBS (2016a)
		Living space area as percentage of total ground area	PBL (2017)
	Amount of productive tree canopy	Number of trees per 100m ²	Gemeente Amsterdam (2019)
	Garden typology	Average m ² of garden per household	BGT Onbegroeid Terreindeel erf (Kadaster, 2019)
	Building size	Percentage of houses with living space area above 80 m ²	BBGA (2016)
		Percentage of houses with living space area between 80 and 100 m ²	BBGA (2016)
		Percentage of houses with living space area above 100 m ²	BBGA (2016)
	Building type	Number of building layers	PBL (2017)
		Percentage of single-family homes	CBS (2016a)
		Percentage of multiple family homes	CBS (2016a)
		Percentage of houses with building year until 2000	CBS (2016a)
		Percentage of houses with building year after 2000	CBS (2016a)
	Building age		
Infrastructural	Home ownership	Percentage of rental housing	CBS (2016a)
		Percentage of owner-occupied housing	CBS (2016a)
	Rental housing type	Percentage of rental housing owned by housing associations	CBS (2016a)
		Percentage of rental housing owned by others	CBS (2016a)
	Surface covered with water	Percentage of surface covered with water	CBS (2016a)
	Vacant houses	Percentage of vacant houses	CBS (2016a)
		Percentage of inhabited houses	CBS (2016a)
	Property value	Average value of houses	BBGA (2015)
		Average value of houses	CBS (2016a)
		Average value of houses per m ²	BBGA (2016)
Infrastructural	Presence of supply network	Percentage of houses connected to district heating	CBS (2016a)

Indicator for 100- and 500-meter squares	Source	Factor	Category
Inhabitants per 100/500 m²	CBS (2016b)	Population density	Spatial
Density of addresses	CBS (2016b)		
Number of trees per 100/500m²	Gemeente Amsterdam (2019)	Amount of productive tree canopy	
Average m² of garden per household	BGT Onbegroeid Terreindeel erf (Kadaster, 2019)	Garden typology	
		Building size	
		Building type	
Percentage of multiple family homes	CBS (2016b)	Building age	
Percentage of houses with building year before 1975	CBS (2016b)		
Percentage of houses with building year before 1945	CBS (2016b)		
Percentage of houses with building year between 1945 and 1964	CBS (2016b)		
Percentage of houses with building year between 1965 and 1974	CBS (2016b)		
Percentage of houses with building year between 1975 and 1984	CBS (2016b)		
Percentage of houses with building year between 1985 and 1994	CBS (2016b)		
Percentage of houses with building year between 1995 and 2004	CBS (2016b)		
Percentage of houses with building year between 2005 and 2014	CBS (2016b)	Home ownership	
Percentage of houses with building year between 2015 and 2024	CBS (2016b)		
Percentage of rental housing	CBS (2016b)		
Percentage of owner-occupied housing	CBS (2016b)	Rental housing type	
Percentage of rental housing owned by housing associations	CBS (2016b)		
		Surface covered with water	
Percentage of vacant houses	CBS (2016b)	Vacant houses	
Average value of houses	CBS (2016b)	Property value	
		Presence of supply network	Infrastructural

Table S4.2 continued

Category	Factor	Indicator for neighbourhoods and districts	Source
Personal consumer characteristics	Income level	Average household income	BBGA (2016)
		Percentage households with highest 20% income	BBGA (2016)
		Percentage of households with income below the social minimum	CBS (2014)
		Percentage of households with lowest income	CBS (2014)
		Percentage of households with highest income	CBS (2014)
		Percentage of households with income of maximum 120% of "Wettelijk Sociaal Minimum" and low fortune	BBGA (2015)
		Average income per inhabitant	CBS (2014)
		Percentage of people on welfare assistance	CBS (2016a)
	Social security	Percentage of people on unemployment assistance	CBS (2016a)
		Percentage of people receiving AO	CBS (2016a)
		Percentage of people receiving AOW	CBS (2016a)
	Lifestyle	Passenger cars per household	CBS (2016a)
	Age	Percentage of people between 0 and 14 years old	CBS (2016a)
		Percentage of people between 15 and 24 years old	CBS (2016a)
		Percentage of people between 25 and 44 years old	CBS (2016a)
		Percentage of people between 45 and 64 years old	CBS (2016a)
		Percentage of people of 65 and older	CBS (2016a)
	Education level	Percentage of inhabitants with higher education level	BBGA (2016)
		Percentage of inhabitants with average education level	BBGA (2016)
		Percentage of inhabitants with low education level	BBGA (2016)
	Male to female ratio	Percentage of men	CBS (2016a)
Social & cultural context	Household size	Household size	CBS (2016a)
		Percentage of households without children	CBS (2016a)
		Percentage of households with children	CBS (2016a)
		Percentage of single-person households	CBS (2016a)
		Percentage of people married	CBS (2016a)
		Percentage of people unmarried	CBS (2016a)
		Percentage of people divorced	CBS (2016a)
	Migration history ²	Percentage of people with Western migration history	CBS (2016a)
		Percentage of people with non-Western migration history	CBS (2016a)
		Percentage of people with migration history from the Dutch Antilles and Aruba	CBS (2016a)
		Percentage of people with migration history from Suriname	CBS (2016a)
		Percentage of people with migration history from Morocco	CBS (2016a)
		Percentage of people with migration history from Turkey	CBS (2016a)
		Percentage of people with other non-Western migration history	CBS (2016a)

¹ Only available for the 500-meter squares.

