URBAN MATERIAL FLOWS AND STOCKS ACCOUNTING: A REVIEW OF METHODS AND THEIR APPLICATION

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Metabolism of Cities

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Abstract	The document presents a thorough review of 29 existing urban material accounting methods used in research projects and academic literature to illustrate the multitude of methods that exist and provide a good understanding of them. The analysis identifies strengths and weaknesses of most accounting techniques informing the adapted sector-wide and urban circularity assessment methods that will be developed in the CityLoops project. This is followed by an overview of how the application of various methods has changed over time, informed by the analysis of 194 publications.
Keywords	Material accounting methods; Accounting methods; Quantification methods; Literature review; Urban metabolism;
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Acronyms and Abbreviations

ABM	Agent-based Modelling
AS-MFA	Activity-based Spatial MFA
CDW	Construction and Demolition Waste
CB	Consumption-based
CE	Circular Economy
CF	Carbon Footprint
EC	European Commission
EF	Ecological Footprint
EE-IOA	Environmentally-Extended Input-Output Analysis
EEA	Extended Exergy Accounting
EEF	Energy Ecological Footprint
EFA	Energy Flow Analysis
EIO-LCA	Economic Input-Output Life-Cycle Assessment
EU	European Union
EW-MFA	Economy-Wide Material Flow Analysis
F&T	Fate and Transport Analysis
FEW	Food, Energy, Waste
GDP	Gross Domestic Product
gha	global hectares
HANPP	Human appropriation of net primary production
I/O	Input/Output
IOA	Input-Output Analysis
LCA	Life Cycle Assessment
LR	Literature Review
MEFA	Material and Energy Flow Analysis
MFA	Material Flow Analysis
MIOT	Monetary Input-Output Table
MoC	Metabolism of Cities
MRIO	Multi-Regional Input-Output
MSA	Material Stock Analysis
MuSIASEM	Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism
NBS	Nature Based Solution
OW	Organic Waste
PB	Production-based
PIOT	Physical Input-Output Tables
SFA	Substance Flow Analysis
UM	Urban Metabolism
UMan	Urban Metabolism Analyst Model
WF	Water Footprint

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1. Introduction

CityLoops is an EU Horizon 2020-funded project that brings together seven ambitious European cities, Høje-Taastrup and Roskilde (Denmark), Mikkeli (Finland), Apeldoorn (the Netherlands), Bodø (Norway), Porto (Portugal) and Seville (Spain) to demonstrate a series of innovative tools and urban planning approaches, aimed at closing the loops of urban material flows and increasing their regenerative capacity. This project started in October 2019 and has a duration of four years. CityLoops will include the development of a circular city scan method and indicators, the roll-out of demonstration actions, the creation of decision support tools, and several other actions aimed at demonstrating, upscaling, and replicating sustainability interventions.

The CityLoops project focuses on construction and demolition waste (including soil), and organic waste. Within this project a number of tools and methods from the field of industrial ecology will be used. Industrial ecology aims at understanding the environmental impact of socio-economic systems through the accounting and analysis of resource flows. The use of systems thinking to understand the whole rather than looking at isolated parts is another key principle in industrial ecology.

Within industrial ecology, the concept of urban metabolism is often used to refer to the “study of the flows of resources in an urban environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of those resources” (Graedel 1999, 11). In order to develop a circular city scan as well as a sector-based circularity scan method, existing methods that relate to urban metabolism may be used or adapted to obtain a comprehensive understanding of the resource flows within the demonstration cities, and how these flows impact construction and demolition waste as well as organic waste.

This document aims to present a thorough review of existing material accounting methods used in research projects and academic literature to illustrate the multitude of methods that exist and provide a good understanding of them. The analysis identifies strengths and weaknesses of most accounting techniques informing the adapted method that will be developed in the CityLoops project. This method will be developed in the next task and ultimately aims at allowing municipal decision makers to make informed decisions. It should be noted that this literature review refrains from making in-depth judgement calls of what the urban material accounting method for CityLoops will be or should look like. Collaboration and continuity with existing and well established research will be sought to build upon them and benefit from the very significant amounts of investments of time, effort and funds they have seen.

Within the scope of this literature review, it was necessary to define the concept of *accounting methods*. All urban sustainability methods that account for flows of materials or energy and that were found are included. Methods that do not seek to directly quantify these flows but instead aim to understand drivers or model different scenarios are not within the scope of this work.

The document is structured in the following way. First, the methodology *of this review* is outlined, explaining how information was obtained, why certain content and approaches were included and others were not, and it provides a rationale for the presentation of the list of methods. The section thereafter describes the identified methods. These are grouped in categories and after highlighting the main features of each category, a more detailed description is given of each individual method before stating their strengths and weaknesses. This is followed by an overview of how the application of various methods has changed over time, informed by the analysis of 194 publications. Lastly, general recommendations with regards to methods, their classifications and recommendations and insights that are relevant to the CityLoops project are discussed.

Further outputs beyond the literature review report are the integration of some of the work on the Metabolism of Cities website:

- The researchers produced an overview that includes the strengths and weaknesses of all methods, their method category, the case studies sorted by method and the number of case studies illustrated in graphs: https://metabolismofcities.org/resources/material-accounting-methods.
- The researchers produced a section that shows all the reviewed urban metabolism case studies that are present in the Metabolism of Cities library. The publications can be case studies done on a single city, or a comparison between various cities. They could be an economy-wide material flow analysis, or a material stock study for a single commodity. The webpage can be found here: https://metabolismofcities.org/resources/publications/casestudies.
- The researchers included projects, mostly if they were undertaken to engage in the quantification of material stocks or flows in a dedicated section: https://metabolismofcities.org/community/research/projects.

2. Methodology of Literature Review

The following chapter describes the steps that were followed to conduct the literature review. It was deemed important to include this part in the report in order for others, who may want to build on this literature review, to understand the reasoning behind decisions that influenced the scope and direction of this work. Furthermore, it also aims to illustrate the deliberations that took place in order to arrive at the report findings.

The literature review was carried out by two researchers from October to December 2019 as the first task of Work Package 4 (Urban Circularity Assessment) of the European Horizon 2020 CityLoops project. The researchers followed a couple of distinct steps which are first stated here, before describing some of them in more detail in the following sub-chapters 2.1-2.6.

Initially, a scope and work approach had to be defined, including a definition of accounting methods and the spatial and material scale to which they should be limited to. Upon that, literature was collected, reviewed and classified, starting with existing review papers. Beyond the literature, other Horizon 2020 and differently funded, mostly EU, projects were also compiled and analysed. From this vast information, an overview of material accounting methods, including their strengths and weaknesses, was made, which were then grouped into "method categories" to compare them more easily.

Based on the review, the analysis section was developed which showcases the methods used over time and for which cities or regions they were applied. Finally, recommendations were made for the development or adaptation of a method for CityLoops.

2.1. Definition of scope and accounting method

The scope of the literature review and the process was defined by a number of research questions and a definition of "accounting method". (Note that method and not methodology was defined.) The aim was to answer these questions through an in-depth analysis of the existing literature and to formulate a well-referenced and clearly articulated answer to each of these questions, forming the core of the literature review.

1. **Which urban material stocks and flows accounting methods exist and where and how have they been used?**
2. **What are the main differences (and advantages and disadvantages) of existing accounting methods?**
3. What kinds of considerations need to be made to the identified method(s) in order for these to be useful for the CityLoops project?

Looking at Research Question 1, it becomes clear that in order to know which literature to review, the **meaning of an accounting method** has to be defined first, so that it can be determined which ones exist. A discussion about what an accounting method is emerged, debating if it should only quantify materials (and balance them) and then stop or quantify materials and then continue with a different analysis (e.g. environmental impact assessment with a LCA). It was agreed that as soon as any gathering of numbers for a method is required and more specifically **anything that involves quantification of material stocks or flows (on an urban level)**, it is considered an accounting method. That also meant that a method where no accounting takes place, is considered as a non-accounting method or an add-on/extension, such as e.g. agent-based modelling. Furthermore, models, simulations and indicators were not included in this review either.

Having defined "accounting method", the scope of the literature review was decided upon by limiting the spatial scale and material scope of the application of such methods. Focus was laid on urban as well as sub-national (below country level) studies. National, supra-national region or global material stock and flow case studies were not included because data gaps and data availability are very different at this level.

As for the material accounting scope, initially it was set to be as comprehensive as possible. Economy-wide accounting as well as methods that relate to specific sectors or specific materials, even if they are not related to organic waste (OW), construction and demolition waste (CDW) and soil, were included. The limitation of methods on OW/CDW/Soil was considered since these are the materials relevant in the CityLoops project, however there was no strongly motivated reason to focus exclusively on accounting methods for these specific flows. It was later agreed that for not-so-clearly-relevant methods like water or GHGs, they would be indexed as long as they were found in the literature review. However, there was no proactive measure to index all possible methods on particular materials like water or GHG.

No temporal boundary, neither in studied years within publications nor of the publication date was set.

Research Question 2 challenges to find an answer as to what the main differences of these accounting methods are and possible strengths and weaknesses (with regards to the CityLoops project goals). These were then listed, mostly from existing sources, for each method, but also for the entire method category.

Although the main focus was on the first two questions, the **third research question** provided direction to the review of the literature and the analysis of the methods, as the end goal was that this work informs the next steps of the project, which is to develop a method that can quantify urban materials and assess the circularity of sectors and cities. Therefore, the question remained in the scope of the work and is answered in the last chapter.

2.2. Review of review papers

Upon defining the direction and scope of the study, the literature review and reading process started with existing review papers. They provided a good baseline and framing for the other reading. Furthermore, certain comparisons, listings, or other ways of classifying the literature that is used helped structure this work, as again, it was the goal to learn from peers and build on existing work.

The following review papers, ordered here by date, were studied:

- Approaches for Quantifying the Metabolism of Physical Economies: Part I: Methodological Overview (Daniels and Moore 2001)
- Approaches for Quantifying the Metabolism of Physical Economies: A Comparative Survey: Part II: Review of Individual Approaches (Daniels 2002)
- The study of urban metabolism and its applications to urban planning and design (Kennedy, Pincetl, and Bunje 2011)
- Addressing sustainability in the aluminum industry: a critical review of life cycle assessments (Gang Liu and Müller 2012)
- General approaches for assessing urban environmental sustainability (Baynes and Wiedmann 2012)
- Urban metabolism assessment tools for resource efficient urban infrastructure (Robinson et al. 2013)
- Concepts and methodologies for measuring the sustainability of cities (Yetano Roche et al. 2014)
- Urban Metabolism: A review of research methodologies (Zhang 2013)
- Urban Metabolism: A Review of Current Knowledge and Directions for Future Study (Zhang, Yang, and Yu 2015)
- Studying construction materials flows and stock: A review (Augiseau and Barles 2016)
- Material Flow Analysis as a Decision Support Tool for Waste Management: A Literature Review (Allesch and Brunner 2015)
- A review of urban metabolism studies to identify key methodological choices for future harmonization and implementation (Beloin-Saint-Pierre et al. 2016)
- A review and comparative assessment of existing approaches to calculate material footprints (Lutter, Giljum, and Bruckner 2016)
- Towards life cycle sustainability assessment of cities. A review of background knowledge (Albertí et al. 2017)
- Urban metabolism for resource efficient cities: From theory to implementation (Musango, Currie, and Robinson 2017)
- Urban metabolism and sustainability: Precedents, genesis and research perspectives (Céspedes Restrepo and Morales-Pinzón 2018)
- How can cities support sustainability: A bibliometric analysis of urban metabolism (Cui 2018)
- Urban sustainability assessment tools: A review (Kaur and Garg 2019)
- Taking Stock of Built Environment Stock Studies: Progress and Prospects (Lanau et al. 2019)

The list shows that quite a number of review papers exist and that publications over a wide range of time were taken into account. Moreover, authors from various geographical areas were included so as to identify as many accounting methods as possible. Through referencing these publications in the following chapters, it will be seen which ones were especially helpful for this report. Again, as stated in the previous chapter, these publications are also in the Zotero collection and could therefore be easily exported and included in other work.

2.3. Literature collection and review

The literature collection was facilitated due to the existence of the library of urban metabolism related publications (https://metabolismofcities.org/resources/publications) from Metabolism of Cities. While this library already contains a number of accounting method publications from scientific literature, books, theses and reports, it was decided to source more papers. In order to optimise the collection of literature between several researchers, the reference tool Zotero was made use of. It helped to work on publications at the same time, share highlighted versions of them and notes. A group was created on Zotero to manage the literature: https://www.zotero.org/groups/2381279/cityloops The group will continue to exist and be available to others, meaning that anyone is welcome to join it and gain access to the indexed literature.

Some keyword searches were done to locate additional literature, using the following keywords:

- Material flow accounting (method)
- Material stock accounting (method)
- Urban material accounting
- Urban material flow
- Urban stock analysis

Furthermore, literature from existing projects (see Chapter 5) were identified and added. Literature written in English was included, and literature in Dutch, German, Spanish and French was considered as well.

The list of publications from Musango et al. (2017) served as starting point for the review. These 165 case studies were imported to the Metabolism of Cities library. In the process of that review, other publications were included as well.

Aside from reviewing the review papers and after organising the literature collection, the scientific papers also had to be studied. A total of 194 papers were reviewed. It was deemed important to keep in mind the various aspects and parameters that can define a method, review papers with this awareness to possibly identify new methods and to classify the publications accordingly, either with a fitting established method or the new one. Aside from specifying the method, it was decided to note the case studies location and material groups under study. As for the materials, note was taken of some materials, namely all those that are related to food /

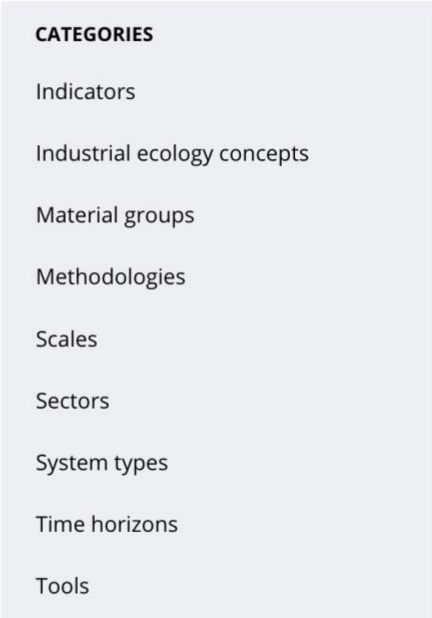

Figure 1: Top-level categories of the tags

organic (waste) and construction materials (/waste). They were tagged to eventually do some further analysis of this and at a minimum to show what those case studies are. If a study followed the economy-wide MFA with its typical material scope, tags were in some cases not specifically added, as it is implied by the method that these materials are included.

For this part, a tagging system was employed to facilitate the processing of the literature and the analysis of the findings later on. A tagging system that is also used in the Metabolism of Cities library was adopted. This tagging system, which was expanded to accommodate more tags, has a hierarchical grouping to manage different tags. In Figure 1, are the top-level entries of the existing categories. When on the bottom of the library webpage, one can click on a tag to see all the sub-categories and a list with relevant publications.

2.4. Methods from projects

Next to the extraction and obtaining a good understanding of the various methods that were included in the review papers and scientific literature, it was aimed to identify more methods from past and ongoing (European) projects and grey literature, such as reports from cities.

There are a few number of projects that were already compiled in the CityLoops project proposal, which served as a baseline for this review. More and more projects were gathered by scanning the funding calls for other, to CityLoops relevant, projects and through mentions of additional ones in other projects' descriptions or deliverables.

Project information such as full name, description, aim, material scope, case study locations, tools and methods that were used or developed, data sources (where evident), relevance of project to CityLoops, project time, funding programme, budget etc. was collected. This data came either from the funding programme website, the projects' own websites or it was gathered from reviewing deliverables. In some instances the projects were too recent or too old to be able to access the desired information and it was assumed that there were deviations from the initial proposals. Therefore, the project leaders and/or people responsible for the material accounting aspects were contacted as well, which resulted in insightful responses. The overview of this compilation of a total of 39 projects and its analysis can be found in Chapter 5.

2.5. Overview of accounting methods

The methods that were identified from the review papers, single publications and projects were all compiled in a large list. Most methods came from the review papers of Daniels and Moore (2001) and Musango et al. (2017), who include their own method categories and specific methods.

It was then crucial to analyse which of these are true urban accounting methods. Their descriptions in review papers as well as in case studies, reading relevant papers and determining the amount of case studies carrying out this method, helped in evaluating if and how these methods are used. It also aided in writing up the descriptions of the methods or realising which of the existing ones are suitable to be included on their own.

In the process of this evaluation, the following few processing notes came up:

- It needed to be defined what is combinational and what is a hybrid method (see Chapter 3.6)
- Methods from theses were not purposefully searched. It became a rule that they would be added if there was a peer reviewed article.
- Some methods were actually found to be tools, like GIS & STAN. It was therefore not a hybrid if used in combination with e.g. MFA.
- A publication on a sub-national level (also referred to as regional level by some) is not a method in itself, but instead on a different scale than urban.

2.6. Grouping of methods

For a number of reasons it is important to group different methods together. Depending on the exact scope and definition of what constitutes a different method, there could be dozens of individual methods being described. The first reason to group methods is for readability and to enhance understanding of how different methods relate. Secondly, there are a number of broad groups or categories of methods that can be identified based on some key characteristics. All methods in these groups will necessarily share a number of features, which means that benefits and shortcomings can also be more easily identified and discussed for the group as a whole. Particular strengths and weaknesses of individual methods can then be highlighted within that group. Finally, when looking at the use of different methods over time it helps to analyse the groups instead of the individual methods, which are sometimes only briefly used and in a few case studies, before being superseded by a new method within the same group.

Most existing review papers use some type of classification system to group different methods. However, there is no standard way of grouping these methods and in fact the parameters used to group methods vary significantly between reviews. In order to settle on a way to group papers for this review, an initial list of all identified methods was used and compared with existing classifications, which was then discussed and the most suitable option was selected. Below follows an overview of different classification systems that have been used by others.

One way of grouping methods is based on the nature of the data collection process (Lutter, Giljum, and Bruckner 2016, 4):

- **top-down** approaches starting from the macro-economic level in terms of economic structures and material extraction
- **bottom-up** approaches using coefficients on material input per product unit
- **hybrid** approaches combining the two previous approaches

Daniels and Moore (2001) group all methods by type of MFA, using four different classifications:

- **MFA1**: Widely acknowledged as MFA on the basis of their inclusion of economy-wide driving forces inducing material flows at any level of aggregation (consistent with Bringezu 2000)
- **MFA2**: Meets many of the criteria of MFA but considerable variation in attribution to the MFA group
- **Bulk MFA**: Commonly regarded as a form of "bulk material flow analysis". Note that the overlapping nature of most materials accounting approaches is widely acknowledged.
- **MFA-related**: Rarely classed as MFA but shares many of the basic methodological features albeit under a specialized methodological approach

Robinson et al. (2013) use the following classification:

1. **Accounting and assessment** approaches, which include material flow analysis (MFA), material system analysis (MSA), substance flow analysis (SFA), energy/carbon flow analysis, input/output analysis (IOA) and ecological foot printing analysis (EF);
2. **Process based analysis**, which essentially includes life cycle assessments (LCA);
3. **Simulation models**, of which systems dynamics modelling (SDM) and agent based modelling (ABM) form part; and
4. **Hybrid methods**.

A schematic overview of MFA approaches and their relevant indicators, as originally structured by the OECD (2008), can be seen in Figure 2.

Yetano Roche et al. (2014) define the approaches in three main groups:

- Territorial (production)
- Supply chain
- Consumption-based

For each group there is an overview of how this is applied in urban sustainability assessments both for energy use and GHG emissions, and for urban metabolism studies. More details are provided in Table 1.

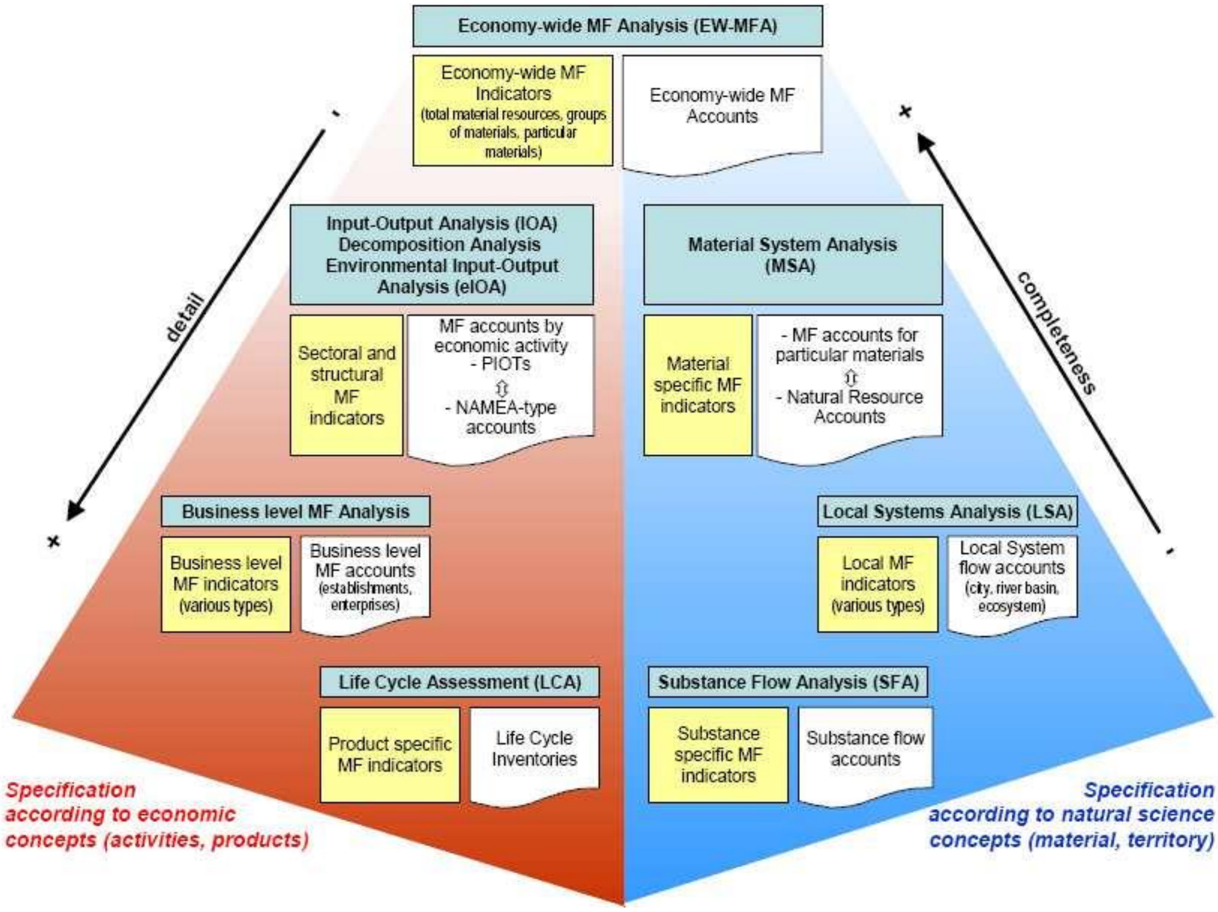

Figure 2: Architecture and level of application of MFA tools, including (in white boxes) the required data/input for each method. (Robinson et al. 2013 adapted from OECD 2008, 12)

Other scholars have categorized urban metabolism methods in different ways (Zhang, Yang, and Yu 2015):

- Material and nonmaterial approaches
- Inventory analysis (material- and substance-flow analysis)
- Biophysical methods such as exergy and emergy.

Another key characteristic of accounting methods that Zhang and colleagues (2015) highlight, revolves around whether or not the system itself is being ‘unpacked’: “(...) the **black box model** (in which the internal components of the system were not considered) and the **subsystem model** (in which the black box was "opened" to reveal its components)."

Table 1: Classification of urban sustainability assessment methods (Yetano Roche et al. 2014)

	Energy use and greenhouse gas (GHG) emissions	**Urban metabolism: material, energy, and substance flows**
Territorial (production)	Use of fuels by households and industries and production of electricity within a city's boundary; associated GHG emissions	Direct use of construction materials or food by households and industries within a city's boundaries; direct outflow of wastewater
Supply chain	Energy use and GHG emissions from energy and infrastructure supply chains (e.g., electricity production or waste treatment plants) that are outside the city boundary	Upstream (i.e., outside the city's boundaries)impacts of materials or supply to serve local demand
Consumption-based	GHG emissions released globally during the production of all goods and services consumed within the city	Food, material, or water inflows or waste outflows attributable to final consumption in the city

In a review of urban metabolism methods, Zhang (2013) identifies four different phases in the use of urban metabolism research (see also Figure 3):

1. Providing a theoretical basis
2. Accounting for and assessing flows and stocks
3. Modelling structure and function
4. Practical applications

For phase 2 and 3, there are a number of main methods listed:

Accounting methods:

- Material flow analysis
- Emergy (energy flow) analysis
- Ecological footprint analysis

Simulation methods:

- Ecological dynamics
- Ecological network analysis
- Input-output analysis
- Process analysis

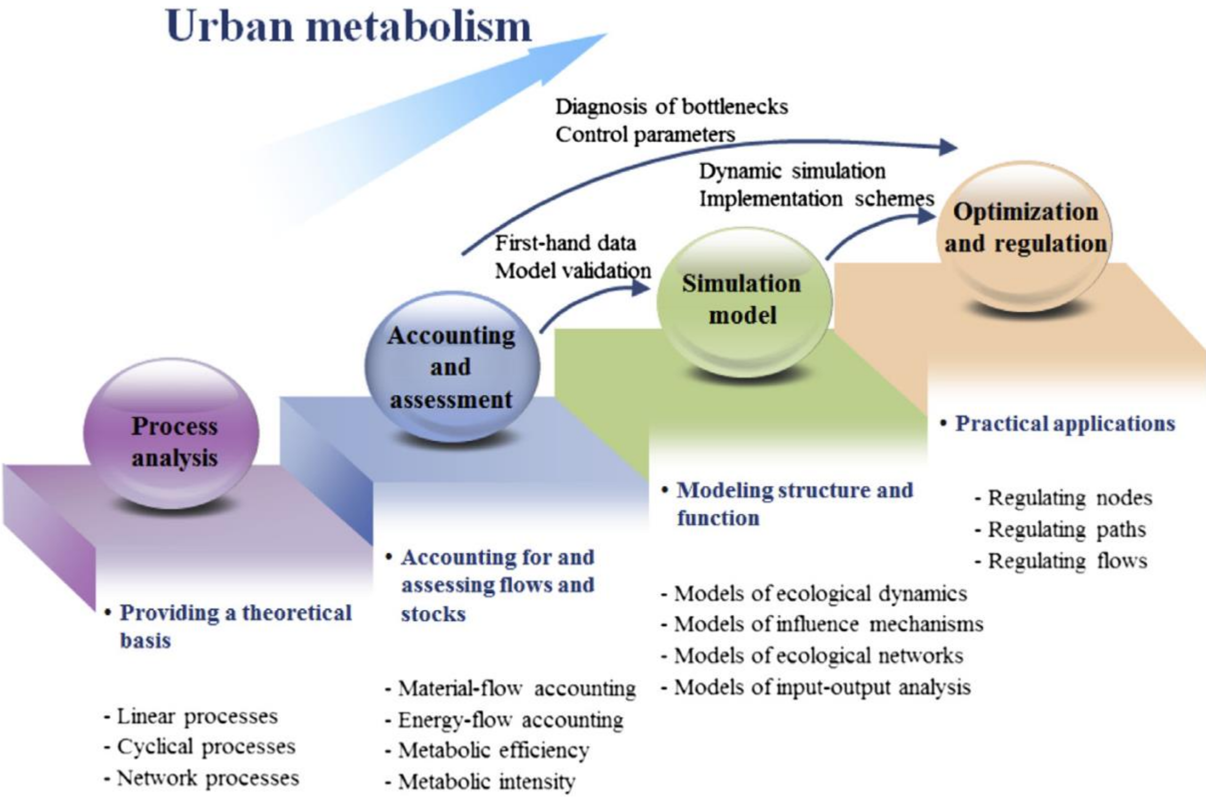

Figure 3: Research methods used to study urban metabolic systems (Zhang 2013)

Beloin-Saint-Pierre et al. (2016) group methods by a number of main categories, based on the nature of the assessment:

Categories:

- Flow analysis
- Energy assessment
- Footprint
- Input/Output
- Life cycle assessment
- Network analysis
- Integrated (combination of the previous methods)

The same authors also define a number of modelling strategies, which are based in part on a similar classification by Zhang (2013):

- Black-box
- Grey-box
- Network

Musango et al. (2017) use the following main classification to group the 165 case studies that they review:

- Accounting approaches
- Input-output analysis
- Ecological footprint analysis
- Life cycle assessment
- Simulation methods
- Hybrid methods

From this overview, it is clear that there is no consistent way to classify urban metabolism and material accounting methods. For this literature review, the classification used by Beloin-Saint-Pierre et al. (2016) has been applied. This classification system was used for the following reasons:

- Methods are classified by the type of assessment that is being done, which means that there is a lot of methodological overlap within each group, making it easier to group benefits and challenges.
- The authors did a classification exercise themselves (with 112 studies), which means that this classification system has been tested.
- The classification system is similar to the groups used by Musango and colleagues (2017), whose 165 case studies were also part of this review.
- There is a clear separation of embedded energy methods from the flow methods.

3. Methods: In-depth Review

In this section a total of 29 methods have been selected for further review and discussion. To facilitate discussion, many different ways exist to group methods, as presented in the previous section. In this chapter, the methods are grouped by categories based on the structure employed by Beloin et al. (2016). Only the category “Network analysis” was removed from the list as it just contained one method, the Ecological Network Analysis (ENA). While this is a useful method, it is not intrinsically material accounting-oriented, and for this reason it was removed as a method, as well as a main category, leaving six main categories, see Table 2.

Table 2 also lists the number of case studies reviewed in each category.

Table 2: Method categories and statistics on reviewed studies

Category	Total amount of reviewed studies
Flow analysis methods	95
Energy assessment methods	21
Input/output methods	13
Footprint methods	11
Life cycle assessment methods	5
Integrated: Hybrid methods + Multi-method	10 + 39
Total individual case studies	**194**

As was stated in the methodology section, the review process brought forward a great number of **methods and tools, a total of 91**, which were taken into consideration and reviewed. Those 35 methods that didn’t meet the scope were excluded from a more detailed review, however the reason for their exclusion and the source where they were found are included in a table in “Annex 1 - Table of excluded methods”. The non-accounting methods and tools are listed in Chapter 0. The remaining methods, their strengths and weaknesses will be described in more detail in the following sub-chapters and the respectively reviewed publications will be listed there too.

3.1. Flow analysis methods

“Flow analysis methods evaluate the sustainability of a system (e.g. UM) by modeling one or more of its substance, material, or energy flows. The model describes, at the very least, the flows entering and leaving the system but inner circulation of materials can also be considered.

They are valid for a specific period and stocks are usually modeled to respect the principle of mass/energy conservation. Flow analysis methods, in their standard forms, are quite simple and easy to implement. This simplicity is quite useful when complex systems like UMs are assessed. The simplicity allows for yearly assessment without requiring unmanageable amounts of data. Those methods are also the only ones that specifically offer information on stocks of materials and/or energy. This type of information can be quite relevant for decision makers even if it is not the main focus when environmental impacts or performances are assessed. The main drawback of using the flow analysis methods is the lack of clear environmental impacts description. For example, the UM studies do not show the environmental effects of those wastes if the flows of wastes are assessed with those methods. Flow analysis has been used to model and analyze different input data and this led to the creation of different methods." (Beloin-Saint-Pierre et al. 2016)

The following methods will be described in this category:

- Material Flow Analysis (MFA)
- Substance Flow Analysis (SFA)
- Economy-Wide Material Flow Analysis (EW-MFA)
- Energy flow assessment methods
- Material and Energy Flow Analysis (MEFA)
- Material Stock Analysis (MSA)
- Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM)
- Urban Metabolism Analyst Model (UMan)
- Abbreviated MFA
- Activity-based Spatial MFA (AS-MFA)
- Greenhouse Gas (GHG) Accounting
- Fate and Transport Analysis (F&T)

3.1.1. Material Flow Analysis (MFA)

One of the most widely used material accounting methods is the Material Flow Analysis (MFA). This method takes a systems-perspective and quantifies the relevant inputs and outputs for these systems. MFA relies on the principles of mass balancing as a way to verify that the model is complete and accurate. One of the reasons that MFA is so widespread is the versatility in its use. MFA can be used in any reference system, which can include global, national, regional, functional, or temporal reference systems. The time horizon can range from a contemporary point in time to a time series or even involve a long-range historical perspective. Finally, depending on the aim of the work, all physical material flows can be studied, or a specific subset that is of interest. Energy flows can also be subjected to an MFA. If only a single substance is studied, then this is called a substance flow analysis instead (see 3.1.2). Many of these main features as well as a historic perspective on MFA are discussed in a great reference paper by Fisher-Kowalski and Hüttler published just over two decades ago (Fischer-Kowalski and Hüttler 1998).

One of the strengths of MFA is the relative straightforward procedure (at the core of this method is 'counting numbers') that does not require advanced operations or mathematical models, and the obtained results (expressed in total weight of materials or quantity of energy flows) can be easily communicated to and understood by a wide audience.

There are some difficulties that arise depending on the chosen scope and system reference. The line between the natural and the socio-economic system is not always clear, which can lead to double counting or reporting inconsistencies. Examples include accounting for livestock and domesticated animals (and their respective nutrient intake and waste flows), defining a water balance within a reference system, accounting for the use of oxygen for respiration, and quantifying all inputs and outputs that are required to properly balance the combustion of fuels.

The method has been thoroughly described in a practical handbook (Brunner and Rechberger 2004). This handbook discussed the following procedural steps:

1. Selection of Substances
2. System Definition in Space and Time
3. Identification of Relevant Flows, Stocks and Processes
4. Determination of Mass Flows, Stocks and Concentrations
5. Assessment of Total Material Flows and Stocks
6. Presentation of Results
7. Materials Accounting

The authors also discuss data uncertainty, software to use for MFA, and relevant evaluation methods (which include a number of methods discussed further on in this report). All in all, this handbook has been a guiding reference for many MFA studies, and together with other books (e.g. Baccini and Brunner 2012) this makes MFA one of the most strongly documented methods.

Despite the well-documented procedure and rationale behind the method, there is no single approach that is adopted across the board. Gerber and Scheidel (2018) highlight a very relevant paragraph from one of the leading books:

Baccini and Brunner (2012: 105, their emphasis) wrote that “there are no theories available to perform MFA/SFA. [...] There are many groups active in MFA/SFA using their individual techniques and accumulating their specific experience and data. [...] [However], despite the many approaches, there are only small differences between the methods *of the individual schools of MFA/SFA. The main divergence is the* focus.*”*

Specific frameworks also exist, for example for water (Kenway, Gregory, and McMahon 2011). However, within this report these were here classified as MFA with their respective material. Another related method is Material Flow Cost Accounting (MFCA). This method is seen as a management tool that has considerable uptake at a corporate level, and which has also been codified in an ISO standard (ISO 14051). This is a tool to improve economic and environmental performance (Christ and Burritt 2015). The focus of MFCA is to allocate all production costs to material flows. MFCA focuses on the costs for product and non-product output (Jasch 2008)

3.1.2. Substance Flow Analysis (SFA)

"Substance flow analysis (SFA) focuses on material flows of just one, chemically defined substance, or a limited group of such substances through the metabolism of a relatively extensive, predefined geographic region. Within this region, all significant economic sources acting as the driving forces behind induced substance flows are considered. "Substances," as chemical elements and their compounds, comprise the "material" under study. Typical examples in existing research include nutrients such as nitrogen and phosphorous, chromium, mercury, lead and other heavy metals, carbon, water, and organochlorine compounds." (Daniels and Moore 2001)

There are a fair number of SFA studies done on an urban scale, with 15 publications identified in this report. Recurring substances in these studies include nitrogen, phosphorus, and metals. Compared to other material flow studies, SFA work requires a more detailed, nuanced understanding of the inner workings of the city under study. Instead of just focusing on the total input and output, SFA studies generally look at specific uses of the substance, which will include details on the types of consumers, as well as transformation that may happen within the city. In this regard, SFA can be much more useful for policy guidance, but it will require a greater depth of data that may be hard to come by.

3.1.3. Economy-Wide Material Flow Analysis (EW-MFA)

The Economy-Wide Material Flow Analysis (EW-MFA) method has become one of the most widely used material accounting methods due to its development and adoption by Eurostat. European countries submit national material flow data to Eurostat using this well-documented accounting method. This has facilitated uptake by researchers, including academics in the field of urban sustainability. This method has also become known as the 'Eurostat method', and its main features are the inclusion of all of the physical material flows moving into or out of a system (thus the 'economy-wide' label). Data is captured at a fairly detailed level (e.g. bananas or limestone), but top-level indicators within this method aggregate at higher level groups (e.g. biomass or non-metallic minerals). Water flows are intentionally excluded, though, due to the difficulty in separating natural water cycles from human water cycles, as well as the tendency of these large volumes to obscure some of the indicators when grouped together with other flows. On an urban level this method has at times been modified slightly (e.g. Barles 2009).

Compared to more narrow MFAs or SFAs, this method has significant data requirements in order to capture the entire, economy-wide (or city-wide in case of urban studies) material flows. However, a more holistic picture of the city's resources becomes available through this all-encompassing approach. Cities do remain a black box, and other methods are required to understand what happens *inside* this box.

3.1.4. Energy flow assessment methods

Energy flow assessment methods are concerned with the energy in fossil fuels and other energy carriers. These energy flow methods should not be confused with energy assessment methods (see Chapter 3.2), which look at the upstream energy requirements of a city's metabolism, whereas energy flow assessments look at the flow of energy and energy carriers within the system boundaries.

Haberl (2001) provided various reasons as to why energy flows should be an integral part of the analysis of societal metabolism. These include:

- Material flows require energy flows to power transport and transformation processes.
- Many interdependencies exist between material flows and energy flows (e.g. the use of energy-rich materials for energy provision, energy use to increase the availability of materials, and material use to reduce energy flows).
- Energy flows are one of the most unifying concepts in ecology and studying them therefore enables better communication between different socio-economic concepts like social organisation, institutions, economic accounting systems, and political decision).

One key method in this field is called Energy Flow Analysis (EFA). However, unlike MFA, EFA has not yet become a household name amongst urban industrial ecologists. This term is infrequently and inconsistently used, often without a clear reference to a specific methodological framework.

Zhang (2013) provides historical context around the concept of energy metabolism. Pioneered by Haberl in 1997, and described in more detail through an analytical framework using indicators a few years later (Haberl 2001), this "energy metabolic method" not only includes the quantification of energy flowing through socio-economic systems, but it also places a strong emphasis on energy present in biomass (food) and land use change as an integral part of the method. Application took place on various spatial scales, including national, urban, and sub-national level, but not before generating academic debate around the suitability of aggregating energy data into single variables (Giampietro 2006) (Haberl 2006).

The picture that emerges when looking in more detail at the urban case studies, however, is fuzzy at best. Various reviews (Zhang 2013, Beloin et al. 2016, Musango et al. 2017) reference conference proceedings or conference presentations as case studies, but these have left a limited permanent record. Nonetheless, Chen and Chen (2015) state that "among all the approaches, energy flow analysis (EFA) has been widely used in assessing urban metabolism (the study of the technical and socio-economic processes that occur in cities)." However, neither of the two studies referenced to back up this statement (Wolman 1965 and Kennedy et al. 2007) mention EFA or "energy flow analysis" in their own work. Similarly, Musango et al. (2017) identify four out of their 165 case studies as using an EFA method, but only two of those are readily available peer reviewed articles (Pincetl et al. 2016 and Porse et al. 2017), and neither of those mention this term in their work. When Belloin and colleagues (2016) define the EFA method, they do so in a description that is shorter than any of the other methodological descriptions, by stating: "*This specific method concentrates on modeling flows of energy instead of materials.*"

To further complicate things, energy flows are often studied and discussed alongside a material flow analysis (e.g. Kennedy et al. 2007). This kind of work could potentially be labelled as a "Material and Energy Flow Analysis (MEFA)" instead. This equally loosely defined method is described in the next section.

In summary, there is no clear agreement on what constitutes an EFA, and researchers do not tend to label their work as such. Application of the Haberl-pioneered energy metabolism framework at an urban scale seems non-existent or spotty at best. However, a different interpretation of EFA seems to have come to the fore that recognizes some logical distinctions between energy flows and material flows, without necessarily focusing on nutritional energy or land use change. Energy could include non-physical flows (e.g. electricity), and energy flows can be aggregated and compared by using units that are different from their mass (e.g. GJ). An energy balance can be drawn up, and linked to the physical material balance, and total energy consumption within a city or within a sector could still constitute an energy flow analysis - depending on one's definition.

It is likely useful to separate these more holistic energy analyses from more specific energy accounting studies. Instead of looking at city-wide energy requirements, some studies look at more sector-specific energy flows (e.g. building energy studies done on Los Angeles (Pincetl et al. 2016) and (Porse et al. 2016)).

For the purpose of classifying existing work, it is important to use a consistent way of labelling different methods, independently from the way individual authors describe their work. The following terminology was used to classify existing literature:

- **Energy accounting**: quantification of specific energy flows, without looking at the city's energy as a whole (example: a study on building energy use).
- **Energy balance**: a more holistic look at the city-wide energy requirements based on the city's physical infrastructure (buildings, vehicles, appliances, etc.), ideally including energy losses and conversion.
- **Energy flow analysis**: study of *all* human-induced energy used in and moving through the city, including energy directly used by humans and animal work (e.g. food flows and livestock grazing).

3.1.5. Material and Energy Flow Analysis (MEFA)

There is no consensus on the scope or definition of "Material and Energy Flow Analysis" (MEFA). At first glance, this method might simply entail undertaking both a Material Flow Analysis (MFA) and an Energy Flow Analysis (EFA). And in fact, some authors do exactly that

(Alfonso Piña and Pardo Martínez 2014). Haberl and colleagues (Haberl et al. 2004) developed a conceptual MEFA framework that not only included MFA and EFA, but that also looks at human appropriation of net primary production (HANPP), in order to understand the land use changes that accompany the material and energy flows.

However, there is no clear unified “materials and energy” approach and within this review MEFA is therefore not considered its own accounting method. Instead, like others, MEFA is considered an umbrella term to refer to the accounting method categories that involve materials and/or energy flows.

It should be noted that undertaking both a material and an energy flow analysis yields a number of advantages. Most importantly, these two flows embody the entirety of the human-environmental interaction and they are furthermore closely related. A large share of the energy used in cities can be traced back to fossil fuels and biomass. At the same time, energy is required to move the material flows through an urban space. The same mass balancing principles apply to energy, which similarly cannot be created or destroyed within a system.

3.1.6. Material Stock Analysis (MSA)

Material flow studies investigate the movement of physical materials into and out of socio-economic systems. However, some of these materials will remain inside this socio-economic system for an extended period of time. This applies in particular to materials used in the built environment, machinery and equipment, and durable consumer goods (e.g. vehicles, electronics or furniture). These materials are referred to as the material stock, and the method to locate and quantify this stock is called Material Stock Analysis (MSA).

Material flows and stocks are intimately connected and for this reason this method is included in the Flows accounting methods. Most material flow methods define the changes in the material stock, either directly or indirectly, because this is equal to the difference between inflows and outflows. In the Eurostat (2001) EW-MFA method, the material accumulation (or Net Addition to Stock) is a clearly defined indicator, for instance, and there are a number of methodological rules defined around calculating the material stock. Because all material stocks ultimately leave the socio-economic system and end up being recycled or disposed of, there has to be a definition as to when to classify a material flow as a stock. Most studies use one year of permanency to be classified as a material stock, but exceptions can be made (Müller et al. 2014).

In order for a case study to be classified within this MSA method, it is important that not just the *change* in material stock is quantified, but instead the focus should be on the quantification of the total available stock within a city, either for a single year or for a longer period of time. MSA could focus on a single material like copper (Beers and Graedel 2003), or a particular sector like residential buildings (Condeixa, Haddad, and Boer 2017).

Information on the material stock is generally obtained using one of two approaches: bottom-up or top-down. In an in-depth review of construction material flows and stocks literature, Augiseau and Barles (2016) define these approaches as follows:

"The bottom-up approach is based on a division of the stock into categories (housing, business premises, etc.), and then by the application of material ratios or intensities (in tonnes/m 2 for example). (...) The top-down approach is to quantify stock as the sum of annual net additions to stock over a long period. Stocks are thus derived from the difference between inflows and outflows, calculated from year-to-year. These flows are known from statistical data (construction and demolition), or are estimated, based on average lifetimes or survival functions."

Data availability often varies significantly between countries and cities, and most studies will select an approach depending on the available data. There is also no standard approach around forecasting (which is often an important component of the study). This makes it difficult to make comparisons between studies (Augiseau and Barles 2016).

MSA can, however, provide insights that MFA studies lack. This type of study can be very spatially explicit, especially when studying the built infrastructure. Furthermore, this method allows for the exploration of the potential for cities to serve as "urban mines", in which the recovery of materials from existing stock can replace import of new materials. Such a study was undertaken recently on the city of Amsterdam, for instance (van der Voet et al. 2017). Another innovative approach is to study the available energy stock and to unpack what this means for the city's resilience in light of possible energy supply shocks (Bristow and Kennedy 2013).

3.1.7. Multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM)

The multi-scale integrated analysis of societal and ecosystem metabolism (MuSIASEM) method has been in development since the 1990s, mainly by one research group centred around Giampietro, Mayumi, and associated researchers (Gerber and Scheidel 2018). The concept and rationale behind this method have been described in detail (Giampietro, Mayumi, and Ramos-Martin 2009) and this method can be seen as an alternative to the MEFA approaches. However, there are a number of key differences with the MEFA accounting family.

Giampietro and colleagues approach metabolism with a broader and more integrated toolset. The focus is not exclusively on top-level material or energy flows, but there is also a strong emphasis on the economic and social components of the system. Furthermore, this method looks by default at multiple scales, "opening up" the black box that a system, such as a city can be seen as, to understand how these different levels relate to each other. MuSIASEM integrates both material and energy flows within a single method instead of developing separate methods for each. Finally, this method provides a *multi-purpose grammar*, instead of facilitating strictly defined guidelines or handbooks. In theory there is therefore more interpretative freedom for researchers to define their exact scope and indicators, but at the same time this makes it more difficult for new researchers to start using this method.

The MuSIASEM method can provide insights and indicators that are uncommon, if not impossible, to obtain using traditional MEFA approaches. These include, for instance, insights into how time is being used by the population, how energy consumption and GDP relate to each other, or the impact of economic development on land use.

Due to the deep level of analysis and unpacking of material and energy flows and socio-economic structures in a system, it is more difficult to approach the entirety of a national or local economy. Instead, most work has been done on particular resources inside an economy. Work on an urban scale has been limited. Examples include waste management in Naples (Chifari et al. 2017), land use in Shanghai (Lu et al. 2016), and more regional work including energy metabolism in Catalonia (Ramos-Martín et al. 2009). Historic studies are difficult to undertake due to the data requirements, so most studies have focused on contemporary economies (Gerber and Scheidel 2018).

Alias: this method was previously abbreviated as MSIASM.

3.1.8. Urban Metabolism Analyst Model (UMan)

The Urban Metabolism Analyst Model (UMan) was developed to address a number of shortcomings that were encountered when researchers applied EW-MFA or other bulk MFA studies on an urban level. The method was described through a case study on the Lisbon Metropolitan Area (Rosado, Niza, and Ferrão 2014). UMan uses a material classification that is based on Eurostat reporting, but top-level aggregation happens for 28 material types (much more than EW-MFA). Spatial and sectoral disaggregation of data allows to comprehend the inner workings of the black box. Product lifespan data is used to gain a better understanding of the recovery of materials from the material stock in the city. Import and export flows that merely flow through an urban system are decoupled from flows that specifically originate in or are destined for urban areas.