² Western migration history is defined as first and second generation migration from Europe (excluding Turkey), North-America, Oceania, Indonesia or Japan by the Central Bureau of Statistics; Non-western migration history comprises first and second generation migration from Africa, Latin-America Asia and Turkey.

Indicator for 100- and 500-meter squares	Source	Factor	Category
Percentage of households with lowest income ^{1 i}	CBS (2016b)	Income level	
Percentage of households with highest income ³	CBS (2016b)		
Percentage of people that receive welfare, unemployment or disability assistance	CBS (2016b)		
		Social security	Personal consumer characteristics
		Lifestyle	
Percentage of people between 0 and 14 years old	CBS (2016b)		
Percentage of people between 15 and 24 years old	CBS (2016b)		
Percentage of people between 25 and 44 years old	CBS (2016b)	Age	
Percentage of people between 45 and 64 years old	CBS (2016b)		
Percentage of people of 65 and older	CBS (2016b)		
		Education level	
Percentage of men	CBS (2016b)	Male to female ratio	
Average household size	CBS (2016b)		
Percentage of single-person households	CBS (2016b)	Household size	
Percentage of people with Western migration history	CBS (2016b)		Social & cultural context
Percentage of people with non-Western migration history	CBS (2016b)		
Percentage of people with Dutch migration history	CBS (2016b)		
		Migration history ²	

S4.2 Data sources

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Many of my LAR colleagues were already there when I started my landscape architecture education in 2007. At that time, I did not have any idea how this education would shape me and my views on the world. Looking back, I am grateful not only that I am taught this landscape-based approach by the Wageningen School, but also that I found my way back to the LAR/LSP group and that I could tap into this field of expertise in my PhD. Thanks to Adrie, Annelies, Audrey and Monique for their support in practical matters. A special thanks to Annet, Wiebke and Kevin for making our PhD room such an open and sharing environment. Thanks Roberta for checking in every now and then: *forza!* Dirk, it was great to have you around at LAR during various stages of my PhD! Not only for some very hands-on discussions on calculations and methodological approaches, but also for sharing (much more important) conversations about joyous and challenging moments in life. Thank you also for your constructive feedback and support in the final preparations for my thesis defense, it was great that I could share this part of my PhD trajectory with you in this way!

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- o Environmental research in context (2015)
- o Research Methodology I: From topic to proposal (2016)
- o Research in context activity: 'Content coordinator "Citizens co-creating sustainable cities", advanced level MOOC' (2017)

Selection of other PhD and Advanced MSc Courses

- o Smart Solutions for the Urban Metropole, PhD summer school Climate-KIC (2016)
- o Systematic approaches to reviewing literature, WASS (2016-2017)
- o Scientific writing, Wageningen Graduate Schools (2016)
- o Orientation on Teaching for PhD candidates, Wageningen Graduate Schools (2017)
- o Career Perspectives, Wageningen Graduate Schools (2020)
- o Basic Statistics, PE&RC & WIMEK (2020)

Selection of Management and Didactic Skills Training

- o Co-organising Urban Metabolism Workshop at AMS Institute (2015)
- o Supervising two MSc internship and four MSc thesis students (2016-2020)
- o Teaching in the MSc courses: 'Master Class Regional Landscape Architecture', 'Planning and Design of Urban Space' and 'Master Studio Landscape Architecture - Regional Design: a Systems Approach' (2015-2017)

Selection of Oral Presentations

- o *Data qualifications and data availability for resource flow analysis in support of urban planning: Amsterdam's energy metabolism.* Smart and Sustainable Built Environments (SASBE), 9-11 December 2015, Pretoria, South Africa
- o *The spatial side of urban resource management; how to equip urban designers for designing the circular city.* Workshop Circular Economy, PBL and Ministry of I&M, 13 March 2017, The Hague, The Netherlands
- o *Urban landscape and consumer characteristics affecting metabolic patterns at neighborhood level.* ISIE Americas 2020, 8 July, Lima, Peru

Selection of Outreach

- o Poster presentation at Habitat III: United Nations Conference on Housing and Sustainable Urban Development, 17-20 October 2016, Quito, Ecuador
- o Measuring Amsterdam's Pulse. Short article in Amsterdam Science Magazine (2017)

SENSE coordinator PhD education

Dr. ir. Peter Vermeulen

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