The additional understanding that UMan provides requires increased data collection and processing. There are relatively few case studies using this method and it has yet to be replicated outside of a small group of core researchers. The method did find uptake outside in a more applied context, as part of the UrbanWINS project (see Chapter 5).

3.1.9. Abbreviated MFA

Abbreviated MFA can be seen as a method that aims to streamline the process of performing a city-wide MFA. Methods like the EW-MFA are known to be time-consuming and data-heavy, while at the same time lacking a number of key flows (e.g. water and electricity). Various researchers have discussed and advocated for an abbreviated approach to mainstream the field of urban metabolism (Kennedy and Hoornweg 2012), and several case studies have taken place that make use of an “abbreviated” or “streamlined” MFA method that allow for a relatively quick assessment of a city's metabolism. The advantage of these methods is that it can be performed much more quickly than more rigorous studies, at the expense of accuracy and completeness. This method allows researchers to make comparisons across different cities by tackling a number of cities in a single study, which is much more difficult to do with other methods. This approach has led to the funding of comparative studies by international agencies like the World Bank and the Asian Development Bank (D Hoornweg et al. 2012; Serrat, Park, and Yoshino 2014).

3.1.10. Activity-based Spatial MFA (AS-MFA)

The Activity-based Spatial MFA (AS-MFA) method was developed by Geldermans et al. (2017) in the European Horizon 2020 REPAiR project (see *Projects* for more info). As the name suggests, it is an MFA that emphasises the importance of opening up the black box by analysing the (economic) activities that take place in a city, their relationships and respective actors (companies) linked to those activities. The actors and their connections provide the "spatial" aspect of this method, since the actors can be georeferenced and their interrelations are expressed by the material flows between them.

The AS-MFA method has already been applied in the case studies of Naples and Amsterdam (Geldermans et al. 2019), Łódź (Czapiewski et al. 2018), Pécs (Varjú et al. 2018) and Hamburg (Arlati et al. 2018). The material scopes for these case studies were wastes along the supply chain, therefore taking into account upstream and downstream processes with the goal to create circular streams and close loops. Therefore, the supply chain perspective was taken starting at the point where the material scope under study became waste for the first time, which in the case of food waste was already at the farmer, for example.

The strengths of this method lie in the refined network approach that highlights the necessity of systems thinking and demonstrates how very many things are interconnected and dependent on each other. The multi-scale consideration aids in this as well, where in principle data can be aggregated from the actor to neighbourhood to district to city to regional levels, illustrating where exactly hotspots occur. By having the flows and stocks spatially mapped (spatial Sankey diagrams) hotspots are revealed, which can inform decision makers.

However, the decision makers won't find a connection to costs or other economic data, as the AS-MFA doesn't account for it, at least in the way that the method is defined so far. Another weakness is that energy flows are not integrated as of yet. Finally, it requires a good understanding of supply chains and flow networks and a significant amount of data on e.g. actor locations, relationships of economic activities, various material amounts and destinations, some of which isn't readily available or can be costly to obtain.

3.1.11. Greenhouse Gas (GHG) Accounting

Greenhouse Gas (GHG) Accounting can in itself be seen as a method, although no single standardised approach exists. While some state that it is the equivalent of a carbon footprint analysis, others acknowledge that it is not necessarily the same. For this report, a distinction is made between the two, where carbon footprint analysis is the assessment of total GHG produced (see more Chapter 3.4.2), whereas GHG accounting is merely the inventorying of GHG emissions. The inventorying can be done according to a smaller, case study specific scope and can also include carbon sinks in the analysis, as opposed to only the emitting sources.

For the case studies of cities, some base their research on a simplified adaptation of the IPCC top-down method (Kennedy et al. 2010), while others apply a bottom-up method (Baldasano, Soriano, and Boada 1999).

3.1.12. Fate and Transport Analysis (F&T)

"Fate and transport analysis is defined as the study of how chemicals degrade and where chemicals travel in the environment when they are released intentionally or unintentionally. This analysis is currently used in the United States to determine pesticide and herbicide residues, industrial process vapors and car exhaust emissions released to the environment.

Fate and transport analysis is a holistic way of looking at chemicals in the environment and involves a modeling system that indicates not only how a chemical moves through the air, water and soil (transport) but also how the chemical changes in the presence of other chemicals and particles (fate). This modeling system is often coupled with sensing and collection systems to find chemical residues left in the environment." (Pacific Northwest National Laboratory 2019)

While the focus of the method is clearly on chemicals, the aspect of considering the fate of materials, included in the method as what from a different perspective could be seen as environmental impact assessment, has merit. However, the application of this method for a city study is rare, but does exist. For example, Boehme et al. (2009) made use of it, in combination with SFA, MFA and LCA, to track contaminants in the New York/New Jersey Harbour.

Table 3 provides an overview of the strength and weaknesses of the methods in the flow analysis category.

Table 3: Strengths and weaknesses of flow analysis methods

<table>
<tr><th>Method</th><th>Case studies</th><th>Strengths</th><th>Weaknesses</th></tr>
<tr><td>Material Flow Analysis (MFA)</td><td>48</td><td>▪ Extremely versatile in its use and can be catered to suit many specific needs.
▪ Plentiful documentation has helped define standard terms and procedures.
▪ Relatively straightforward procedure around ‘counting numbers’.
▪ Results can be easily communicated to and understood by a wide audience.</td><td>▪ Inconsistencies or double counting need to be carefully considered when defining the exact scope and system boundaries, especially where the natural and human systems directly interact.
▪ Lack of a single methodological framework has led to a multitude of specific approaches.
▪ Difficult to translate results to policy interventions.</td></tr>
<tr><td>Substance Flow Analysis (SFA)</td><td>15</td><td>▪ Better at unpacking the black box by looking at how a particular substance is used within the city.
▪ May be used for policy recommendations</td><td>▪ Requires in-depth urban data on this particular substance
▪ Not suitable for holistically understanding interrelationships with different materials</td></tr>
<tr><td>Economy-Wide Material Flow Analysis (EW-MFA)</td><td>21</td><td>▪ Availability of a well-documented methodological guide.
▪ Ability to (nearly) capture the entire physical economy.</td><td>▪ Data required on a large group of materials not necessarily available on an urban level.
▪ Cities are seen as black boxes with no insights into what happens inside the box.</td></tr>
<tr><td>Energy Flow Analysis (EFA)</td><td>3</td><td rowspan="2">▪ Energy and material flows have many interdependencies, which makes the study of energy flows highly relevant:
– Energy can be used to increase availability of materials.
– Materials can be used to reduce energy flows.
– Energy-rich materials are used for energy provision.
▪ Total energy consumption is a useful headline indicator.
▪ Studying energy flows enables better communication between different socioeconomic concepts like social</td><td rowspan="2">▪ A number of energy flows are not obvious and calculating them can be difficult (e.g. energy (conversion) losses or nutritional energy).
▪ Energy flows do not directly relate to environmental impacts.
▪ Some consider single-scale and single-variable (energy) indicator work a reductionist approach.
(Haberl 2001, Giampietro 2006)</td></tr>
<tr><td>Energy Balance</td><td>10</td></tr>
</table>

Method	Case studies	Strengths	Weaknesses
Energy Accounting	11	organisation, institutions, economic accounting systems, and political decision). ▪ Lots of energy statistics already provide a strong baseline for energy flow analyses. (Haberl 2001)	
Material Stock Analysis (MSA)	16	▪ Can be very spatially explicit, especially when studying the built infrastructure. ▪ Allows for the exploration of the potential for cities to serve as “urban mines”. ▪ Natural complement to urban MFA studies.	▪ Lack of standard approaches makes comparisons more difficult. ▪ Data quality and availability limit the feasibility or increase the uncertainty of MSA.
Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)	3	▪ Unpacks the black box and allows for in-depth understanding of the socio-economic system at different levels. ▪ More fine-grained and nuanced than traditional MEFA studies, which tend to aggregate and simplify entire economies/cities into a few headline indicators. ▪ Integration of materials and energy with the socio-economic system. ▪ Provides a multi-purpose grammar which allows for studies to be catered to the local needs.	▪ Difficult to apply on a city-wide level. ▪ Data requirements make it time-consuming to perform and difficult to do historic studies. ▪ Provides a multi-purpose grammar which requires more time to set up than a ready-made handbook or methodological framework.
Urban Metabolism Analyst Model (UMan)	3	▪ Specifically developed to be applied at the urban scale ▪ Higher number of top-level material types ▪ Spatial and sectoral disaggregation of data ▪ Product lifespan data is used to gain a better understanding in recovery of materials from the material stock in the city ▪ Better understanding of cross-flows that merely use the city as a trade hub	▪ Uses Eurostat-based product classification, making it more difficult to use outside of the EU ▪ Higher data collection and data processing requirements than most MFA methods ▪ The use of multiple different tools increases the uncertainty of the results
Abbreviated MFA	3	▪ Developed to take advantage of commonly available urban flow data.	▪ Speed comes at a loss of accuracy and completeness

Method	Case studies	Strengths	Weaknesses
		▪ Can be done more quickly than EW-MFA or similar methods. ▪ Facilitates comparative studies across cities.	
Activity-based Spatial MFA (AS-MFA)	4	▪ Refined network approach that highlights the necessity of systems thinking ▪ Demonstrates how very many things are interconnected and dependent on each other ▪ Consideration for multiple spatial scales ▪ Spatial mapping of flows and stocks, illustrating location of hotspots	▪ Lack of integration of economic data or analysis ▪ No accounting of energy flows ▪ Good understanding of supply chains and flow networks is required ▪ Data intensive method
Greenhouse Gas (GHG) Accounting	5	▪ Simple inventorying ▪ Fairly easy to carry out	▪ Focus is only on GHGs ▪ No universally used method
Fate and Transport Analysis (F&T)	1	▪ Modelling can provide insights on fate of chemicals ▪ Behaviour of many chemicals is known and so results are reliable	▪ Very specific to chemicals and contaminants Rather applied to industrial facilities

3.2. Energy assessment methods

"The methods from this category offer information on the upstream energy needs of UMs. They usually consider the network of components in the UM to model the flows of energy. The period covered by those methods is relatively long because it ascends the stream up to natural resources. Their main advantage is their capacity to simplify the aggregation of different types of flows (e.g. mass, energy, area, volume, money) by defining specific energy equivalents with the use of pre-calculated conversion factors for all components/processes. This single type of information is however difficult to tie with environmental impacts. For example, it is almost impossible to correlate the energy content of emissions and their specific toxicity levels. Emergy and Exergy are the two types of methods from this category that have been used in UM studies." (Beloin-Saint-Pierre et al. 2016)

3.2.1. Emergy Analysis

Emergy analysis is an energy-based approach that quantifies *emergy*, which is the total energy required to produce a product or material flow, through all processes and transformations that may be involved and also known as embodied energy. Total energy is reported in a single, consistent unit – Emergy Joule. This approach allows for quantification of all of the embedded energy of products.

The use of emergy was first described by Odum (1996). Uptake of this method at an urban level has been limited, and most of the case studies are geographically bound to Asia, with the majority of the work being undertaken in Chinese cities.

The term *emergy synthesis* is also used to describe the use of a series of indices to understand the observed emergy patterns. "Emergy synthesis combines principles from general systems theory, thermodynamics, and systems ecology to account for the total environmental resources contributed for the generation of a product or a service" (Odum 1988 in Huang and Chen 2009, 78). Sometimes this kind of work is called an *emergy evaluation*. In this report, all of this work will be grouped under the single term *emergy analysis*.

In order to provide environmental impact insights, a number of hybrid approaches (e.g. MFA-Emergy and Emergy-LCA) have been introduced (see more in Chapter 3.6.1 under *Hybrid methods*).

3.2.2. Extended Exergy Accounting (EEA)

"Exergy describes the maximum work which can be produced from a system under a given environment. This concept is commonly used in process engineering to estimate (or design) various energy systems such as co-generation systems. Exergy is one of the most widely used goal functions in the structural dynamic modeling." (Banerjee, Rakshit, and Ray 2019)

Extended Exergy Accounting (EEA) is *"a systematic attempt to integrate into a unified coherent formalism both Cumulative Exergy Consumption and Thermo-economic methods, and constitutes a generalisation of both, in that its framework allows for a direct quantitative comparison of non-energetic quantities like labour and environmental impact (hence the apposition 'Extended')."*

In one case study on the city of Karachi, the main energy supply as well as flows of labour and capital were quantified using extended exergy accounting (Jahangir, Chen, and Wakeel 2016). Other exergy work on an urban level covers Beijing and Castelnuovo Berardenga. However, urban exergy studies are few and far apart, hinting at difficulties in application and limitations in the usefulness.

Table 4 provides an overview of the strength and weaknesses of the methods in the energy assessment category.

Table 4: Strengths and weaknesses of energy assessment methods

Method	Case studies	Strengths	Weaknesses
Emergy Analysis	19	(Zhang 2019) ▪ Ensures that the flows of energy that underlie the creation and flow of all materials is accounted for along with the flows of materials, and accounts for differences in the quality of the materials or energy.	(Zhang 2019) ▪ Determining appropriate transformity values for specific objects or flows is a difficult problem that has not yet been solved
Extended Exergy Accounting (EEA)	3	▪ Can be used as a unified metric for estimating the resource use efficiency and environmental impact.	▪ Method is very underused on an urban level and far removed from more common material and energy flow analyses.

3.3. Input/output methods

"Methods of the input/output (I/O) category start their modeling with the description of direct links among components of a global structure (e.g. national exchanges). The direct and indirect needs of a component (e.g. economic sector) can then be accounted for to offer relevant information on the sustainability of the global structure. The general concepts underlying the I/O methods are based on the pioneer work of Leontief in the 1930's. The main advantage of I/O based methods is the inherent completeness of analysis they allow. All flows inside the

system boundary (e.g. UM) are considered and the proportion of effects from each component of a UM can be put into perspective with the global effects. For instance, if using a multi-regional I/O framework. Still, this completeness may come with coarse definition of the full system. This prevents the targeted audience of a study from choosing precise solutions to improve the sustainability of components that are found in a UM. For example, it is rather difficult to identify the type of vehicle that is responsible for the majority of GHG emissions in a city if the model only says that the transport sector is responsible for 35% of the GHG emissions from a UM. The I/O methods usually use economic flows to describe the link between components of a system. This monetary modeling does not offer information for the evaluation of environmental impacts. Therefore, other methods have been proposed to overcome this missed opportunity." (Beloin-Saint-Pierre et al. 2016)

As becomes evident from the above description, input-output methods make up another crucial accounting family that is relevant for the quantification of resources, including materials, energy and land of a system, albeit originally stemming from expressing inter-industrial trades in monetary terms, which is the method known as input-output analysis. This method and the following four will be described in this category: Multiregional input-output (MRIO) tables, physical input-output (PIOT) tables, environmentally extended input-output analysis (EE-IOA) and throughflow analysis.

3.3.1. Input-Output Analysis (IOA)

Since the general category introduction already explains this method quite sufficiently, it is only being stressed here that this method typically follows a top down approach, accounting for the *monetary* transactions between sectors on a macroeconomic level, but have also been applied to urban and sub-national areas. The information is arranged in tables and "used in economics to represent the structure of production and final consumption within an economy (single-region input-output SRIO model) or amongst multiple economies (multi-region input-output MRIO model)" (Schaffartzik et al. 2014).

In some cases, a hybrid method is applied, which is not always pointed out as such and which in this context means that both economic and material data are employed and integrated in the tables (Sinclair et al. 2005).

The strengths and weaknesses of this method are mainly the same as the one of the category in general, except that a big advantage for the monetary tables is that they are put together regularly by national statistical offices and therefore readily available (Schaffartzik et al. 2014).

Alias: MIOT (monetary input-output tables)

3.3.2. Multi-Regional Input-Output (MRIO)

For multi-regional input-output (MRIO) tables, it can be debated, much like for PIOT or EE-IOA, whether these are their own type of method or analysis or simply tables that are used for another method. In this report, they are listed as their own method although the analysis of the literature case studies of this report shows that MRIO tables were usually used to carry out another analysis like a carbon or water footprint.

MRIO tables, not to be confused with MIOT (monetary input-output tables), "group local or national IO-tables into one balanced model often including a model for representing the rest of the world economy" (Athanassiadis et al. 2018, 5), instead of focusing on a single region. There is no definition if a MRIO table can only include monetary or material flows or both. Several large databases exist that publish MRIO tables such as the Asian International Input–Output Table, Eora, EXIOPOL, GTAP 7 and World Input-Output Database (Wiedmann et al. 2011). These vary with regards to the amount of sectors, base year and environmental extensions that they include and number of countries and world regions, without a focus on the urban scale.

3.3.3. Physical Input-Output Tables (PIOT)

"Physical input-output tables (PIOT) allow national-level analysis that extends upon conventional input-output methodology and classifications to incorporate environmental resource and waste output "sectors" to provide measures of the physical flow of materials and goods within the economic system and between the economic system and the natural environment. This approach involves the exhaustive physical coverage of the movement (origins and uses) of most environmentally relevant materials induced by an economic region (sometimes disaggregated to the level of elements or simple chemical compounds). The PIOT method traces how natural resources enter, are processed, and subsequently as commodities, are moved around the economy, used, and finally returned to the natural environment in the form of residuals. It undertakes the detailed investigation of intersectoral physical flows of environmental resources inputs and commodity weights and residuals, and given this intersectoral specification and transactions matrix structure, has the ability to evaluate the cumulative environmental burden (total direct and indirect effect material requirements and pressures) of private consumption and other final demand for the products of different industries" (Daniels and Moore 2001).

This physical quantification is of course a contrast to the economic or monetary input-output tables that reflect the flows only in monetary values. As Giljum and Hubacek (2004) pointed out, it needs to be noted "that a PIOT is not simply a unit conversion of a MIOT and cannot be derived by multiplying the MIOT with a vector of prices per tons for each sector. This is mainly due to aggregation of non-homogeneous sectors into one category, differences in prices for different consumers of the products and different methods of establishing material versus money flows. However, increases in resource productivity of production processes as well as changes in pollution abatement technologies can also rapidly alter the physical technological coefficients of particular sectors in a PIOT and the production of waste per unit of physical input. These aspects have to be taken into account, in particular when working with sequential PIOTs over time."

3.3.4. Environmentally-Extended Input-Output Analysis (EE-IOA)

A natural extension of the physical input-output tables is the inclusion of environmentally relevant materials, which is done in the environmentally-extended input-output analysis (EE-IOA). While it can be argued that all materials have an environmental impact, it is those that have a direct influence on e.g. environmental pollution, climate change, degradation of natural resources and biodiversity loss as a result of economic activities that are quantified (Kitzes 2013). Since they include direct and indirect material (or energy) flows they can be very well expressed as environmental impact indicators such as carbon or water footprints, for which many studies exist, with a handful on cities (Beloin-Saint-Pierre et al. 2016; Dias et al. 2014).

An advantage of the EE-IOA method is that it can identify the sectors responsible for the largest share of environmental burden, as it links environmental data (e.g. carbon dioxide emissions) with monetary flows. However, since "the input-output model is in monetary units and the environmental extension is in physical units (e.g. in joules of energy, tons of material, or kilograms of pollutant), this integration is non-trivial" because of the required assumptions that IOA makes around homogenous products, prices and the exclusion of non-market flows (Schaffartzik et al. 2014, 1). Several other strengths and weaknesses of this method are listed in the category overview table.

3.3.5. Throughflow analysis

Since "throughflow analysis is similar to input–output analysis", according to Zhang et al. (2010), it is listed in this category as well. Throughflow analysis may not be too familiar in the industrial ecology field, as it stems from natural ecology. However, due to the comparable nature of the two systems, man-made ecosystems and natural ecosystems, it has been borrowed and applied to a few urban case studies.

"Throughflow analysis investigates the relationship between environmental inputs and compartmental throughflows" (Ma and Kazanci 2012), accounting for the matter and energy flows departing from compartments, and measures both direct and indirect flows with a matrix (Matamba et al. 2009; Zhang, Yang, and Fath 2010). The compartments that are referred to here have to be previously defined, which can be done with an ecological network analysis (see chapter 0) or they can become evident from the relevant sectors that emerge in the input-output tables. For example, in the study of an urban water metabolic system the identified compartments were local environment, rainwater collection, industry, agriculture, domestic sector, and wastewater recycling (Zhang, Yang, and Fath 2010).

Table 5 provides an overview of the strength and weaknesses of the methods in the input/output category.

Table 5: Strengths and weaknesses of input/output methods

Method	Case studies	Strengths	Weaknesses
Input-Output Analysis	8	▪ Strengths of it are mainly the same as the one of the category in general. ▪ Monetary tables are put together regularly by national statistical offices and therefore readily available.	▪ Weaknesses of it are mainly the same as the one of the category in general ▪ If not a hybrid table, it merely includes monetary data.
Multi-Region Input-Output (MRIO) Analysis	7	(Wiedmann et al. 2011) ▪ Provides the ability to track the impacts of international production and supply chains, spanning multiple sectors in multiple countries. MRIO covers all indirect impacts caused by upstream production. ▪ Frameworks are closely linked to standard economic and environmental accounting (United Nations, 1993, 1999) which ensures that, at least at the national level, a continuous process of data compilation takes place. ▪ MRIO calculus can be extended to forecasting and projection applications, and could be used as a basis for CGE modelling. ▪ Consistency at the global scale: Total global emissions/resource use can consistently be allocated to detailed production and consumption activities, preserving mass balances.	(Wiedmann et al. 2011) ▪ A substantial effort is required to set up and update a system of MRIO tables and related physical extensions (Peters et al., 2011a). Most MRIO initiatives require significant manual labour and time to complete one MRIO table. ▪ A limitation for certain MRIO analyses is given by the number of industries and product groupings distinguished in the model. Most current initiatives do not provide for maximum sector disaggregation, but opt for a compromise between the number of sectors and countries. ▪ In order to assess impacts of individual products or processes with MRIO, hybridisation is required, i.e. the integration of specific process data (for example for an explicit representation of recycling/secondary resources). This entails additional data compilation and computation efforts. ▪ Additional, spatially explicit impact assessment models are required to locate environmental impacts below the sub-national level (e.g. Local water use). ▪ MRIO time series data is limited ▪ Since, in general, trade and transport margins are aggregated in input–output tables, the allocation of impacts in the distribution stage of consumer goods is not straightforward. Separate margin matrices for trade and transport are currently not routinely produced. ▪ Most databases do not provide information on reliability and uncertainty.

Physical Input-Output Table (PIOT)	3	▪ Integration of physical data beyond only monetary data ▪ Availability of national data tables ▪ Combination of material accounting with other aspects such as social, environmental and/or economic, depending on extension	▪ High aggregation within sectors ▪ No sufficient differentiation of products ▪ Data requirements are large and therefore also the costs
Environmentally-Extended Input-Output Analysis (EE-IOA)	8	(Kitzes 2013) ▪ Follow "product trees" back for an infinite number of steps; ▪ Use publicly available input-output tables to infer the production recipes used for the creation of goods and services; ▪ Address the existence of loops or cycles in production practices, which occur when a product is used in the production of itself; ▪ Avoid double counting by allocating, in a mutually exclusive manner, environmental impacts between sectors; ▪ Capture trade in secondary, processed products, including feed fed to livestock; ▪ Capture trade in services (if a monetary input-output table is used).	(Kitzes 2013) ▪ Assumption of homogeneity: assumption that each sector in the economy produces a single, homogeneous good or service. ▪ Sector resolution of input-output tables may be low. ▪ Tables may not capture all activities in the economy. ▪ Usage of linear models that assume a constant, fixed proportion of inputs is used to create a sector's output; ▪ The accuracy of global input-output tables is limited by disparities in the collection and standardization of raw data in different nations; ▪ Input-output tables are generally not available for every nation and may be published with large time lags (i.e., every five years); ▪ Accurate assessment of environmental impacts themselves, and the assignment of these impacts to sectors, is often difficult. ▪ Inventories of environmental impacts, especially at large spatial scales, such as nations, often reflect a mix of empirically measured data and modeled estimates, both of which can introduce biases and uncertainties into EEIO analyses.
Throughflow Analysis	4	▪ dynamics of a system become obvious once the compartments and their relationship are identified ▪ compartments and relationships will likely remain similar over time, although dynamics may change, but should allow for time-series analysis ▪ inter-compartmental flows can be analysed as well, refining the analysis	▪ entire network and the relationships have to be understood to be able to balance the matrix ▪ little experience with this method in urban studies

3.4. Footprint methods

"The footprint methods can evaluate the direct and often indirect environmental effects of a UM for a particular indicator (e.g. global warming potential). As for the energy assessment methods, all flows between components of the assessed system must be considered to evaluate a footprint. Once this step is done, the goal is to add the environmental effects of those components and translate them into one type of environmental impact per habitant (i.e. footprint). The main advantage of the footprint methods is the simplicity of the message it offers to its target audience, that is to say, decision makers. However, this great advantage is counterbalanced by the lack of consideration for other relevant impacts (e.g. human health, biodiversity) that are also linked with the activities of UM. The ecological footprint and the carbon footprints are the two types of footprints that have been used to assess UM in the reviewed studies but others variants (e.g. water footprint) also exist." (Beloin-Saint-Pierre et al. 2016)

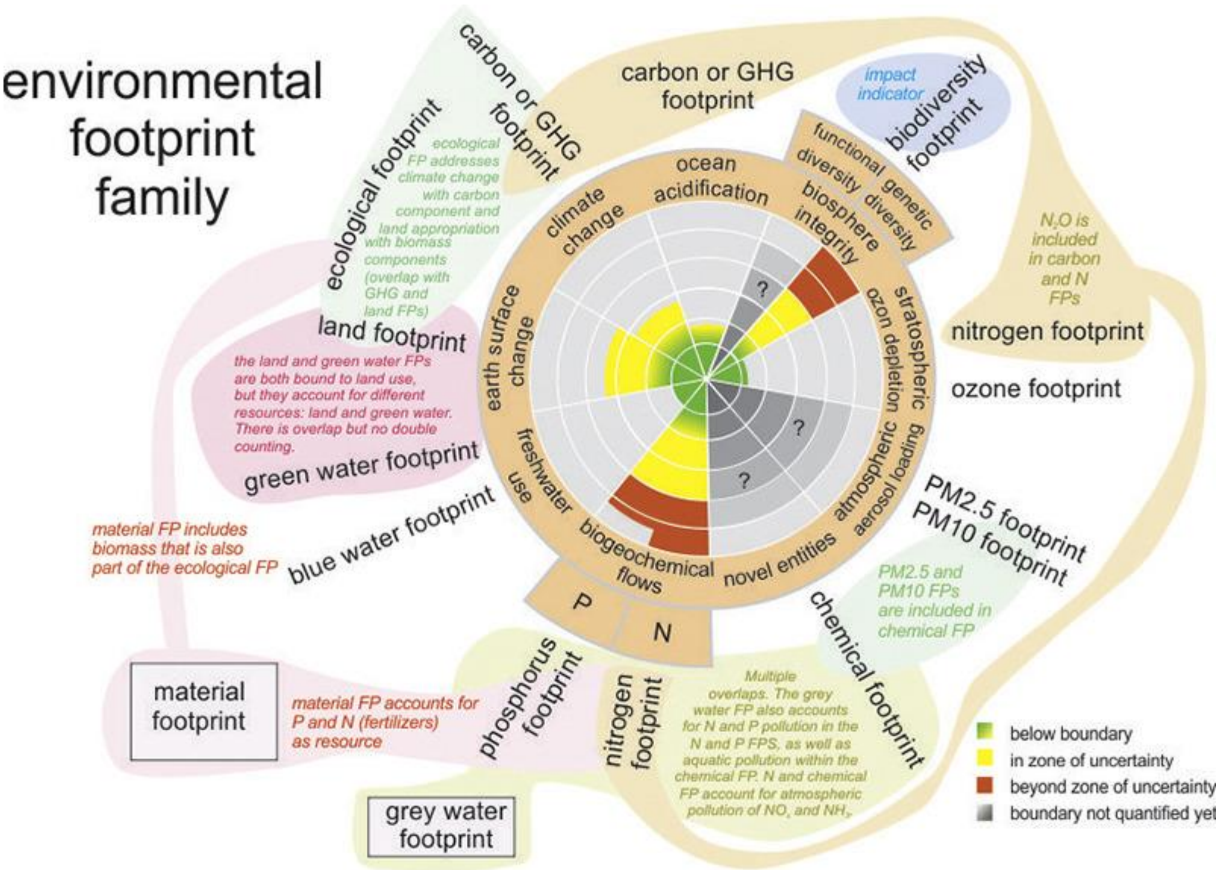

Figure 4: The environmental footprint family with their many footprint indicators, their overlapping and how they correspond with the nine planetary boundaries (Vanham et al. 2019)

The original idea behind the concept of the footprint was to account for the physical space that the production of a good or service "costs", measured in global hectares (gha) (Galli et al. 2011). If that were still the case, then the footprint methods would not actually be included in this review as the focus is not on the quantification of land mass, but of materials. However, there are many other forms of footprint that steer away from the physical space and look at the amount (in mass) of a particular material that it takes, is embodied or was emitted during the production of a good, for example.

Figure 4 illustrates the multitude of these individual footprints that can be assessed, encompassed in the “environmental footprint family”. There are various approaches to determine these footprints, which can be grouped under EE-IOA, LCA (process-based) or a hybrid of the two (Vanham et al. 2019). Ecological, carbon and water footprints are the most prominent ones in terms of number of studies, followed by the analysis of energy, material and land footprint (Vanham et al. 2019).

Again, the footprint methods’ main strength lies in the fact that they are rather easy to understand and are therefore also very suitable for communication with decision-makers and the public. However, exactly herein also remains one of their largest weaknesses in that trade-offs or problem shifting to either other footprints or even concerns that are not expressed in a footprint, are not reflected by only looking at an individual footprint. This issue could be remedied by integrating multiple footprints, which a handful of authors have already called for (Galli et al. 2012; Vanham et al. 2019). This could either be done around the idea of the footprint family or by developing specific footprints around material groups. For example, Goldstein et al. (2017, 2) suggest that there may be a need to develop methods for the urban foodprint, “to capture the various elements of diverse resource consumption and environmental impacts associated with the production, processing, distribution, and waste generation of food demanded by urban residents. The foodprint may be measured in a variety of ways and include units of mass, embodied carbon, ecological footprint (EF), nutrient flows, or other relevant indicators.” Since CityLoops deals with organic waste as well, investigating an urban foodprint may be of interest.

In addition to the issue of integrating footprints, there is difficulty with this method category as well, as they “have so far been calculated using different methodological approaches” (Vanham et al. 2019). In their review of studies, Goldstein et al. (2017, 7) remarked that it was an obstacle to deal with “studies using equally distinct methodologies within assessment study categories (e.g., input output [I-O] vs. process), entity accounted (household vs. city), and data sources (national, regional, or city).”

Adding to that criticism, it could be argued that the single components of the footprint family are not actually methods on their own but indicators that are derived by applying other methods (e.g. EE-IOA or LCA). Since it is not the goal of this literature review to redefine or reclassify these various fields, it will remain in this list of methods here, as people know or understand it as such.

The three most studied footprints (ecological, carbon and water) are described in further detail below.

3.4.1. Ecological Footprint (EF)

The ecological footprint (EF) "was designed as a readily comprehended indicator of the sustainability of the human economy vis-à-vis the Earth's remaining "natural" capacity to supply resources (sometimes considered equivalent to the planet's terrestrial "carrying capacity"). It groups and calculates material and energy requirements of nations (or regions) for a limited number of consumption functions, converts these metabolic flows into the ecologically productive land area required to produce the resources used in these activities, and compares the required areas to available regional, national, and global ecologically productive areas. Existing studies have typically been restricted to the ecological resource output potential of terrestrial areas." (Daniels and Moore 2001)

"Particularly, the application of EF at city level has been conducted by several scholars. Such applications usually can be categorized into two kinds, namely, the top-down compound and the bottom-up component methods (Moore et al., 2013). The compound method uses national per capita ecological footprint data that is scaled to reflect the city as much as possible. The advantage to the compound method is that total national production, import and export data for key sectors are readily available and easier to locate than city-specific data. However, this method has limited ability to reflect the impacts of local policy and action (Chamberset al., 2000). The component method starts with local data that reflect the study population's consumption activities and therefore can better assess the local development performances; however, such a method requires more accurate local data, which may be unavailable in some regions (Barrett et al., 2002). Two sub-approaches were proposed for the component method, namely the input output analysis (Bicknell et al., 1998) and the direct estimates of material and energy throughput using local data (Moore et al., 2013)." (Geng et al. 2014, 4)

"Although widely used, EFs have also been criticized considerably and the two main criticisms are still difficult to properly incorporate in footprint calculations (van den Bergh and Verbruggen, 1999; van Kooten and Bulte, 2000; McDowell, 2002). First, the original formulation of EFs assumes spatial homogeneity, which is rarely the case over the spatial scales relevant to urban ecosystem service withdrawal. Second, the aggregation of all ecosystem services ignores the fact that several services may be provided by the same surface area. Based on these and related problems, much discussion has ensued about the applicability of EFs [...] and solving these problems is an area of active research (Wackernagel et al., 2004)." (Jenerette et al. 2006)

Since the EF is actually a measure of biologically productive land area and therefore does not fall under the scope, it could also not have been included in the review. However, as can be seen from the case studies and as should be evident from the description now, materials are first quantified before they are translated into global hectares and there are often other methods applied within a study as well, which warranted a closer look. For more information about the history of EF, ways of calculating it and critique, the paper of McDonald and Patterson (2004) is recommended.

For the sake of completeness, two members of the EF are here also mentioned, as they emerged in the review. First, the **energy ecological footprint (EEF)**, which is "utilized to characterize the pressure of energy consumption on the ecological environment" (Yang and Fan 2019). As there was only one case study that made use of it and its scope (energy within EF) does not directly pertain to urban material accounting, it was excluded from further review. Second, the **Sustainable Process Index (SPI)** is also a member of the EF family and "is calculated as the ratio of total land area required to sustainably manufacture a product or provide a service to the average available land area per individual, specific to the location of the production facility" (Doble and Kruthiventi 2007) converted from material and energy flows (Gwehenberger and Narodoslawsky 2007). Although this may not be suitable for the urban system as a whole, it is worthwhile to mention it, because it could either be used for the demonstration projects or the sector level of CityLoops.

3.4.2. Carbon Footprint (CF)

The carbon footprint (CF), or also referred to as the GHG footprint, deals with the carbon component and accounts for anthropogenic greenhouse gas emissions associated with the production of goods or services, a specific event or an entire organisation, depending on the aim. Inconsistent terminology is also a concern here, with some authors calling it "carbon accounting", even if they determined a carbon footprint. The carbon footprint method should also not be confused with GHG accounting, which is an inventorying of emissions, at least in the publications that were reviewed for this report. Adding to the confusion is that carbon is sometimes used as a catch all term for GHG emissions, such as carbon dioxide, methane, and nitrous oxide, which are all expressed in carbon dioxide (CO_2) equivalents.

The analysis of a CF "follows the same basic modeling principals as the EF, but only considers the greenhouse gas (GHG) emissions for the evaluation of the environmental impacts" (Beloin-Saint-Pierre et al. 2016). There are three main accounting approaches for GHG emissions on the city scale, which are 1) territorial (geographic)-based, 2) trans-boundary community-wide infrastructure and 3) consumption-based accounting (Chavez and Ramaswami 2013). The territorial approach, also called **production-based (PB) accounting**, *"measures emissions generated in the place where goods and services are produced. However, the growth of emissions embodied in trade has raised the question whether we should switch to, or amalgamate PB accounting, with other accounting approaches.* ***Consumption-based (CB)*** *accounting has so far emerged as the most prominent alternative. This approach accounts for emissions at the point of consumption, attributing all the emissions that occurred in the course of production and distribution to the final consumers of goods and services"* (Afionis et al. 2017) and uses household expenditure data most often, although input-output tables adjusted from national to urban scales are also used (Ramaswami et al. 2011). The **trans-boundary infrastructure supply chain footprint (TBIF)** was developed by Ramaswami et al. (2008) and is a demand-centered hybrid LCA-based inventory method for GHG emissions of cities. "The TBIF method utilizes the concept of scopes from corporate GHG emissions accounting protocols to include both in-boundary and trans-boundary GHG emissions associated with key community-wide activities; hence it has also been referred to as an expanded geographic inventory or a community-wide infrastructure GHG footprint. The TBIF method recognizes that cities include both producers and consumers, and focuses on infrastructure supply chains that serve the entire community as a whole. The GHG emissions accounted for by the TBIF method are (1) direct in-boundary GHG emissions (scope 1), (2) indirect GHG emissions from the generation of purchased electricity (scope 2), and (3) GHG emissions from essential trans-boundary infrastructures serving cities (scope 3), such as water supply, transportation fuels, airline and commuter travel, and other critical supply chains. The inclusion of trans-boundary infrastructures (scope 3) warrants careful allocation of GHGs to avoid double counting (Ramaswami et al. 2008)" (Chavez et al. 2012).

For CityLoops it will have to be seen if a CF analysis will be carried out at all in conjunction with the circularity assessment, but in any case it may be useful for others to know what CF entails.

3.4.3. Water Footprint (WF)

Following the logic of the carbon footprint, the water footprint (WF) is related to the quantification of water. It "accounts for both the direct (domestic water use) and indirect (water required to produce industrial and agricultural products) water use of a consumer or producer" (Vanham and Bidoglio 2013). The WF is expressed in total volume of freshwater measured over the entire supply chain. "It is a multi-dimensional indicator, showing water consumption volumes by source and polluted volumes by type of pollution; all components of a total water footprint are specified geographically and temporally. The blue water footprint refers to consumption of blue water resources (surface and ground water) along the supply chain of a product. 'Consumption' refers to loss of water from the available ground-surface water body in a catchment area, which happens when water evaporates, returns to another catchment area or the sea or is incorporated into a product. The green water footprint refers to consumption of green water resources (rainwater stored in the soil as soil moisture). The grey water footprint refers to pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards" (Hoekstra et al. 2009, 8).

As with previously described methods and with the footprint methods in particular, there is also no consensus about the scope and exact accounting procedure of a WF, although there is an excellent manual called "The Water Footprint Assessment Manual: Setting the Global Standard" (Hoekstra et al. 2011) developed by the Water Footprint Network. Discrepancies in reported values may be due to authors not communicating their results according to the components of blue-, green- and grey water or researchers simply not following the proposed manual stringently enough (Harding 2019). Either way, the WF has so far not seen much application on a city scale as is evident from the small number of case studies.

Table 6 provides an overview of the strengths and weaknesses of the methods in the footprint category.

Table 6: Strengths and weaknesses of footprint methods

Method	Case studies	Strengths	Weaknesses
Ecological Footprint (EF)	15	(Robinson et al. 2013) ▪ Presents the merits of combining socioeconomic development demands with ecosystems in a simple framework. ▪ Informs researchers and practitioners on whether a given metabolism is overshooting its carrying capacity or sustainably ensuring an ecological surplus ▪ Unsustainable situations are clearly brought to the fore	(Robinson et al. 2013) ▪ A number of researchers have criticized the ecological footprint method as it was originally proposed An oversimplification of the complex task of measuring the sustainability of consumption
Carbon Footprint (CF)	12	(Galli et al. 2011) ▪ Ability to allocate responsibility for production-related GHG emissions to consuming entities or activities; ▪ Consistency with standards of economic and environmental accounting; ▪ Ability to track the impacts of international supply chains, spanning multiple sectors in multiple countries; ▪ Allows the adoption of different accounting perspectives according to the producer, consumer, or shared responsibility principle; ▪ Compatible and comparable with existing global economic and trade models; ▪ Enables scenario simulations of the combined effects of implementing economic, social and environmental policies.	(Galli et al. 2011) ▪ By looking at GHGs only, the Carbon Footprint is not able to track the full palette of human demands on the environment (e.g., resource depletion); ▪ Substantial effort is needed to create and update a system of MRIO tables and related environmental extensions. ▪ Much of the data necessary for producing these tables is not yet available, particularly accurate data on GHG emissions from production sectors in transition and developing countries; ▪ Currently, no uncertainty studies are available; ▪ The EE-MRIO accounting framework itself only allows ex-post analyses, based on data of the past, although by its nature accounting often has to look historically backwards. ▪ Additional, spatially explicit climate change impact models are required to assess the impacts of climate change at sub-national level and below;

			▪ Without the integration of specific process data ('hybridisation'), the resolution of EE-MRIO analysis is limited to the number of sectors, i.e. industry and product groupings, in the model; ▪ Hybridisation –required to assess the environmental impacts of single products or processes –entails additional data compilation and computational efforts. Though already pioneered in the 1970s, hybridisation is still rapidly evolving and not standardised.
Water Footprint (WF)	3	(Galli et al. 2011) ▪ Not restricted to blue water use (as most of the existing water indicators), but also includes green and grey water ▪ Includes both direct and indirect water use; ▪ Visualizes the link between (local) consumption and (global) appropriation of water resources; ▪ Provides a wide perspective on how a consumer or producer relates to the use of freshwater systems; ▪ Integrates water use and pollution over the complete production chain; ▪ Give spatiotemporally explicit information on how water is appropriated for various human purposes.	(Galli et al. 2011) ▪ Lack of required data. A major challenge is therefore to develop more detailed guidelines on what default data can be used when accurate local estimates are not available; ▪ A practical issue in Water Footprint accounting is to identify what should be included and what could be excluded from the analysis (such truncation problem is also common in Ecological and Carbon Footprint assessments); ▪ The uncertainties in data used in Water Footprint accounting can be very significant, which means that outcomes should be carefully interpreted. Currently, no uncertainty studies are available; ▪ In case of the grey Water Footprint, a challenge is to develop guidelines on how to define natural and maximum allowable concentrations. Both should ideally be catchment-specific, but in many cases such data are not available; ▪ Water stress characterization factors are not included thus limiting the capacity of the Water Footprint to give clear indications on the actual potentials for harm. ▪ Water footprint is not a measure of the severity of the local environmental impact of water consumption and pollution. ▪ Often communicated as a single figure aggregating blue and green water (and sometimes grey) footprints despite the fact that the impacts of these three water footprints are very different.

3.5. Life cycle assessment (LCA) methods

"Life-cycle assessment (LCA) is an environmental management tool for identifying (and comparing) the whole life cycle, or cradle-to-grave, environmental impacts of the creation, marketing, transport and distribution, operation, and disposal of specific human artifacts. The approach is intrinsically holistic in nature and considers direct and, ideally, related processes and hidden, nonmarket flows of raw materials and intermediate inputs, and waste and other material and energy outputs associated with the entire existence or "product chain" or "system" (Guinee et al. 1993). The LCA procedure often involves a comparison of a small number of substitutable products assumed to provide a similar consumption service." (Daniels and Moore 2001)

This method is well-documented in the ISO 14040 and 14044 standards. The outcome of an LCA study generally provides insights into a number of different impact categories, which can for instance include climate change, acidification, eutrophication, and resource depletion. There is a significant use of LCA inside and outside of academia. There are many applications of this tool in industry, and the approach has been expanded with complementary methods like Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA), which focus on the economic and social aspects, respectively. The combination of LCA, LCC and S-LCA has been termed Life Cycle Sustainability Assessment (LCSA) (Kloepffer 2008).

Despite a clearly-defined guiding framework and unparalleled opportunities to understand the global impacts of material flows, LCA has not yet found wide uptake in urban metabolism assessments. Firstly, LCA faces data requirements that exceed those of other methods, and requires an understanding of production, distribution, disposal, and other operations outside of the city of study. Furthermore, a "functional unit" must be defined before being able to undertake an LCA. However, the city itself cannot be taken as a single functional unit. Instead, a particular product, material, or a service within the city should be defined as a functional unit.

A number of hybrid methods have been developed that take advantage of LCA but that can be combined with other assessment methods on an urban level. These methods are discussed in more detail in the *Hybrid methods* section below. For strengths and weaknesses, see Table 9.

3.6. Integrated methods

Instead of limiting a study to a single method, it is also possible to combine different methods. In this report, studies are differentiated between "hybrid" and "multi-method" studies by looking closely at the interaction *between* the methods within the study. If one method is used as a 'building block', as some sort of input or other type of influencing factor in another method, then this is labelled as a hybrid method. However, if the use of one method does not influence the outcome of the other, then this is merely labelled as a multi-method study.

This difference can be best illustrated by looking at two case studies. In the first case study, Ohnishi and colleagues (2017) looked at the impact that industrial symbiosis practices had on Kawasaki city in Japan. They did this by performing an MFA, a carbon footprint analysis, and an emergy analysis. However, these three methods were applied independently in order to look at the environmental impact of the various practices from different angles, and to better grasp and monitor the overall environmental impact. In their results, the researchers discuss the Direct Material Input indicator (obtained through the MFA), the total carbon footprint, and the emergy sustainability index. The benefit of using their comprehensive framework stems from the fact that different methods obtain different insights.

On the other hand is a case study from Lavers Westin and colleagues (2019) who look at three Swedish cities by combining MFA and LCA approaches. The MFA is used to quantify the Domestic Material Consumption, broken down by product group. Then, LCA is used to calculate the environmental impact of each of these individual product groups based on the most representative product in each group. In this work, the outcome from the MFA serves as input into the LCA. These methods cannot be seen as independent components in this study and for this reason we label this as a hybrid method.

Lastly, when discussing integration of methods, it is also important to highlight that in this report the primary focus has been on accounting methods, on *quantitative methods.* However, there are also non-accounting or *qualitative methods* that can be integrated with these accounting methods. An example would be to combine an MFA with an Ecological Network Analysis (ENA). The ENA is a qualitative method that will be able to shed new light on the quantitative results obtained from the MFA.

The number of combinations between quantitative and qualitative methods are limitless and the divide between industrial ecology and other disciplines becomes blurred when these additional methods get involved. There can be great merit in doing so, but providing a comprehensive review of these options was outside of the scope of this review. However, after discussing quantitative hybrid methods and multi-method studies, a brief review of some of the most interesting non-accounting methods will be provided below.

3.6.1. Hybrid methods

Four different methods have been identified that integrate two different accounting methods. Three of these methods involve LCA. The likely reason for the proliferation of LCA in the hybrid methods is that this method can bring a much needed environmental impact understanding to other methods that lack this. Furthermore, the method itself is not necessarily independently applicable as an urban metabolism method, making it more widely used in combination with other methods.

When naming methods, a convention in this report is used to list the methods in order of their usage within a study (one method generally follows the other). Individual authors may use different terminology, as there is no established protocol.

Hybrid MFA-LCA

One of the drawbacks of an MFA is the inability to quantify the environmental impacts of the urban resource flows. By combining MFA and LCA approaches, it becomes possible to better understand various environmental impacts for each type of material flow. There is no single methodological framework that describes this hybrid method. Instead, a number of different approaches have been implemented. The MFA that precedes the LCA could be based on the Brunner and Rechberger approach (García-Guaita et al. 2018), or it could follow the UMAn model (Westin et al. 2019), for instance. The challenge within this method is that generally high-level material flow data obtained from an MFA are not compatible with product-specific required input into an LCA. To overcome this issue, various approaches exist. One option is to limit the scope of the MFA on the most relevant flows, rather than undertaking an EW-MFA (for instance, (García-Guaita et al. 2018) focus on seven material flows in Santiago de Compostela). Another option is to select a few representative products for each category (Westin et al. 2019).

Independently from the chosen strategy, this approach inherently relies on a large number of assumptions and generalisations, as product-based breakdowns are unattainable for entire sectors or material groups, let alone cities. A degree of uncertainty is therefore necessarily introduced to the LCA results. However, exact precision is not necessarily required to identify hotspots. This hybrid method does allow for an understanding of impacts on a number of environmental impact categories and provide new insights that can be actionable and useful in policy (Westin et al. 2019).

Aliases: this method is sometimes referred to as UM-LCA (e.g. (González-García and Dias 2019)).

Emergy-LCA

By introducing LCA to an emergy analysis, it becomes possible to understand the various environmental impacts, in addition to the embedded energy. This is generally only feasible when a single product or product group is being analysed.

Economic Input-Output Life-Cycle Assessment (EIO-LCA)

An economic input-output life-cycle assessment (EIO-LCA) uses input-output data aggregated on a sector-level, which is then subjected to an LCA. This method allows for a relatively fast understanding of the impacts within the supply chain, albeit at the expense of accuracy due to using sector-level averages.

MFA-Emergy

This approach was used in Liuzhou city to allow for a better comparison of the impact of industrial symbiosis practices (Sun et al. 2017). The MFA provided insights into savings of certain materials, which yielded environmental benefit insights. By converting these material flows to emergy, it becomes possible to also understand the ecological benefits in terms of total energy savings.

3.6.2. Multi-method studies

The table below (Table 7) provides an overview of the 39 studies that use multiple methods. As can be seen, many studies combine footprint studies with other methods. This confirms the earlier observation in the discussion of footprinting methods that this could also be considered a tool or an indicator, which is applied to the results obtained through another method. It can also be observed that energy balances are also often undertaken jointly with another analysis, which confirms that the balance itself is not the core of the work but rather an addition to other insights that can be gained and they help paint a more complete picture of a city's metabolism.

Table 7: Title and year of publications, showing their accounting and non-accounting methods and case study location(s)

Title	Method	City	Year
Incorporating Metabolic Thinking into Regional Planning: The Case of the Sierra Calderona Strategic Plan	EF Energy Accounting MFA	Valencia	2019
Comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan	CF Emergy Analysis MFA	Kawasaki	2017
City Carbon Footprint Networks	CF MRIO	Adelaide Brisbane Melbourne Perth Sydney	2016
Surveying the Environmental Footprint of Urban Food Consumption	CF EF MFA		2016
The Concept of City Carbon Maps: A Case Study of Melbourne, Australia	CF EE-IOA	Melbourne	2016
Towards a Dynamic Approach to Urban Metabolism: Tracing the Temporal Evolution of Brussels' Urban Metabolism from 1970 to 2010	Energy Balance MFA	Brussels	2016
Transnational city carbon footprint networks - Exploring carbon links between Australian and Chinese cities	CF MRIO	Adelaide Beijing Brisbane + 7 more	2016
Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input-output analysis	CF MRIO hybrid	Melbourne Sydney	2016

Title	Method	City	Year
Metabolism of Brussels-Capital Region: identification of flows, economic actors and activities on the territory and tracks of reflection for resource optimisation	EW-MFA MFA	Brussels	2015
Urban energy consumption: Different insights from energy flow analysis, input-output analysis and ecological network analysis	ENA EFA IOA	Beijing	2015
Urban metabolism: Measuring the city's contribution to sustainable development	Energy Accounting MFA	Curitiba	2015
Analysis of the energy metabolism of urban socioeconomic sectors and the associated carbon footprints: Model development and a case study for Beijing	CF ENA Energy Accounting IOA	Beijing	2014
Ecological network analysis of an urban metabolic system based on input-output tables: Model development and case study for Beijing	ENA IOA PIOT	Beijing	2014
Urban material flow analysis: An approach for Bogotá, Colombia	Energy Balance MFA	Bogotá	2014
An input-output approach to evaluate the water footprint and virtual water trade of Beijing, China	EE-IOA WF	Beijing	2013
Carbon footprints of cities and other human settlements in the UK	CF MRIO		2013
Consumption based footprint of a city	CF EE-IOA LCA MFA hybrid	Paris	2013
Sustainable design of sanitation system based on material and value flow analysis for urban slum in Indonesia	MFA Scenario analysis SFA	Bandung	2013
Comparison of energy flow accounting, energy flow metabolism ratio analysis and ecological footprinting as tools for measuring urban sustainability: A case-study of an Irish city-region	EF Energy Balance MFA	Limerick	2012

Title	Method	City	Year
Material Flows and Energy Analysis of Glass Containers Discarded in New Jersey, USA	Energy Accounting MFA Scenario analysis	New Jersey	2012
Analyses of water footprint of Beijing in an interregional input-output framework	MRIO WF	Beijing	2011
Analysis of water consumption using a regional input-output model: Model development and application to Zhangye City, Northwestern China	EE-IOA IOA	Zhangye	2009
Collaborative Problem Solving Using an Industrial Ecology Approach	F&T LCA MFA SFA	New Jersey New York City	2009
Combined MFA-LCA for Analysis of Wastewater Pipeline Networks	Hybrid MFA-LCA MSA	Oslo	2009
A Demand-Centered, Hybrid Life-Cycle Methodology for City-Scale Greenhouse Gas Inventories	Greenhouse Gas Accounting LCA	Denver	2008
A method for regional-scale material flow and decoupling analysis: A demonstration case study of Aichi prefecture, Japan	IOA MFA Method	Aichi	2008
Applying physical input–output tables of energy to estimate the energy ecological footprint (EEF) of Galicia (NW Spain)	EF EEF EE-IOA	Galicia	2008
The energy and mass balance of Los Angeles County	Energy Balance MFA	Los Angeles	2008
Service Sector Metabolism: Accounting for Energy Impacts of the Montjuic Urban Park in Barcelona	Energy Balance LCA	Barcelona	2007
The Changing Metabolism of Cities	Energy Balance MFA	Brussels Cape Town Hamburg Hong Kong: + 5 more	2007

Title	Method	City	Year
Contrasting water footprints of cities in China and the United States	EF WF	Beijing Chicago Chongqing + 5 more	2006
Ecological Footprints and interdependencies of New Zealand regions	EF IOA	Auckland	2004
Long-term Coordination of Timber Production and Consumption Using a Dynamic Material and Energy Flow Analysis	Energy Accounting MFA	Swiss lowland region	2004
Estimating the urban metabolism of Canadian cities: Greater Toronto Area case study	Energy Accounting MFA	Toronto	2003
A comparison of the sustainability of public and private transportation systems: Study of the Greater Toronto Area	Energy Accounting Greenhouse Gas Accounting	Toronto	2002
A material flow analysis and ecological footprint of York	EF Energy Balance MFA	York	2002
Escalating trends in the urban metabolism of Hong Kong: 1971-1997	Energy Balance MFA MSA	Hong Kong: City	2001
Energy and material flow through the urban ecosystem	Energy Balance MFA	Bangkok Beijing Buenos Aires + 22 more	2000
The metabolism of a city: the case of Hong Kong	Energy Balance MFA MSA	Hong Kong: City	1978

3.6.3. Non-accounting methods

All of the methods discussed earlier focus primarily on the quantification of material or energy flows. While these methods may yield deep insights into the materiality of the socio-economic system under study, there are inherent shortcomings to these approaches. The extraction, transformation, use, and disposal of resources are influenced by and have in turn also an impact on the economic, political, social, technological and natural systems. Methods that help understand the interaction between the physical economy and these components can enhance understanding, impact potential, relevance, or applicability of a study. The drawback of involving non-accounting methods to a quantitative approach is that it increases complexity and requires an understanding of both quantitative and qualitative methods that are applied. The combination of these approaches may ultimately not be of merit, and this is sometimes only found out after completing a study.

The list below includes **18 qualitative methods** that have been used in combination with material accounting literature. This is not an exhaustive list and most of these methods were identified by Musango and colleagues (2017) in their review of 165 case studies. Some of these methods are described in more detail below.

- Agent-based modelling (ABM)
- Bio-social indicators
- Classification tree analysis
- Cost-Benefit Analysis (CBA)
- Ecological Network analysis (ENA)
- Economic cost analysis
- Infrastructure studies (IS)
- Life Cycle Costing (LCC)
- Multi-criteria evaluation (MCE)
- Multiattribute Utility Theory (MAUT)
- Planetary boundary analysis
- Policy analysis
- Political industrial ecology (PIE)
- Resilience assessment
- Scenario analysis
- System dynamics modelling (SDM)
- Typology
- Value flow analysis

The list includes a variety of different methods, most of which have their own place outside of industrial ecology. Some methods are widely used in a large number of different fields. Policy analysis can be done in nearly any field, where the study may have policy relevance. The planetary boundaries framework (Rockström et al. 2009) is widely applied in the sustainability field, and combining these well-known (global) indicators with material accounting practices on an urban level is worth exploring. Initial work has been done by (Daniel Hoornweg et al. 2016). Vanham and colleagues (2019) discuss the potential for footprinting methods to be linked to planetary boundaries.

Ecological Network analysis (ENA) is independently listed as one of the methodological categories in the review by Beloin-Saint-Pierre et al. (2016). This method is most often applied to natural ecosystems, but in some cases also to cities. ENA seeks to define complex system structures and relationships of components, which on their own can still be complex. However, it opens up the “black box” and is an attractive approach to find out about the network and relationships of sectors and actors

The report by Musango and colleagues (2016) “stresses the importance of using simulation methods, particularly system dynamics”. System dynamics modeling looks at complex systems and unpacks the interlinked causal relationships within it. It can allow for a better understanding of “how exogenous variables affect the system”, but the authors warn that subjective perceptions of the modeller or stakeholders affect the outcome of this model. The other simulation model that the authors recommend to be used within urban metabolism research is agent-based modeling, which aims to identify and understand how individual actors within a system are motivated and what the impacts of their behaviour is.

Table 8 provides an overview of the strength and weaknesses of the methods in the integrated category.

Table 8: Strengths and weaknesses of integrated methods

Method	Case studies	Strengths	Weaknesses
Hybrid MFA-LCA	7	▪ Greatly enhances impact understanding of MFA results	▪ High-level material flow data obtained from an MFA are not compatible with product-specific required input into an LCA
Economic Input-Output Life-Cycle Assessment (EIO-LCA)	1	▪ Very fast to get a supply-chain impact understanding	▪ Sector-based averages affect accuracy
Emergy-LCA	2	▪ Allows for impact understanding of an emergy analysis	▪ Only works if a single product or product group is being evaluated
MFA-Emergy	1	▪ Makes it possible to understand the ecological (energy-based) impacts	▪ Additional insights may be too limited to justify additional time and complexity

3.7. Summary

In this section, the strengths and weaknesses of the various **method categories** are summarised in Table 9.

Table 9: Brief summary of strengths and weaknesses of method categories. Note: each time a method is used, another point is added to the number of case studies.

Method category	Case studies	Strengths	Weaknesses
Flow analysis methods	143	▪ Suitable for obtaining a higher level overview on material and energy flows on different scales and hence a proper tool to inform policy formulation at macro-level. ▪ Adaptable and can be combined with other methods. (Robinson et al. 2013) ▪ Although most methodologies do not explicitly address the setting of resource efficiency targets, they implicitly provide a basis for this by allowing for the analysis of metabolic flows.	▪ Usually dependant on modelling exercises at the output side, while the input side is reported data. ▪ It is difficult to compare cities using these methods due to a lack of standardised data. (Robinson et al. 2013) ▪ Dynamics of internal flows and stocks are generally not accounted for in most methodologies. ▪ Do not allow for infrastructure interventions to be evaluated in terms of their impact on city resource efficiency.
Energy assessment methods	22	▪ Their capacity to simplify the aggregation of different types of flows (e.g. mass, energy, area, volume, money) by defining specific energy equivalents with the use of pre-calculated conversion factors for all components/processes	▪ This single type of information is difficult to tie with environmental impacts

Input/output methods	30	• Inherent completeness of analysis (Robinson et al. 2013) ▪ Includes all direct and indirect flows and is therefore embodied accounting ▪ Can prove a valuable tool to inform policy decisions at a city level ▪ Urban and infrastructure managers can make use of critical information on upstream infrastructure interdependencies	▪ Completeness may come with coarse definition of the full system. This prevents the targeted audience of a study from choosing precise solutions to improve the sustainability of components that are found in a UM. ▪ I/O methods usually use economic flows to describe the link between components of a system. This monetary modeling does not offer information for the evaluation of environmental impacts. (Robinson et al. 2013) ▪ Static and linear nature of the input-output relationship ▪ No standardised accounting method exists ▪ Differ significantly with regard to the number of sectors reported and product group disaggregation, as well as in terms of the inclusion or exclusion of specific materials
Footprint methods	30	(Browne, O'Regan, and Moles 2012) ▪ It is conceptually simple and allows for comprehensive and comparative analyses ▪ It provides an effective heuristic and pedagogic tool that captures human resource use in an easily comprehensible form ▪ It promotes discussion on issues directly relevant to sustainable development, including the finite dimensions of human activity and the consequences of increasing consumption patterns ▪ It allows for estimation of sustainability gap/ecological deficit or, conversely, ecological surplus ▪ It may be used to monitor progress towards closing the sustainability gap by use in a time-series ▪ It measures both actual land appropriation and carbon emissions and indicates biophysical impact ▪ National data are widely available for agricultural and industrial production and trade ▪ It can be used to indicate global environmental impact of consumption and inequitable environmental burden from trade ▪ It facilitates scenario analysis using footprint as criteria	(Browne, O'Regan, and Moles 2012) ▪ It is based on a simple model, whereas both nature and the economy are complex, dynamic systems ▪ It is only capable of predictive forecasting if used in a time-series ▪ It is not inclusive of all factors of sustainability ▪ Reveals little about the socio-political or economic dimensions of sustainability ▪ It may significantly underestimate actual ecosystem appropriation or depletion of natural capital ▪ Physical consumption-land conversion factors do not reflect relative scarcity changes over time or variation over space ▪ It cannot propose policy solutions unless a component-based approach is used ▪ It does not allow for trade-offs between efficiency, equity and sustainability ▪ It does not distinguish between sustainable and unsustainable use of land ▪ It implies that land use is associated with single functions only, whereas in reality land use provides multiple services or functions ▪ It assumes that afforestation is the preferred option for sequestration although sufficient land may not be available ▪ It may be overly dominated by energy use ▪ Many national boundaries are arbitrary and of a geo-political and cultural nature ▪ It implies that an 'ecological deficit' can only be reduced by expansion of bio-productive land or reduction in population ▪ It does not factor in comparative advantages of countries and regions such as ecological resources or low population density

Life cycle assessment methods	9	(Beloin-Saint-Pierre et al. 2016) ▪ The methods of the life cycle category use a global analysis perspective that fits perfectly with the requirements of an environmental sustainability assessment ▪ It helps in avoiding unintended trade-offs by making multi-criteria assessment within a life-cycle perspective ▪ This means that results of this type of assessment offer simple and relevant information to choose sustainable development paths for UMs (Robinson et al. 2013) LCA is an invaluable tool when comparing the environmental impacts of various products and processes	(Beloin-Saint-Pierre et al. 2016) ▪ Such a comprehensive assessment of anthropic systems requires important amount of work and data ▪ This specific approach requires the consideration of market evolution to offer more representativeness when the environmental impacts of macro system are assessed. For example, a city that decides to favor wood for its new buildings, might affect the regional wood industry dramatically and the environmental performance of their product might change. (Robinson et al. 2013) ▪ Performing LCAs can be resource and time intensive. ▪ Significant material input data at each stage of production is required to calculate indirect flows for semi-manufactured and finished products. ▪ Defining the system boundary is also a challenging task
Integrated methods	11	▪ By integrating different methods, new insights or applications can be achieved that would not be feasible when these methods are applied separately.	▪ Additional time and/or data requirements. ▪ Knowledge of both methods will be required.

4. Methods used over time

In the last two decades the number of urban metabolism and material accounting studies has increased and a greater variety of approaches has been developed and tested. Musango et al. (2017) reviewed 165 case studies and classified the methods that were used in each study. As can be seen in Figure 5, there has been a great increase in the number of case studies in the past decade.

It is important to note that this graph does not provide a complete picture of the trends over the last few years. This report used the 165 case studies reviewed by Musango, Currie, and Robinson (2017) as a baseline, and expanded from there. The aim was not to provide an exhaustive case study list for the missing years, but instead to do a very thorough analysis of the methodological classifications used in the identified case studies. New case studies were added when they surfaced throughout the literature review process, but the portrayed dip in the number of case studies in the graph is an indication of the strong baseline leading up to 2017 rather than an indication that the total number of case studies has decreased. Over time, new case studies will continue to be added to the publications database at Metabolism of Cities and a fairer representation will then be available online.

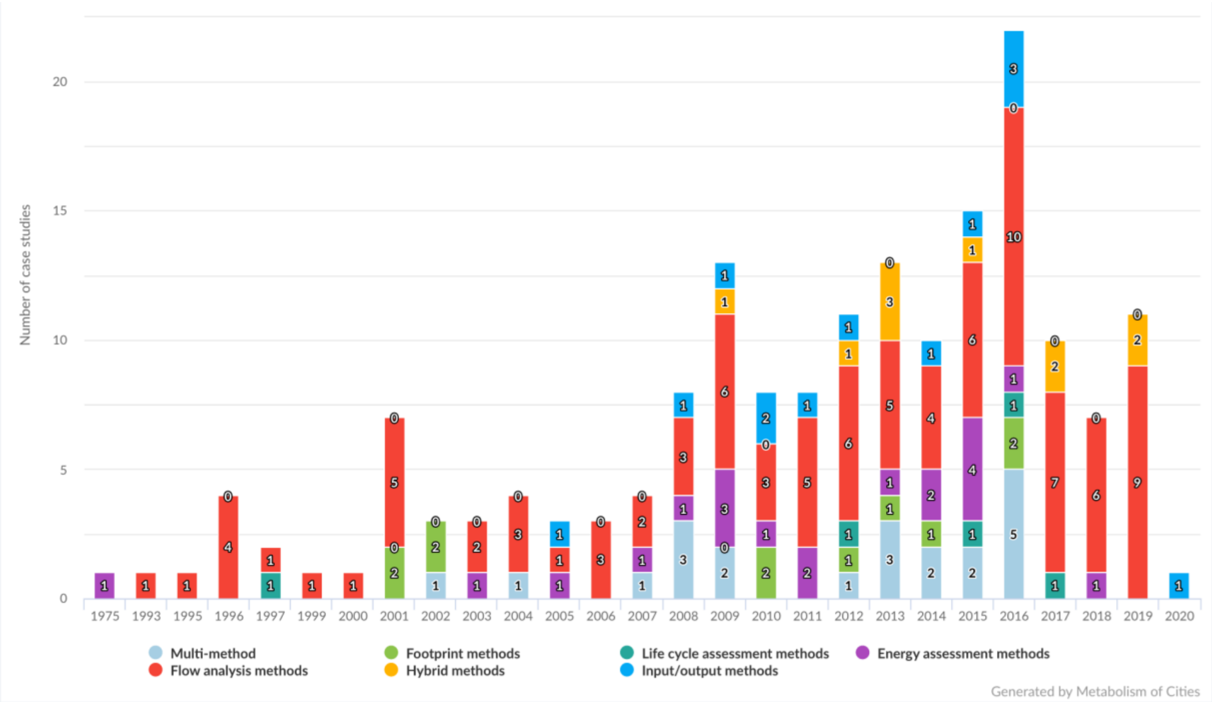

Figure 5: Number of urban material accounting studies and their methods over time

For many years, most resource flow studies used either a single material accounting method, or applied a material footprint analysis. Hybrid methods have been around since the beginning of the century, but in the last few years their use has grown significantly. As discussed in the previous section, each methodological family provides certain advantages and has particular gaps, and combining different types of methods is one way of addressing these gaps.

Figure 6: Map of Musango et al.'s (2017) case studies

It is furthermore important to note that the geographical spread of case studies displays a strong bias towards cities in OECD countries and China. Only a small portion of the studies are done on cities outside these 37 countries. For lack of a map with the studies of this review, Figure 6 from Musango et al. (2017) can be referred to, illustrating this situation..

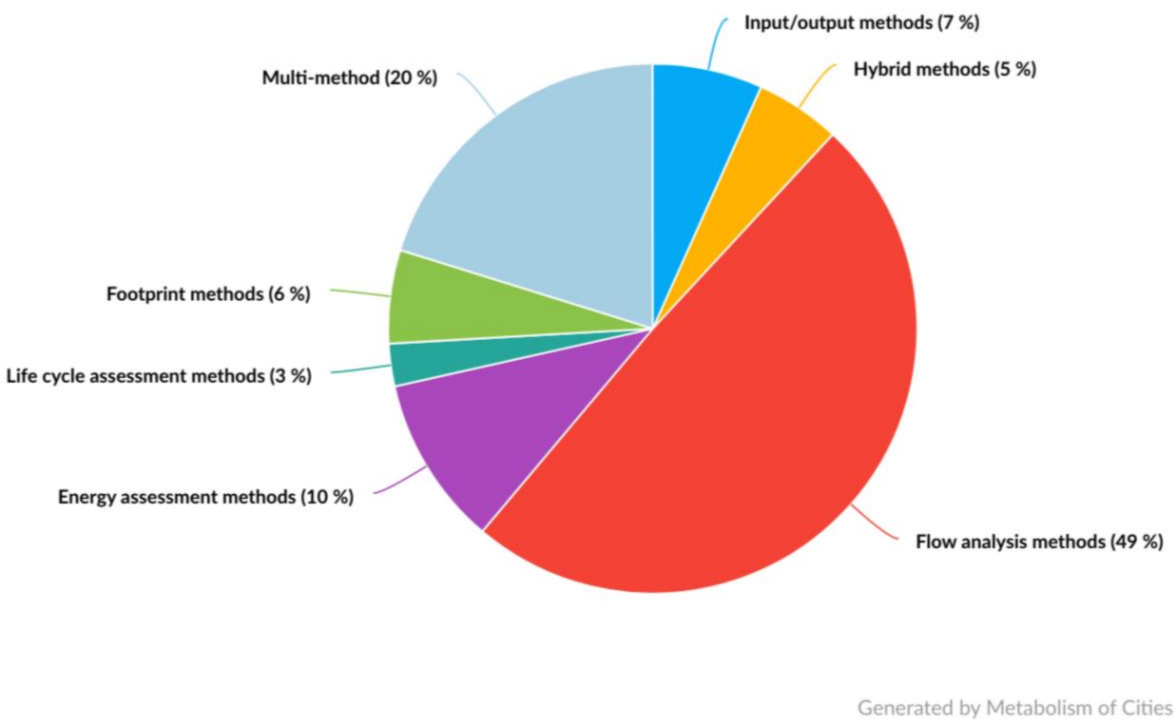

Figure 7: The share of methods utilised in the 194 case studies, broken down by method category

Considering again the 194 case studies that were reviewed in this report, Figure 7 depicts the share of the five main method categories with multi-method and hybrid method studies accounted for separately. It can be seen that the flow analysis methods clearly are a dominating method, even on their own, accounting for almost half. 20% of the publications applied at least two methods, which is a trend that can also be observed in Figure 5. LCA has only been used in 3% of the studies, supporting what has previously been stated about their poor suitability, on their own, for the urban scale.

The work by Musango and colleagues focuses primarily on resource *flows*. A similarly fascinating in-depth review of existing case studies in the field of material *stock* research has been done by (Lanau et al. 2019). This work looks at material stock studies at all spatial levels: from global to building level. Urban studies do feature strongly in this field, with about 25% of the work done within urban boundaries, as can be seen in Figure 8. Other interesting findings from this literature review include the dominance of static work (single point in time) compared to dynamic studies (time series) when a bottom-up approach was used, and the prominence of concrete, copper, aluminium, steel, and timber within the studies. Geographically, the same bias that was observed before can be seen in the literature on material stock studies.

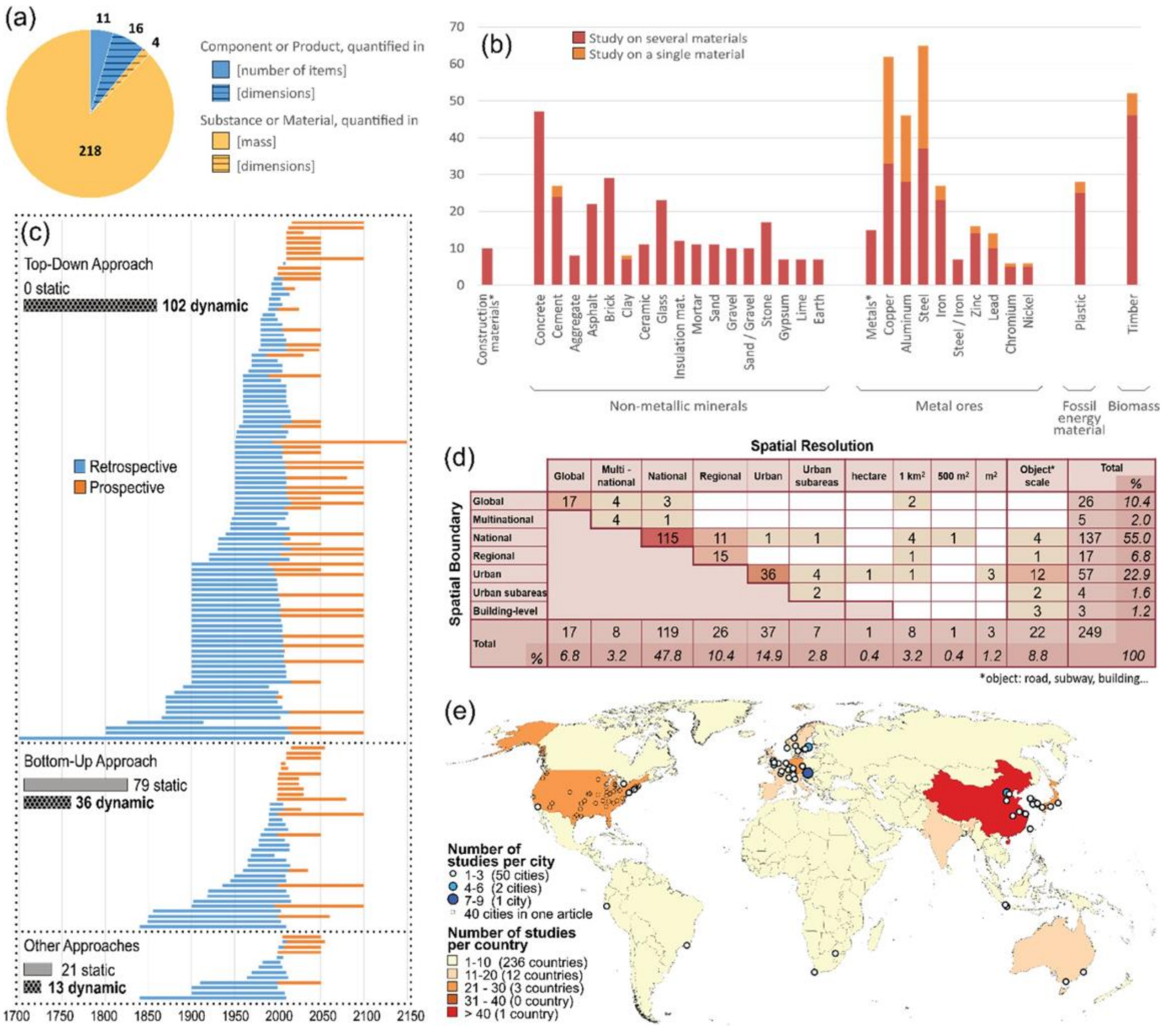

Figure 8: Overview of results of literature review of material stock by Lanau et al. (2019)

5. Projects

Over the past 15-20 years, a number of international collaborations have enabled the roll-out of urban interventions in multiple cities with the aim to experiment, compare, scale, or otherwise study the impact of certain technologies, methods, policy interventions and other approaches across national boundaries. Within Europe, there have been a large number of funding programmes - most of them involving the EU - including Horizon 2020, FP7, and JPI Urban Europe, which have funded such projects.

In total, 39 projects that specifically look at urban sustainability and relate to resource flows have been identified. Most of the projects have a duration between 3-4 years, and take place in 4-6 cities. Budgets vary significantly, from €845,000 to more than €10 million. In total, the selected projects have a combined budget exceeding €150 million. About half of these projects have already been completed (the earliest project in the database started in 2002), with 21 projects currently ongoing.

There is a large variety in the nature of these projects. Some focus on experimenting with new building technologies by constructing a number of new buildings in different cities (BAMB), whereas other projects look at the interrelation between energy and material flows and urban structure (BRIDGE).

The projects' relevance to CityLoops was analysed, rating them as high, medium, low or unknown. The deciding criteria for this ranking was based on whether or not they made use of material accounting methods that could be relevant to CityLoops, their material scope and their spatial relevance. If a project addresses sustainability issues in the organic/food and/or construction sector and an accounting method was used for a city, then it has high relevance for CityLoops and collaboration with the project would be worthwhile and should be sought. If the methods used were unknown, the relevance was marked as unknown too.

Table 10 below provides an overview of the 39 projects, sorted by relevance to CityLoops, revealing that there are 8 high, 13 medium, 12 low and 6 unknown relevance projects. The case study location is only provided if it is urban, not if it is national. A table with even more details of all 39 projects can be found in Annex 3. (The researchers are aware that other projects exist that are potentially relevant to CityLoops, but the scope was limited to these 39 projects due to time constraints. A number of others are listed by the "Circular City" project in Appendix 1 of Deliverable 2.)

The projects with high relevance and unknown relevance are looked at more closely in this section. From the first group it can be seen that these are very recent projects, where two finished in 2019 and six are still ongoing. Most deal with the topics of waste; the food, energy, waste (FEW) nexus or circular economy or a combination of all. There does not seem to be one dominant method nor one dominating category that is used by all projects. Instead methods applied typically include a mix of several accounting methods or a combination of accounting and non-accounting methods, while the utilisation of a type of MFA and LCA are most common.

As for projects with unknown relevance, it seems that all of them are likely to be of high relevance as well, as they are all on the urban scale and also deal with CityLoops relevant materials. Unfortunately, no further information was found or made available at the time of the analysis, but their progress and communication will be observed.

Overall, the review of these initiatives made clear that there are a number of promising projects that can be considered either for collaboration and/or method sharing and knowledge transfer, which will be further pursued for shared benefits.

Table 10: Overview of projects with their full title, project phase, case study location, methods used, materials analysed and relevance to the CityLoops project. Methods in grey are non-accounting methods according to the definition of this analysis.

Project - full title Project phase *case study location*	Methods & materials	Relevance
CINDERELA - New Circular Economy Business Model for More Sustainable Urban Construction 2018 - 2022 *Amsterdam, Katowice, Madrid, Maribor, Trento*	AS-MFA LCA LCC S-LCA ---------------- secondary raw materials (SRM)	*High* Accounting method, circular economy approach on urban level and material group are relevant.
ENLARGE - Enabling large-scale adaptive integration of technology hubs to enhance community resilience through decentralized urban FWE nexus decision support 2018 - 2021 *Amsterdam, Marseille, Miami*	CF CBA Energy Accounting MFA WF ---------------- food, energy, water (FEW)	*High* Material accounting of relevant material groups on urban scale.
FEW-meter - An integrative model to measure and improve urban agriculture towards circular urban metabolism 2018 - 2021 *Dortmund, Gorzów Wielkopolski, London, Nantes, New York City, Poznań*	MFA ---------------- food	*High* Usage of MFA and trying to understand urban food flows based on urban case studies.

METABOLIC - Intelligent Urban Metabolic Systems for Green Cities of Tomorrow: an FWE Nexus-based Approach 2018 - 2021 *Chicago, São Paulo, Taipei, Tokyo*	CF EF LCA Scenario analysis WF ---------------- food, energy, water (FEW)	*High* Focused on local intervention and FEW nexus assessed with accounting methods.
REPAiR - REsource Management in Peri-urban AReas: Going Beyond Urban Metabolism 2016 - 2020 *Amsterdam, Ghent, Hamburg, Naples, Łódź*	AS-MFA LCA ---------------- construction and demolition waste (CDW) organic waste (OW) food waste municipal solid waste (MSW)	*High* Lots of overlap in method (urban metabolism and CE approach) and a strong focus on urban waste.
SIRIUS - Sustainable, Innovative, Resilient, and Interconnected Urban food System 2019 - 2022 *Amsterdam, Liverpool, Urumqi, Xiamen*	LCA MRIO Scenario analysis ---------------- food	*High* Very interesting in terms of collaboration, food scope, accounting methods and urban scale.
URBAN WASTE - Urban Strategies for Waste Management in Tourist Cities 2016 - 2019 *Copenhagen, Dubrovnik, Florence, Kavala, Lisbon, Nice, Nicosia, Ponta Delgada, Santander, Syracuse, Tenerife*	CBA LCA LCC MFA S-LCA ---------------- municipal solid waste (MSW)	*High* Very interesting application of methods on urban level with circular thinking, although focus is on tourism waste.
UrbanWINS - Urban metabolism accounts for building Waste management Innovative Networks and Strategies 2016 - 2019 *Albano Laziale, Bucharest, Cremona, Leiria, Manresa, Pomezia, Sabadell, Turin*	LCA UMan ---------------- construction and demolition waste (CDW)	*High* Material scope (CDW), urban scale and accounting method match with CityLoops' aim.

BAMB - Buildings as Material Banks: Integrating Materials Passports with Reversible Building Design to Optimise Circular Industrial Value Chains 2015 - 2019 *Brussels, Essen, Mostar, Ridderkerk*	*No accounting methods used* ---------------- construction and demolition waste (CDW) construction materials	*Medium* Lots of relevance to the building material flow world and circular thinking. However focus is on individual building level more than a city level and no relevant accounting method was used.
BRIDGE - sustainaBle uRban plannIng Decision support accountinG for urban mEtabolism 2009 - 2011 *Athens, Firenze, Gliwice, Helsinki, London*	CBA MCE ---------------- energy water carbon	*Medium* Accounting methods were not necessarily at the core of this project, but the involvement of local governments as decision makers and working on the translation between urban metabolism and decision is relevant.
CIRCuIT - Circular Construction In Regenerative Cities 2019 - 2023 *Copenhagen, Hamburg, London, Vantaa*	*Unknown* ---------------- construction and demolition waste (CDW)	*Medium* Material group, circular economy and strategies developed are important, but no information on methods used.
CRUNCH - Climate Resilient Urban Nexus CHoices: operationalising the Food-Water-Energy Nexus 2018 - 2021 *Eindhoven, Gdańsk, Glasgow, Miami, Southend-on-Sea, Taipei, Uppsala*	*No accounting methods used* ---------------- food, energy, water (FEW)	*Medium* Urban scale and FEW scope, yet no use of accounting method.
FUSE - Food-water-energy for Urban Sustainable Environments 2018 - 2021 *Amman, Pune*	*No accounting methods used* ---------------- food, energy, water (FEW)	*Medium* Urban and sub-national geographical scale and the FEW material group are relevant, yet there is no material accounting in the CityLoops sense and models instead.
HISER - Holistic Innovative Solutions for an Efficient Recycling and Recovery of Valuable Raw Materials from Complex Construction and Demolition Waste 2015 - 2019	LCA LCC MFA ---------------- construction and demolition waste (CDW)	*Medium* Deals with CDW, CE and relevant methods but focus is on entire building value chain and while some of it can be on urban level, it is not specifically around a city or region.

IN-SOURCE - INtegrated analysis and modelling for the management of sustainable urban FWE ReSOURCEs 2018 - 2021 *Ludwigsburg, New York City, Vienna*	Scenario analysis ---------------- food, energy, water (FEW)	*Medium* Deals with urban data and FEW, but no quantification of material flows.
LCA-IWM - The use of life cycle assessment tools for the development of integrated waste management strategies for cities and regions with rapid growing economies 2002 - 2005 *Barcelona, Kaunas, Nitra, Tarragona, Wrocław, Xanthi*	LCA ---------------- municipal solid waste (MSW)	*Medium* Project ran more than 10 years ago, but LCA based waste planning on urban level may still be interesting.
MinFuture - Global material flows and demand-supply forecasting for mineral strategies 2016 - 2018	MFA ---------------- minerals	*Medium* Strong focus on material flow analysis but rather on a theoretical level and only globally for minerals.
PAPERCHAIN - New market niches for the Pulp and Paper Industry waste based on circular economy approaches 2017 - 2021	LCSA ---------------- paper	*Medium* Uses CE and life cycle accounting, but material is paper and pulp and on a sub-national level.
REFRESH - Resource Efficient Food and dRink for the Entire Supply cHain 2015 - 2019	LCA LCC MFA ---------------- food waste	*Medium* Deals with food waste, systems thinking and a combination of accounting methods, albeit on national scale.
ReBirth - Promotion of the recycling of industrial waste and building rubble for the construction industry 2012 - 2014	LCA ---------------- construction and demolition waste (CDW)	*Medium* Material accounting of CDW for better recycling but mostly on national level.
UNCNET - Urban Nitrogen Cycles: New Economy Thinking to master the challenges of climate change 2019 - 2022 *Beijing, Shijiazhuang, Vienna, Zielona Gora*	MFA ---------------- nitrogen	*Medium* Specifically focused on nitrogen as part of OW in cities, but MFA is employed.

AgroCycle - Sustainable techno-economic solutions for the agricultural value chain 2016 - 2019	LCA LCC S-LCA ---------------- food waste	*Low* Not focused on urban level and case studies are extremely specific. However, there is a link with organic waste.
CITYFOOD - Smart integrated multitrophic city food production systems – a water and energy saving approach for global urbanisation 2018 - 2021 *Arendal, Berlin, Grimstad, São Paulo*	*Unknown* ---------------- food	*Low* Mostly focused on a particular technology around aquaponics.
CODALoop - Community data-loops for energy-efficient urban lifestyles 2016 - 2019 *Amsterdam, Delft, Graz, Yildiz*	*No accounting methods used* ---------------- energy	*Low* Focus on energy, while some of the highlights they mention are buildings and food, yet no relevant accounting method.
FUSIONS - Food Use for Social Innovation by Optimising waste prevention Strategies 2012 - 2016	*No accounting methods used* ---------------- food waste	*Low* Very useful insights on food waste, but not on urban level and no accounting method.
GtoG (from gypsum to gypsum) - From cradle to cradle: a CE approach for the European Gypsum Industry with the Demolition Recycling Industry. 2013 - 2015	CF Scenario analysis ---------------- construction and demolition waste (CDW) minerals	*Low* Relevant methods, life cycle thinking and closing loop goal, but gypsum as a very specific material within its sector in Europe.
ProSUM - Prospecting Secondary raw materials in the Urban mine and Mining waste 2015 - 2017	MFA ---------------- e-waste critical raw materials (CRM)	*Low* Although about MFA, project is national scale and e-waste oriented.
SUME - Sustainable Urban Metabolism for Europe 2008 - 2011 *Athens, Marseille, Munich, Newcastle, Porto, Stockholm, Vienna*	ABM MFA Scenario analysis ---------------- various materials greenhouse gases (GHGs) waste energy	*Low* Relevant methods and systems thinking, but lacks CE approach, CityLoops material scope and is fairly old.

SYSTEMIC - Systemic large scale eco-innovation to advance circular economy and mineral recovery from organic waste in Europe 2017 - 2021 *Beltrum, Kent, Ottersberg, Pavia, Pittem*	LCA ---------------- organic waste (OW)	*Low* Project deals with CE and OW, but specifically nutrients and in demonstration plants, not cities.
URBANREC - New approaches for the valorisation of URBAN bulky waste into high added value RECycled products 2016 - 2019	*Unknown* ---------------- textiles plastics wood	*Low* Although applied methods are unknown, with focus on sub-national and national level and bulky waste, it doesn't seem very relevant.
UrbanData2Decide - Integrated data visualisation and decision making solutions to forecast and manage complex urban challenges 2014 - 2016 *Copenhagen, Malmö, Oxford, Vienna*	*No accounting methods used* ----------------	*Low* Neither focus on stocks/flows accounting, nor on data on materials and mostly about decision making support tools.
Urbanising in Place - Building the Food-Water-Energy Nexus from Below 2018 - 2021 *Brussels, London, Riga, Rosario*	*No accounting methods used* ---------------- food, energy, water (FEW)	*Low* Focus on food in the urban FEW nexus, but no consideration of quantification of flows.
Waste4Think - Moving towards Life Cycle Thinking by integrating Advanced Waste Management Systems 2016 - 2019 *Athens, Lisbon, Seveso, Zamudio*	*No accounting methods used* ---------------- waste food waste	*Low* Despite a focus on waste data on urban level, no accounting methods were used.
Circular City - Implementing nature based solutions for creating a resourceful circular city 2018 - 2022	*Unknown* ----------------	*Unknown* Deals with CE, but neither materials nor methods used are known.
IFWEN - Understanding Innovative Initiatives for Governing Food, Water and Energy Nexus in Cities 2018 - 2021 *Antananarivo, Dodoma, Florianópolis, Gangtok, Johannesburg, Lilongwe, Nagpur, São José dos Campos*	*Unknown* ---------------- food, energy, water (FEW)	*Unknown* FEW scope and urban scale are relevant, but it is unknown which methods are used.

M-NEX - The Moveable NEXUS: Design-led urban food, water and energy management innovation in new boundary conditions of change 2018 - 2020 *Amsterdam, Belfast, Detroit, Doha, Sydney, Yokohama*	*Unknown* ---------------- food, energy, water (FEW)	*Unknown* Potentially of high relevance due to material scope and urban scale and mentioning of a "quantitative stock and flow modeling", but methods are unknown.
RECREATE - Resource nexus for transformation to circular, resilient, and liveable cities in the context of climate change. 2019 - 2022 *Beijing, Malmö, Shanghai, Vienna*	*Unknown* ---------------- energy water various materials	*Unknown* Very new project and not too focused on CityLoops flows, but they may include a relevant accounting method.
REFLOW - constRuctive mEtabolic processes For materiaL flOWs in urban and peri-urban environments across Europe 2019 - 2022 *Amsterdam, Berlin, Cluj-Napoca, Milan, Paris, Vejle*	*Unknown* ---------------- energy plastics construction materials food textiles	*Unknown* Relevant material scope and urban scale, but methods used are unknown.
WASTE FEW ULL - Waste Food-Energy-Water Urban Living Labs – Mapping and Reducing Waste in the Food-Energy-Water Nexus 2018 - 2021 *Bristol, Franschhoek, Rotterdam, São Paulo*	*Unknown* ---------------- food, energy, water (FEW)	*Unknown* Closing loop of waste in FEW nexus on urban level, yet methods employed unknown.

6. Recommendations

6.1. Lessons learned and general recommendations

Describing and comparing material accounting methods is no straightforward exercise. Again, a total of 91 subjects were reviewed, 35 excluded, 18 labelled as non-accounting methods, 9 tools identified and the remaining 29 methods described. Various elements contribute to the difficulty of this task. Both industrial ecology and urban metabolism are relatively young disciplines, and methods, tools, and conventions have all been changing constantly. This makes for a situation in which there is no clear structure to follow. Even the decision of how to group the methods was laborious given the many different approaches that currently exist.

Ultimately, the core of this comparative work is based on Musango, Currie, and Robinson's (2017) previous work and this report should be seen as a continuation and hopefully is an improvement. The methodological grouping has been replicated from the work of Beloin-Saint-Pierre et al. (2016). By basing this report on some of the most thorough, existing reviews that are currently available, the authors aim to contribute to the process of consolidation and standardisation.

However, despite the existence of numerous other reviews, one of the primary lessons from this analysis was the proliferation of poorly defined and inconsistently used labelling of existing "methods". It became evident that some methods were mentioned once in a publication, which was then picked up by others as if these are an actual method, although a case study applying it never existed. This self-perpetuating made it appear as if there is an established method, without authors properly questioning its existence. Attempting to "once and for all" clarify if it does was incredibly time consuming, but worth it in the opinion of the authors.

Despite this laborious process, the chosen classification and definitions are by no means universally acknowledged and they carry a degree of subjectivity. From the list of multi-method studies it can be easily observed that footprinting "methods" are very frequently used alongside other accounting methods and labelling them as indicators instead may be more appropriate. Similarly, the energy flow assessment methods that were assigned to individual case studies often contradict the terminology that was used in the actual paper. However, the need for consistent labelling required a redefinition of the conflicting terminology present in existing work.

This tendency towards inconsistency and the resulting overlapping terminology will not be resolved overnight. However, from this exercise it seems worthwhile for researchers and practitioners to consider an industry-wide, exhaustive deliberation and standardisation process to try and agree on a way to define existing methods and consolidate this field. Such a procedure would require a significant support structure and can likely not be undertaken by only a few individual researchers. Instead, it will require the collaboration of a large share of the active researchers and it likely involves a lengthy process of discussion and negotiation to agree on standard definitions. Nonetheless, if this could lead to well-supported methodological definitions, it will greatly enhance consistency and comparability, and it will strengthen the research field as a whole.

6.2. CityLoops recommendations

There are a number of lessons and insights from this review of existing projects and methods that could be useful for the CityLoops project. When looking at past and ongoing projects, it is clear that a lot of money and time has already been spent on the development of similar work in other cities. There are also some similar projects currently starting in other cities, and seeking collaboration may lead to time and cost savings, increased impacts, or greater exposure. It is recommended that the identified projects be considered for collaboration or for review to learn from their experiences.

In terms of accounting methods, it is clear that many existing methods may provide useful insights to the CityLoops project. The current trend towards using multiple or hybrid methods is no coincidence, and there are clearly benefits around more complete insights and better options for policy making when methods are combined (Daniels and Moore (2001), (Baynes and Wiedmann 2012), (Musango, Currie, and Robinson 2017)). It is therefore recommended that a combination of different methods is used in the CityLoops project.

In order to select the most appropriate methods, a number of criteria should be taken into account:

- Most of the flow and energy analysis methods can provide insights into the urban system as a whole, but are unable to provide insights into the environmental impacts of these flows. Combining one of these methods with an approach that can identify impacts will be beneficial.
- Depending on the interest and potential options for project collaboration, it may be useful to select a method that matches those that were used at other projects. This will make comparison and data exchange much easier.
- Over the past decade, many new methods have been put forward. Several of them have done this with the aim to become a new and better standard method. However, it has actually led to a proliferation of methods. Caution should be taken when developing a new method and it is likely best if there is greater overlap with existing methods. Figure 9 is relevant.
- Different methods share a large baseline when it comes to the required input data. By selecting different methods strategically, it may require little additional data gathering while enabling a very different assessment approach.
- The methods often require different *types* of data. Some use bottom-up information, others require top-down data. Depending on the local experience with data gathering and confidence of the local stakeholders, it may be possible to select a method first

and thus dictate the data requirements. However, it may be more prudent to let the data availability dictate the method selection instead.

- The CityLoops project explicitly mentions an interest in soil waste, which is considered a “hidden flow” in most material accounting frameworks. Few methods take into account these hidden flows, and selecting one that does is therefore instrumental.

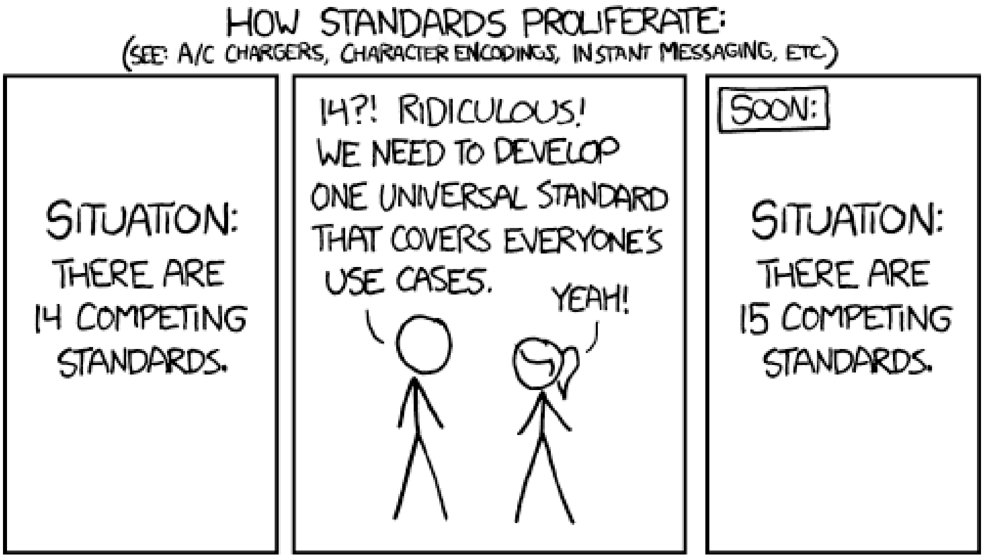

Figure 9: How standards proliferate (XKCD) CC BY-NC 2.5

Every accounting method will come with a level of uncertainty. This could be inherent to the chosen method, or it could be a result from the uncertainty in the underlying datasets. However, it is important to acknowledge and where possible qualify or quantify this level of uncertainty, especially when figures are compared to previous years or other cities where different levels of uncertainty may apply (Allesch&Brunner 2015).

In addition to using material accounting methods within CityLoops, it is recommended to make a connection with economic and social indicators or frameworks. Ultimately, the environmental impacts of resource extraction, consumption, and disposal is intricately linked with the socio-economic system and make a methodological connection will enable valuable additional insights.

The literature review and analysis of projects have shown the multitude of methods and approaches within them that exist, their strengths and weaknesses, and the limitations and opportunities when applied to an urban level. Going forward, it is recommended to closely look at the material scope for the circularity assessment as well as other assessments of CityLoops and the desired indicators, as it could be seen that accounting for a specific material can necessitate a certain method. Since the material scope has not been explicitly defined beyond organic waste, construction and demolition waste, and soil, no recommendation is made at this point as to which method should be employed. Furthermore, data availability and time constraints may also limit the use of certain methods, which should be considered in more detail before making a final choice. Ultimately, the aim of the selected method(s) is to enable decision makers of municipalities to make informed decisions based on most suitably quantified urban material flows and stocks.

This review intentionally does not go beyond describing and comparing different existing methods. Methodological selection and development is part of upcoming work packages, and justification for inclusion or exclusion of particular methods will be part of this future work instead.

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Annex 1 - Table of excluded methods

Method name	Origin and reason of exclusion
Carbon analysis	From Musango, Currie, and Robinson (2017). Single publication classified as such is actually emergy analysis.
Citymass (Civil Infrastructure Typology Material Stock Analysis)	From Bellstedt (2015). Developed in a Master thesis, but not used in a peer reviewed case study.
Coefficient approaches based on process analysis	From Lutter et al. (2016). Could be argued that it is its own method, but is seen as an approach to calculate footprint indicators.
Company-level MFA: Eco-balance, company materials accounting, eco-audits	From Daniels and Moore (2001). Not for urban scale.
Consumption-Based Footprint (CBF)	From Chavez and Ramaswami (2013). Could be argued that it is its own method, but is seen as an approach to limit the system boundary of several footprint methods.
Emergy	From Musango, Currie, and Robinson (2017). Renamed to "Emergy analysis" and "Emergy synthesis" is an alias (as is "Emergy" if it is used by others).
Emergy and other materials	From Musango, Currie, and Robinson (2017). Single publication classified as such, was tagged with emergy analysis, MFA and MSA.
Energy analysis	From Musango, Currie, and Robinson (2017). Renamed to "Energy accounting" and "Energy balance".
Energy Ecological Footprint (EEF)	From Yang and Fan (2019). Member of the ecological footprint family, but too specific on energy within EF.
Energy Flow Metabolism Ratio Analysis	From Browne, O'Regan, and Moles (2012) Applied once and not very relevant to CityLoops. It is also not very different from other energy approaches.
Environmental space (ES)	From Daniels and Moore (2001). Fairly old concept and rather superseded by EF. No awareness of any work on urban scale.
Hybrid approaches combining elements of EE-IOA and process analysis	From Lutter, Giljum, and Bruckner (2016). More of a group and was replaced with specific hybrid methods themselves.
Hybrid Ecological network analysis / MSA	From Musango, Currie, and Robinson (2017). Two publications classified as such only made use of ENA.
Hybrid EFA and bio-social	From Musango, Currie, and Robinson (2017). Single publication

indicators	classified as such only applied several indicators, including an EF indicator.
Hybrid LCA & carbon accounting	From Musango, Currie, and Robinson (2017). Single publication classified as such merely used life cycle emissions and LCA as keywords in their publication, but it was focused on energy use and GHG emissions.
Hybrid LCA and GIS	From Musango, Currie, and Robinson (2017). Since GIS is not considered an accounting method, it is referred to here as a combined application.
Hybrid material and economic IOA	From Musango, Currie, and Robinson (2017). Hybrid only refers to inclusion of both material and economic datasets, which is common in IOA and not an independent method.
Hybrid MFA & boundary Analysis	From Musango, Currie, and Robinson (2017). Single publication classified as such, but only a multitude of indicators, some of which are MFA-related, were used to calculate the planetary boundary score. Method assumes that those were at some point already obtained.
Hybrid MFA & Infrastructure Studies	From Musango, Currie, and Robinson (2017). Since Infrastructure Studies is not considered an accounting method, it is referred to here as a combined application.
Hybrid MFA & political analysis	From Musango, Currie, and Robinson (2017). Single publication classified as such did not apply an MFA, but discussed how PIE (non-accounting) can be used to understand water flows.
Hybrid MFA & Value flow analysis	From Musango, Currie, and Robinson (2017). Since value flow analysis is not considered an accounting method, it is referred to here as a combined application.
Hybrid MFA and policy analysis	From Musango, Currie, and Robinson (2017). Single publication classified as such didn't apply an MFA, but discussed how the concept of urban metabolism can inform the integration of land use and water management.
Hybrid MSA / IOA	From Musango, Currie, and Robinson (2017). Single publication classified as such only used MSA.
Hybrid: IOA and Environmental Network Analysis	From Musango, Currie, and Robinson (2017). Since Environmental Network Analysis is not considered an accounting method, it is referred to here as a combined application.
Integrated Sustainable Cities Assessment Method (ISCAM)	From Ravetz (2000). Integrated assessment framework, bundling several indicators and models, but no quantification of materials.
Local systems analysis (LSA)	From OECD (2008). Part of pyramid image that groups methods. It is only ever referenced in this graph and never applied.

Material and Energy Flow Analysis (MEFA)	From Haberl et al. (2004). Considered an umbrella term for material and/or energy flow analysis studies. Not an own, independently developed method.
Material Flow Cost Accounting (MFCA)	From ISO 14051:2011. A management tool for organisations, not the urban scale.
Material intensity per unit service (MIPS)	From Daniels and Moore (2001). Method has not been used on an urban scale.
Socially extended MFA	From Hobbes et al. (2007). Mentioned in one publication, but has not been applied in urban peer reviewed paper.
Sustainable Process Index (SPI)	From Daniels and Moore (2001). Member of the ecological footprint family and specific to a product or service unit.
Total material requirement and domestic output (TMRO)	From Daniels and Moore (2001). These are two indicators merged into one and on the national scale. No application on urban scale.
Trans-Boundary Infrastructure Supply Chain Footprint (TBIF)	From Chavez and Ramaswami (2011). Could be argued that it is its own method, but is seen as an approach to limit the system boundary of (carbon) footprint methods.
Urban metabolism and resource optimisation in the urban fabric: the BRIDGE methodology.	From Chrysoulakis (2007). Methodology of how BRIDGE project was carried out.
Water mass balance analysis	From Kenway, Gregory, and McMahon (2011). Could be argued that it is its own method, but is seen as a framework to do an MFA for water here.

Annex 2 - Case studies over time

	Year																										
Method category	**1975**	**1993**	**1995**	**1996**	**1997**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Input/output methods	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	2	1	1	0	1	1	3	0	0	0	1
Hybrid methods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	3	0	1	0	2	0	2	0
Flow analysis methods	0	1	1	4	1	1	1	5	0	2	3	1	3	2	3	6	3	5	6	5	4	6	10	7	6	9	0
Energy assessment methods	1	0	0	0	0	0	0	0	0	1	0	1	0	1	1	3	1	2	0	1	2	4	1	0	1	0	0
Life cycle assessment methods	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0
Footprint methods	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	2	0	1	1	1	0	2	0	0	0	0
Multi-method	0	0	0	0	0	0	0	0	1	0	1	0	0	1	3	2	0	0	1	3	2	2	5	0	0	0	0

Annex 3 - Detailed table of projects

Project Project phase	**Full project title** Aim	**Materials**	**Methods**	**Budget**	**Funding programme**
AgroCycle 2016 - 2019	**Sustainable techno-economic solutions for the agricultural value chain** To deliver and pilot sustainable waste utilisation/valorisation pathways for agri-food waste. Four case studies of very specific companies were carried, so not a city-oriented approach, but instead company/product oriented.	food waste	LCA LCC S-LCA	€ 7,650,049	Horizon 2020
BAMB 2015 - 2019 *Brussels, Essen, Mostar, Ridderkerk*	**Buildings as Material Banks: Integrating Materials Passports with Reversible Building Design to Optimise Circular Industrial Value Chains** Focus on building construction and process industries (from architects to raw material suppliers) and prevention of CDW, the reduction of virgin resource consumption and the development towards a CE through industrial symbiosis.	construction and demolition waste (CDW) construction materials	*No accounting methods used*	€ 9,918,629	Horizon 2020
BRIDGE 2009 - 2011 *Athens, Firenze, Gliwice, Helsinki, London*	**sustainaBle uRban plannIng Decision support accountinG for urban mEtabolism** Bridge the gap between bio-physical sciences and urban planners and to illustrate the advantages of accounting for environmental issues on a routine basis in design decisions.	energy water carbon	CBA MCE	€ 4,101,983	FP7
CINDERELA 2018 - 2022 *Amsterdam, Katowice, Madrid, Maribor, Trento*	**New Circular Economy Business Model for More Sustainable Urban Construction** To unlock the potential for a resource-efficient urban and peri-urban construction sector by developing new circular business model CinderCEBm using SRM based construction products produced from different waste streams within urban and peri-urban area.	secondary raw materials (SRM)	AS-MFA LCA LCC S-LCA	€ 7,635,365	Horizon 2020
CIRCuIT 2019 - 2023 *Copenhagen, Hamburg, London, Vantaa*	**Circular Construction In Regenerative Cities** Develop urban planning instruments to support cities in implementing circular construction solutions and initiate changes at system level; implement a Circularity Hub, a data platform to evaluate progress of circular economy and regenerative capacity; and set up a knowledge sharing structure, the CIRCuIT Academy, to promote upscaling of solutions	construction and demolition waste (CDW)	Unknown	€ 10,595,250	Horizon 2020
CITYFOOD 2018 - 2021 *Arendal, Berlin, Grimstad, São Paulo*	**Smart integrated multitrophic city food production systems – a water and energy saving approach for global urbanisation** Develop strategies to further the popularity and application of this space and resource friendly food production system in urban areas. The multidisciplinary project team will involve city planners, urban farmers, scientists, entrepreneurs, community leaders, and engaged citizens to reach its goals.	food	Unknown	€ 1,876,956	JPI Urban Europe

Project Project phase	**Full project title** Aim	**Materials**	**Methods**	**Budget**	**Funding programme**
CODALoop 2016 - 2019 *Amsterdam, Delft, Graz, Yildiz*	**Community data-loops for energy-efficient urban lifestyles** Combine information, cognitive and social sciences into a real-life experiment in urban neighborhoods to reduce energy consumption, prototype interactive web-based platform and develop a tailored set of policy and market recommendations.	energy	*No accounting methods used*	€ 962,947	JPI Urban Europe
CRUNCH 2018 - 2021 *Eindhoven, Gdańsk, Glasgow, Miami, Southend-on-Sea, Taipei, Uppsala*	**Climate Resilient Urban Nexus CHoices: operationalising the Food-Water-Energy Nexus** Create an interconnected knowledge platform with cross-sectorial indicators for a support tool and assessment framework (the Integrated Decision Support System - IDSS).	food, energy, water (FEW)	*No accounting methods used*	€ 1,503,400	JPI Urban Europe
Circular City 2018 - 2022	**Implementing nature based solutions for creating a resourceful circular city** Establish a network testing the hypothesis that: "A circular flow system that implements NBS for managing nutrients and resources within the urban biosphere will lead to a resilient, sustainable and healthy urban environment".		Unknown		COST Action Circular City
ENLARGE 2018 - 2021 *Amsterdam, Marseille, Miami*	**Enabling large-scale adaptive integration of technology hubs to enhance community resilience through decentralized urban FWE nexus decision support** Better understand, through modelling of urban development scenarios and the use of decision support tools, how community resilience in relation to natural and anthropogenic stresses can be strengthened by the optimal integration of FWE technology hubs at varying scales.	food, energy, water (FEW)	CF CBA Energy Accounting MFA WF	€ 1,509,008	JPI Urban Europe
FEW-meter 2018 - 2021 *Dortmund, Gorzów Wielkopolski, London, Nantes, New York City, Poznań*	**An integrative model to measure and improve urban agriculture towards circular urban metabolism** Develop a truly comprehensive system to measure existing Urban Agriculture practices (FEW-meter).	food	MFA	€ 1,516,738	JPI Urban Europe
FUSE 2018 - 2021 *Amman, Pune*	**Food-water-energy for Urban Sustainable Environments** Construct multi-agent urban-FWE system models to capture interactions among users, producers, distribution mechanisms, and resources under changes in climate, demographics, land use, and economics. Develop and evaluate policy interventions to identify sustainability options.	food, energy, water (FEW)	*No accounting methods used*	€ 1,850,645	JPI Urban Europe

Project Project phase	Full project title Aim	Materials	Methods	Budget	Funding programme
FUSIONS 2012 - 2016	**Food Use for Social Innovation by Optimising waste prevention Strategies** Establish a European Multi-Stakeholder Platform to generate a shared vision and strategy to prevent food loss and waste across the whole supply chain through social innovation.	food waste	*No accounting methods used*	€ 5,040,503	FP7
GtoG (from gypsum to gypsum) 2013 - 2015	**From cradle to cradle: a CE approach for the European Gypsum Industry with the Demolition Recycling Industry.** Transform the European gypsum demolition waste market to achieve higher recycling rates of gypsum waste, thereby helping to achieve a resource efficient economy.	construction and demolition waste (CDW) minerals	CF Scenario analysis		EU LIFE
HISER 2015 - 2019	**Holistic Innovative Solutions for an Efficient Recycling and Recovery of Valuable Raw Materials from Complex Construction and Demolition Waste** The main objective in HISER is to develop and demonstrate novel cost-effective holistic solutions (technological and non-technological) for a higher recovery of raw materials from ever more complex construction and demolition waste (CDW) by considering circular economy approaches throughout the building value chain (from End-of-Life Buildings to new Buildings).	construction and demolition waste (CDW)	LCA LCC MFA	€ 7,665,262	Horizon 2020
IFWEN 2018 - 2021 *Antananarivo, Dodoma, Florianópolis, Gangtok, Johannesburg, Lilongwe, Nagpur, São José dos Campos*	**Understanding Innovative Initiatives for Governing Food, Water and Energy Nexus in Cities** Develop a framework and tools to assess changes in FWEN, their related trade-offs and the building of innovative capabilities in cities for developing innovative solutions to FWEN and manage GBI at the urban level.	food, energy, water (FEW)	Unknown	€ 1,309,831	JPI Urban Europe
IN-SOURCE 2018 - 2021 *Ludwigsburg, New York City, Vienna*	**INtegrated analysis and modelling for the management of sustainable urban FWE ReSOURCEs** Develop a shared urban data and modeling framework to help decision makers (such as governments, utilities, developers, investors) identify, quantify and visualize FWE systems and their interrelations for urban strategic planning and FWE infrastructure investments.	food, energy, water (FEW)	Scenario analysis	€ 1,518,657	JPI Urban Europe
LCA-IWM 2002 - 2005 *Barcelona, Kaunas, Nitra, Tarragona, Wrocław, Xanthi*	**The use of life cycle assessment tools for the development of integrated waste management strategies for cities and regions with rapid growing economies** Develop practical tools (e.g. waste generation prognostic model and decision supporting tools) to support (i) planning of new and (ii) optimisation of the existing waste management systems in the European cities.	municipal solid waste (MSW)	LCA	€ 1,602,219	FP5-EESD

Project Project phase	**Full project title** Aim	**Materials**	**Methods**	**Budget**	**Funding programme**
M-NEX 2018 - 2020 *Amsterdam, Belfast, Detroit, Doha, Sydney, Yokohama*	**The Moveable NEXUS: Design-led urban food, water and energy management innovation in new boundary conditions of change** Co-design new food futures with stakeholders that leave them less vulnerable to forces disturbing the nexus. Lessons learned from these stakeholder workshops will be shared outside the team, so that lessons learned locally can be applied globally.	food, energy, water (FEW)	Unknown	€ 1,670,883	JPI Urban Europe
METABOLIC 2018 - 2021 *Chicago, São Paulo, Taipei, Tokyo*	**Intelligent Urban Metabolic Systems for Green Cities of Tomorrow: an FWE Nexus-based Approach** Promote Green Urban Centers of Tomorrow by constructing effective transport and exchange mechanisms for FEW nutrients from sources to urban centers and then quantifying and optimizing the FEW factors related to societal health.	food, energy, water (FEW)	CF EF LCA Scenario analysis WF	€ 1,516,738	JPI Urban Europe
MinFuture 2016 - 2018	**Global material flows and demand-supply forecasting for mineral strategies** Identify, integrate, and develop expertise for global material flow analysis and scenario modelling.	minerals	MFA	€ 1,162,835	Horizon 2020
PAPERCHAIN 2017 - 2021	**New market niches for the Pulp and Paper Industry waste based on circular economy approaches** Deploy five novel CE models centred in the valorisation of the waste streams generated by the pulp and paper industry for resource intensive sectors: construction sector, mining sector and chemical industry.	paper	LCSA	€ 9,217,196	Horizon 2020
ProSUM 2015 - 2017	**Prospecting Secondary raw materials in the Urban mine and Mining waste** Deliver the first Urban Mine Knowledge Data Platform, provide harmonised data and establish a European network of expertise on secondary sources of critical raw materials (CRMs).	e-waste critical raw materials (CRM)	MFA	€ 3,704,327	Horizon 2020
RECREATE 2019 - 2022 *Beijing, Malmö, Shanghai, Vienna*	**Resource nexus for transformation to circular, resilient, and liveable cities in the context of climate change.** Developing, establish and implement quantitative methods for urban metabolism, and proposing urban resource cycles, to provide foundations for building urban resilience to social, economic, and environmental stress.	energy water various materials	Unknown	€ 983,400	JPI Urban Europe
REFLOW 2019 - 2022 *Amsterdam, Berlin, Cluj-Napoca, Milan, Paris, Vejle*	**constRuctive mEtabolic processes For materiaL flOWs in urban and peri-urban environments across Europe** Provide realistic best practices aligning market and government needs in order to create favourable conditions for the public and private sector to adopt circular principles.	energy plastics construction materials, food, textiles	Unknown	€ 10,288,060	Horizon 2020

Project Project phase	Full project title Aim	Materials	Methods	Budget	Funding programme
REFRESH 2015 - 2019	**Resource Efficient Food and dRink for the Entire Supply cHain** Contribute significantly towards the objective of reducing food waste across the EU by 30% by 2025 and maximizing the value from unavoidable food waste and packaging materials.	food waste	LCA LCC MFA	€ 9,444,757	Horizon 2020
REPAiR 2016 - 2020 *Amsterdam, Ghent, Hamburg, Naples, Łódź*	**REsource Management in Peri-urban AReas: Going Beyond Urban Metabolism** Provide local and regional authorities with an innovative transdisciplinary open source geodesign decision support environment (GDSE) developed and implemented in living labs in six metropolitan areas.	construction and demolition waste (CDW), organic waste (OW), food waste, municipal solid waste (MSW)	AS-MFA LCA	€ 5,089,636	Horizon 2020
ReBirth 2012 - 2014	**Promotion of the recycling of industrial waste and building rubble for the construction industry** Increased and better recycling of industrial waste and CDW in the construction sector, turn-around in illegal dump practices and increased awareness of recycling possibilities at national, regional and local level.	construction and demolition waste (CDW)	LCA	€ 845,543	EU LIFE
SIRIUS 2019 - 2022 *Amsterdam, Liverpool, Urumqi, Xiamen*	**Sustainable, Innovative, Resilient, and Interconnected Urban food System** Shed light on trends of urban food production and consumption in Chinese and European cities, identify natural and societal factors that will influence the vulnerability and resilience of urban food supply chains, and reveal how new business models, social entrepreneurship, and other innovations in the urban food sector are evolving locally.	food	LCA MRIO Scenario analysis	€ 862,751	JPI Urban Europe
SUME 2008 - 2011 *Athens, Marseille, Munich, Newcastle, Porto, Stockholm, Vienna*	**Sustainable Urban Metabolism for Europe** Analyse impacts of existing urban forms on resource use and estimate future potential to transform urban building and spatial structures in order to significantly reduce resource and energy consumption, taking into account differences in urban development dynamics.	various materials greenhouse gases (GHGs) waste energy	ABM MFA Scenario analysis	€ 3,630,576	FP7
SYSTEMIC 2017 - 2021 *Beltrum, Kent, Ottersberg, Pavia, Pittem*	**Systemic large scale eco-innovation to advance circular economy and mineral recovery from organic waste in Europe** Reach a break-through to re-enter recovered nutrients from organic waste into the production cycle. Consequently, this will offer solutions for pressing environmental issues and to reduce the import of P as finite irreplaceable resource in mines.	organic waste (OW)	LCA	€ 9,723,586	Horizon 2020

Project Project phase	**Full project title** Aim	**Materials**	**Methods**	**Budget**	**Funding programme**
UNCNET 2019 - 2022 *Beijing, Shijiazhuang, Vienna, Zielona Gora*	**Urban Nitrogen Cycles: New Economy Thinking to master the challenges of climate change** Systematically develop “urban nitrogen budgets” to understand the reasons, pathways and possible intervention points of the release of such compounds.	nitrogen	MFA	€ 803,570	JPI Urban Europe
URBAN WASTE 2016 - 2019 *Copenhagen, Dubrovnik, Florence, Kavala, Lisbon, Nice, Nicosia, Ponta Delgada, Santander, Syracuse, Tenerife*	**Urban Strategies for Waste Management in Tourist Cities** Perform an analysis leading to a state of art of urban metabolism in 11 pilot urban areas to support the switch to a circular model where waste is considered as resource and reintegrated in the urban flow of tourist cities.	municipal solid waste (MSW)	CBA LCA LCC MFA S-LCA	€ 4,248,782	Horizon 2020
URBANREC 2016 - 2019	**New approaches for the valorisation of URBAN bulky waste into high added value RECycled products** Develop and implement an eco-innovative and integral bulky waste management system (enhancing prevention, improving logistics and allowing new waste treatments to obtain high added value recycled products) and demonstrate its effectiveness in different regions.	textiles plastics wood	Unknown	€ 9,978,981	Horizon 2020
UrbanData2Decide 2014 - 2016 *Copenhagen, Malmö, Oxford, Vienna*	**Integrated data visualisation and decision making solutions to forecast and manage complex urban challenges** Develop new methods to combine existing big data pools (public social media and open data libraries) and expert knowledge into one optimal framework to support holistic decision making for urban management.		*No accounting methods used*	€ 1,138,202	JPI Urban Europe
UrbanWINS 2016 - 2019 *Albano Laziale, Bucharest, Cremona, Leiria, Manresa, Pomezia, Sabadell, Turin*	**Urban metabolism accounts for building Waste management Innovative Networks and Strategies** Develop and test methods for designing and implementing innovative and sustainable Strategic Plans for Waste Prevention and Management in various urban contexts that will enhance urban environmental resilience.	construction and demolition waste (CDW)	LCA UMan	€ 4,966,516	Horizon 2020
Urbanising in Place 2018 - 2021 *Brussels, London, Riga, Rosario*	**Building the Food-Water-Energy Nexus from Below** Define components of an “agroecological urbanism”: a model of urbanisation which places food, metabolic cycles and an ethics of land stewardship, equality and solidarity at its core.	food, energy, water (FEW)	*No accounting methods used*	€ 1,124,416	JPI Urban Europe

Project Project phase	**Full project title** Aim	**Materials**	**Methods**	**Budget**	**Funding programme**
WASTE FEW ULL 2018 - 2021 *Bristol, Franschhoek, Rotterdam, São Paulo*	**Waste Food-Energy-Water Urban Living Labs – Mapping and Reducing Waste in the Food-Energy-Water Nexus** Establish four Urban Living Labs to map resource flows, identify critical dysfunctional linear pathways, agree on response, model market and non-market economic value of each intervention and engage with decision makers to close each loop.	food, energy, water (FEW)	Unknown	€ 1,153,558	JPI Urban Europe
Waste4Think 2016 - 2019 *Athens, Lisbon, Seveso, Zamudio*	**Moving towards Life Cycle Thinking by integrating Advanced Waste Management Systems** Move forward the current waste management practices into a CE motto, demonstrating the value of integrating and validating a set of 20 eco-innovative solutions that cover all the waste value chain.	waste food waste	*No accounting methods used*	€ 10,521,412	Horizon 2020

Annex 4 – Overview of all reviewed case study publications

Title	Method	Location	Year
Flow analysis methods			
Material Flow Analysis (MFA)			
Incorporating Metabolic Thinking into Regional Planning: The Case of the Sierra Calderona Strategic Plan	EF Energy Accounting MFA	Valencia	2019
Pathways towards regional circular economy evaluated using material flow analysis and system dynamics	MFA SDM	Guangdong (province)	2019
Using spatially explicit commodity flow and truck activity data to map urban material flows	MFA	Singapore: City United States of America	2019
Understanding the mechanism of urban material metabolism with ecological network analysis: An experimental study of Wuxi, China	ENA MFA	Wuxi	2018
Urban Metabolism of Bangalore City: A Water Mass Balance Analysis	MFA Scenario analysis Water mass balance analysis	Bangalore	2018
Comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan	CF Emergy Analysis MFA	Kawasaki	2017
African Urbanization: Assimilating Urban Metabolism into Sustainability Discourse and Practice	MFA		2016
Evaluating urban sustainability potential based on material flow analysis of inputs and outputs: A case study in Jinchang City, China	MFA	Jinchang City	2016
Flows, system boundaries and the politics of urban metabolism: Waste management in Mexico City and Santiago de Chile	MFA	Mexico City Santiago de Chile	2016
Surveying the Environmental Footprint of Urban Food Consumption	CF EF MFA		2016
Towards a Dynamic Approach to Urban Metabolism: Tracing the Temporal Evolution of Brussels' Urban Metabolism from 1970 to 2010	Energy Balance MFA	Brussels	2016

Title	Method	Location	Year
An application of system dynamics for evaluating planning alternatives to guide a green industrial transformation in a resource-based city	MFA Scenario analysis SDM	Linfen	2015
Metabolism of Brussels-Capital Region: identification of flows, economic actors and activities on the territory and tracks of reflection for resource optimisation	EW-MFA MFA	Brussels	2015
Urban metabolism: Measuring the city's contribution to sustainable development	Energy Accounting MFA	Curitiba	2015
Urban material flow analysis: An approach for Bogotá, Colombia	Energy Balance MFA	Bogotá	2014
Consumption based footprint of a city	CF EE-IOA LCA MFA hybrid	Paris	2013
Nitrogen Flow Analysis in Bangkok City, Thailand: Area Zoning and Questionnaire Investigation Approach	MFA	Bangkok	2013
Sustainable design of sanitation system based on material and value flow analysis for urban slum in Indonesia	MFA Scenario analysis SFA	Bandung	2013
Comparison of energy flow accounting, energy flow metabolism ratio analysis and ecological footprinting as tools for measuring urban sustainability: A case-study of an Irish city-region	EF Energy Balance MFA	Limerick	2012
Efficiency Through Proximity: Changes in Phosphorus Cycling at the Urban–Agricultural Interface of a Rapidly Urbanizing Desert Region	MFA	Maricopa County Phoenix	2012
Material Flows and Energy Analysis of Glass Containers Discarded in New Jersey, USA	Energy Accounting MFA Scenario analysis	New Jersey	2012
Pathways and Management of Phosphorus in Urban Areas	MFA	Gothenburg	2012
The Development and Practice in City Level of Material Flow Analysis (MFA) in China	MFA	Tianjin	2011
Urban Water Mass Balance Analysis	MFA Method	Melbourne, Perth, South East Queensland,	2011

Title	Method	Location	Year
	Water mass balance analysis	Sydney	
Input, stocks and output flows of urban residential building system in Beijing city, China from 1949 to 2008	MFA	Beijing	2010
Collaborative Problem Solving Using an Industrial Ecology Approach	F&T LCA MFA SFA	New Jersey New York City	2009
The food-print of Paris: long-term reconstruction of the nitrogen flows imported into the city from its rural hinterland	MFA	Paris	2009
A method for regional-scale material flow and decoupling analysis: A demonstration case study of Aichi prefecture, Japan	IOA MFA Method	Aichi	2008
The energy and mass balance of Los Angeles County	Energy Balance MFA	Los Angeles	2008
The flow of phosphorus in food production and consumption — Linköping, Sweden, 1870–2000	MFA	Linköping	2008
Nitrogen balance for the urban food metabolism of Toronto, Canada	MFA	Toronto	2007
The Changing Metabolism of Cities	Energy Balance MFA	Brussels, Cape Town, Hamburg, Hong Kong: City, Sydney, Tokyo Toronto, Vienna	2007
The ecological sustainability of regional metabolisms: Material flow analyses of the regions of Hamburg, Vienna and Leipzig	MFA	Hamburg, Leipzig, Vienna	2006
Long-term Coordination of Timber Production and Consumption Using a Dynamic Material and Energy Flow Analysis	Energy Accounting MFA	Swiss lowland region	2004
Managing the Flow of Construction Minerals in the North West Region of England	MFA	United Kingdom of Great Britain and Northern Ireland	2004
Transition towards improved regional wood flows by integrating material flux analysis and agent analysis: the case of Appenzell Ausserrhoden, Switzerland	MFA	Appenzell Ausserrhoden	2004
Estimating the urban metabolism of Canadian cities: Greater Toronto Area case study	Energy Accounting MFA	Toronto	2003
A material flow analysis and ecological footprint of York	EF	York	2002

Title	Method	Location	Year
	Energy Balance MFA		
Escalating trends in the urban metabolism of Hong Kong: 1971-1997	Energy Balance MFA MSA	Hong Kong: City	2001
Stockhome: A Spreadsheet Model of Urban Heavy Metal Metabolism	MFA	Stockholm	2001
Urban Metal Management The Example of Lead	MFA	Vienna	2001
Urban nutrient balance for Bangkok	MFA	Bangkok Province	2001
Energy and material flow through the urban ecosystem	Energy Balance MFA	Bangkok, Beijing, Buenos Aires, Cairo, Delhi, Dhaka, Jakarta, Karachi, Kolkata, Lagos, London, Los Angeles, Manila, Mexico City, Moscow, Mumbai, New York City, Osaka, Rio de Janeiro, Seoul, Shanghai, São Paulo, Tehran, Tianjin, Tokyo	2000
Lead and zinc flows from technosphere to biosphere in a city region	MFA	Stockholm	1996
The Anthropogenic Metabolism of the City of Vienna	MFA Method	Vienna	1996
The city of Vienna's anthropogenic material balance	MFA	Vienna	1996
The ecological backpack of the Ruhr area: a comparison with North Rhine-Westphalia and the Federal Republic of Germany	MFA	Ruhr region	1996
The metabolism of a city: the case of Hong Kong	Energy Balance MFA MSA	Hong Kong: City	1978
Substance Flow Analysis (SFA)			
Monitoring Urban Copper Flows in Stockholm, Sweden: Implications of Changes Over Time	SFA	Stockholm	2016
Changing urban phosphorus metabolism: Evidence from Longyan City, China	SFA	Longyan City	2015
Sustainable design of sanitation system based on material and value flow analysis for urban slum in Indonesia	MFA Scenario analysis SFA	Bandung	2013
Network environ perspective for urban metabolism and carbon emissions: a case study of Vienna, Austria	SFA	Vienna	2012

Title	Method	Location	Year
Nitrogen food-print: N use and N cascade from livestock systems in relation to pork, beef and milk supply to Paris	SFA	Paris	2012
Flows and fates of nickel--cadmium batteries in the City of Cape Town	SFA	Cape Town	2010
Collaborative Problem Solving Using an Industrial Ecology Approach	F&T LCA MFA SFA	New Jersey New York City	2009
A material flow analysis of wood and paper in Cape Town: is there potential to redirect flows in formal and informal sectors to foster use as a renewable resource?	SFA	Cape Town	2007
Food Consumption and Nutrient Flows: Nitrogen in Sweden Since the 1870s	SFA	Linköping	2006
Key drivers of the e-waste recycling system: Assessing and modelling e-waste processing in the informal sector in Delhi	SFA	Delhi	2005
What can we learn from local substance flow analyses? The review of cadmium flows in Swedish municipalities	SFA	Finspång, Linköping, Stockholm	2004
Nitrogen Balance for the Central Arizona–Phoenix (CAP) Ecosystem	SFA	Phoenix	2001
Urban Metal Flows - A Case Study of Stockholm. Review and Conclusions	SFA	Stockholm	2001
Mass balance for wastewater nitrogen in the Central Arizona–Phoenix ecosystem	SFA	Phoenix	2000
A Phosphorus Budget for a Swedish Municipality	SFA	Gävle	1995
Economy-Wide Material Flow Analysis (EW-MFA)			
Examining urban metabolism: A material flow perspective on cities and their sustainability	EW-MFA	Guangzhou	2019
Urban Metabolism of Intermediate Cities: The Material Flow Analysis, Hinterlands and the Logistics-Hub Function of Rennes and Le Mans (France)	EW-MFA	Le Mans Rennes	2018
Downscaling Aggregate Urban Metabolism Accounts to Local Districts	EW-MFA Method	London	2017
Urban metabolism: A review with reference to Cape Town	EW-MFA	Cape Town	2017
Cape Town's Metabolism: Insights from a Material Flow Analysis	EW-MFA	Cape Town	2016
Lisbon's womb: an approach to the city metabolism in the turn to the twentieth century	EW-MFA	Lisbon	2016
Metabolism of Brussels-Capital Region: identification of flows, economic actors and activities on the territory and tracks of reflection for resource optimisation	EW-MFA MFA	Brussels	2015
Urban Economies Resource Productivity and Decoupling: Metabolism Trends of 1996--2011 in Sweden, Stockholm, and Gothenburg	EW-MFA	Gothenburg, Stockholm	2015

Title	Method	Location	Year
Incorporating Bio-Physical Sciences into a Decision Support Tool for Sustainable Urban Planning	EW-MFA Method		2014
Spatial allocation of material flow analysis in residential developments: a case study of Kildare County, Ireland	EW-MFA		2014
Data Mining for Material Flow Analysis: Application in the Territorial Breakdown of French Regions	EW-MFA Method		2013
Sustainable urban metabolism as a link between bio-physical sciences and urban planning: The BRIDGE project	EW-MFA Method	Athens, Gliwice, Helsinki, London, Poland	2013
The physical structure of urban economies — Comparative assessment [Report]	EW-MFA Method	Lisbon, Paris, Seoul, Shanghai	2013
Material flow accounting in an Irish city-region 1992-2002	EW-MFA	Limerick	2011
Urban Metabolism in China Achieving Dematerialization and Decarbonization in Suzhou	EW-MFA	Suzhou	2011
Assessment of total urban metabolism and metabolic inefficiency in an Irish city-region	EW-MFA	Limerick	2009
Urban Metabolism of Paris and Its Region	EW-MFA	Paris	2009
Urban metabolism: Methodological Advances in Urban Material Flow Accounting Based on the Lisbon Case Study	EW-MFA	Lisbon	2009
Metabolism of Neighborhoods	EW-MFA	Toronto	2008
Material Flow Analysis of the City of Hamburg	EW-MFA	Hamburg	2003
Material Flow Accounting and Information for Environmental Policies in the City of Stockholm	EW-MFA Method	Stockholm	1997
Energy Flow Analysis (EFA)			
Metabolic relationships between cities and hinterland: a political-industrial ecology of energy metabolism of Saint-Nazaire metropolitan and port area (France)	EFA PIE	Saint-Nazaire	2019
Urban energy consumption: Different insights from energy flow analysis, input-output analysis and ecological network analysis	ENA EFA IOA	Beijing	2015
Analysis on the Characteristic of Energy Flow in Urban Ecological Economic System—A Case of Xiamen City	EFA	Xiamen	2012
Energy Balance			
Towards a Dynamic Approach to Urban Metabolism: Tracing the Temporal Evolution of Brussels' Urban Metabolism from 1970 to 2010	Energy Balance MFA	Brussels	2016

Title	Method	Location	Year
Urban material flow analysis: An approach for Bogotá, Colombia	Energy Balance MFA	Bogotá	2014
Comparison of energy flow accounting, energy flow metabolism ratio analysis and ecological footprinting as tools for measuring urban sustainability: A case-study of an Irish city-region	EF Energy Balance MFA	Limerick	2012
The energy and mass balance of Los Angeles County	Energy Balance MFA	Los Angeles	2008
Service Sector Metabolism: Accounting for Energy Impacts of the Montjuic Urban Park in Barcelona	Energy Balance LCA	Barcelona	2007
The Changing Metabolism of Cities	Energy Balance MFA	Brussels, Cape Town, Hamburg, Hong Kong: City, Sydney, Tokyo, Toronto, Vienna	2007
A material flow analysis and ecological footprint of York	EF Energy Balance MFA	York	2002
Escalating trends in the urban metabolism of Hong Kong: 1971-1997	Energy Balance MFA MSA	Hong Kong: City	2001
Energy and material flow through the urban ecosystem	Energy Balance MFA	Bangkok, Beijing, Buenos Aires, Cairo, Delhi, Dhaka, Jakarta, Karachi, Kolkata, Lagos, London, Los Angeles, Manila, Mexico City, Moscow, Mumbai, New York City, Osaka, Rio de Janeiro, Seoul, Shanghai, São Paulo, Tehran, Tianjin, Tokyo	2000
The metabolism of a city: the case of Hong Kong	Energy Balance MFA MSA	Hong Kong: City	1978
Energy Accounting			
Conceptualizing Household Energy Metabolism: A Methodological Contribution	Energy Accounting	Cape Town	2019

Title	Method	Location	Year
Incorporating Metabolic Thinking into Regional Planning: The Case of the Sierra Calderona Strategic Plan	EF Energy Accounting MFA	Valencia	2019
Structural, geographic, and social factors in urban building energy use: Analysis of aggregated account-level consumption data in a megacity	Energy Accounting	Los Angeles	2016
Analysis of High-Resolution Utility Data for Understanding Energy Use in Urban Systems: The Case of Los Angeles, California	Energy Accounting	Los Angeles	2015
Urban metabolism: Measuring the city's contribution to sustainable development	Energy Accounting MFA	Curitiba	2015
Analysis of the energy metabolism of urban socioeconomic sectors and the associated carbon footprints: Model development and a case study for Beijing	CF ENA Energy Accounting IOA	Beijing	2014
Material Flows and Energy Analysis of Glass Containers Discarded in New Jersey, USA	Energy Accounting MFA Scenario analysis	New Jersey	2012
Long-term Coordination of Timber Production and Consumption Using a Dynamic Material and Energy Flow Analysis	Energy Accounting MFA	Swiss lowland region	2004
Estimating the urban metabolism of Canadian cities: Greater Toronto Area case study	Energy Accounting MFA	Toronto	2003
A comparison of the sustainability of public and private transportation systems: Study of the Greater Toronto Area	Energy Accounting Greenhouse Gas Accounting	Toronto	2002
Tackling Urban CO2 Emissions in Toronto	Energy Accounting	Toronto	1993
Material Stock Analysis (MSA)			
In-use Product and Steel Stocks Sustaining the Urbanization of Xiamen, China	MSA	Xiamen	2019

Title	Method	Location	Year
Spatial analysis of urban material stock with clustering algorithms: A Northern European case study	MSA	Gothenburg	2019
Spatially explicit material stock analysis of buildings in Eastern China metropoles	MSA	Beijing, Changzhou, Fuzhou, Guangzhou, Hangzhou, Jinan, Nanjing, Qingdao, Shanghai, Shenzhen, Shijiazhuang, Suzhou, Tianjin, Xiamen	2019
Material flow analysis of the residential building stock at the city of Rio de Janeiro	MSA	Rio de Janeiro	2017
Prospecting the Urban Mine of Amsterdam	MSA	Amsterdam	2017
Quantifying and mapping embodied environmental requirements of urban building stocks	MSA	Melbourne	2017
Using Material and Energy Flow Analysis to Estimate Future Energy Demand at the City Level	MSA Scenario analysis	Riyadh	2017
Toward Social Material Flow Analysis: On the Usefulness of Boundary Objects in Urban Mining Research	IS MSA	Norrköping	2015
Urban Metabolism and the Energy Stored in Cities	MSA Resilience assessment	Toronto	2013
Combined MFA-LCA for Analysis of Wastewater Pipeline Networks	Hybrid MFA-LCA MSA	Oslo	2009
Urban stock over time: spatial material stock analysis using 4d-GIS	MSA		2009
Exploration of Urban Stocks	MSA	Switzerland	2008
Stock dynamics for forecasting material flows—Case study for housing in The Netherlands	MSA	Netherlands	2006
The Magnitude and Spatial Distribution of In-use Copper Stocks in Cape Town, South Africa	MSA	Cape Town	2003
Escalating trends in the urban metabolism of Hong Kong: 1971-1997	Energy Balance MFA MSA	Hong Kong: City	2001
The metabolism of a city: the case of Hong Kong	Energy Balance MFA MSA	Hong Kong: City	1978
Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM)			
Development of a municipal solid waste management decision support tool for Naples, Italy	MuSIASEM	Naples	2017

Title	Method	Location	Year
Changes of human time and land use pattern in one mega city's urban metabolism: a multi-scale integrated analysis of Shanghai	Method MuSIASEM	Shanghai	2016
Catalonia's energy metabolism: Using the MuSIASEM approach at different scales	MuSIASEM	Catalonia	2009
Urban Metabolism Analyst Model (UMan)			
Urban metabolism profiles. An empirical analysis of the material flow characteristics of three metropolitan areas in Sweden	UMan	Gothenburg, Malmö, Stockholm	2016
Uncertainty in Material Flow Analysis Indicators at Different Spatial Levels	Method UMan	Gothenburg, Malmö, Stockholm, Sweden	2015
A Material Flow Accounting Case Study of the Lisbon Metropolitan Area using the Urban Metabolism Analyst Model	UMan	Lisbon	2014
Abbreviated MFA			
Material Quickscan for Rotterdam and Den Haag	Abbreviated MFA	Rotterdam, The Hague	2016
Urban Metabolism of Six Asian Cities	Abbreviated MFA	Bangalore, Bangkok, Ho Chi Minh City, Manila, Seoul, Shanghai	2014
Mainstreaming Urban Metabolism: Advances And Challenges In City Participation	Abbreviated MFA	Amman, Beijing, Buenos Aires, Cape Town, Manila, Rio de Janeiro, São Paulo	2012
Activity-based Spatial MFA (AS-MFA)			
Deliverable 3.3 Process model for the two pilot cases: Amsterdam, the Netherlands & Naples, Italy	AS-MFA	Amsterdam, Naples	2019
D.3.5. Process model for the follow-up cases: Łódź	AS-MFA	Łódź	2018
D3.6 Process Model Hamburg	AS-MFA	Hamburg	2018
D3.7 Process model Pécs	AS-MFA	Pécs	2018
Greenhouse Gas Accounting			
Estimating GHG emissions of marine ports—the case of Barcelona	Greenhouse Gas Accounting	Barcelona	2011
Methodology for inventorying greenhouse gas emissions from global cities	Greenhouse Gas Accounting Method	Bangkok, Barcelona, Cape Town, Denver, Geneva, London, Los Angeles, New York City, Prague, Toronto	2010

Title	Method	Location	Year
A Demand-Centered, Hybrid Life-Cycle Methodology for City-Scale Greenhouse Gas Inventories	Greenhouse Gas Accounting LCA	Denver	2008
A comparison of the sustainability of public and private transportation systems: Study of the Greater Toronto Area	Energy Accounting Greenhouse Gas Accounting	Toronto	2002
Emission inventory for greenhouse gases in the City of Barcelona, 1987–1996	Greenhouse Gas Accounting	Barcelona	1999
Fate and Transport Analysis (F&T)			
Collaborative Problem Solving Using an Industrial Ecology Approach	F&T LCA MFA SFA	New Jersey New York City	2009
Energy assessment methods			
Emergy Analysis			
Development of an urban FEW nexus online analyzer to support urban circular economy strategy planning	Emergy Analysis	Beijing	2018
Comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan	CF Emergy Analysis MFA	Kawasaki	2017
Emergy Synthesis for Three Main Industries in Wuyishan City, China	Emergy Analysis	Wuyishan	2015
Emergy-based indicators of regional environmental sustainability: A case study in Shanwei, Guangdong, China	Emergy Analysis	Shanwei	2015
Mass, energy, and emergy analysis of the metabolism of Macao	Emergy Analysis	Macao	2015
Urban metabolism based on emergy and slack based model: A case study of Beijing, China	Emergy Analysis	Beijing	2015
Evaluating spatiotemporal differences and sustainability of Xiamen urban metabolism using emergy synthesis	Emergy Analysis	Xiamen	2014
The urban metabolism of the city of Uppsala (Sweden)	Emergy Analysis	Uppsala	2014
An emergy analysis for urban environmental sustainability assessment, the Island of Montreal, Canada	Emergy Analysis	Montreal	2013
Analysis of the indicators between urban metabolism and land use change in Guangzhou	Emergy Analysis	Guangzhou	2011

Title	Method	Location	Year
Emergy analysis of the urban metabolism of Beijing	Emergy Analysis	Beijing	2011
Evaluation of urban metabolism based on emergy synthesis: A case study for Beijing (China)	Emergy Analysis	Beijing	2009
Urban ecosystem health assessment based on emergy and set pair analysis—A comparative study of typical Chinese cities	Emergy Analysis	Beijing, Chengdu, Chongqing, Fushun, Guangzhou, Haikou, Hangzhou, Harbin, Kunming, Nanjing, Qingdao, Shanghai, Shenzhen, Tangshan, Urumchi, Wuhan, Wuyishan, Xi'an, Xiamen	2009
Urbanization and Socioeconomic Metabolism in Taipei	Emergy Analysis	Taipei	2009
Emergy synthesis and simulation for Macao	Emergy Analysis	Macao	2008
An Integrated Framework for Regional Studies: Emergy Based Spatial Analysis of the Province of Cagliari	Emergy Analysis	Cagliari	2007
Theory of urban energetics and mechanisms of urban development	Emergy Analysis	Taipei	2005
Materials Flow Analysis and Emergy Evaluation of Taipei's Urban Construction	Emergy Analysis	Taipei	2003
Energy-economic theory and mathematical models for combining the systems of man and nature, case study: The urban region of Miami, Florida	Emergy Analysis	Miami	1975
Extended Exergy Accounting (EEA)			
Extended Exergy Accounting for Karachi	EEA	Karachi	2016
Extended exergy-based urban ecosystem network analysis: a case study of Beijing, China	ENA EEA	Beijing	2010
Using exergy to analyze the sustainability of an urban area	EEA	Castelnuovo Berardenga	2004
Input/output methods			
Input-Output Analysis (IOA)			
Spatial flow analysis of water pollution in eco-natural systems	IOA		2016
Urban energy consumption: Different insights from energy flow analysis, input-output analysis and ecological network analysis	ENA EFA IOA	Beijing	2015
Analysis of the energy metabolism of urban socioeconomic sectors and the associated carbon footprints: Model development and a case study for Beijing	CF ENA Energy Accounting	Beijing	2014

Title	Method	Location	Year
	IOA		
Ecological network analysis of an urban metabolic system based on input-output tables: Model development and case study for Beijing	ENA IOA PIOT	Beijing	2014
Analysis of water consumption using a regional input-output model: Model development and application to Zhangye City, Northwestern China	EE-IOA IOA	Zhangye	2009
A method for regional-scale material flow and decoupling analysis: A demonstration case study of Aichi prefecture, Japan	IOA MFA Method	Aichi	2008
Measuring the embodied energy in household goods: application to the Lisbon City	IOA	Lisbon	2008
Ecological Footprints and interdependencies of New Zealand regions	EF IOA	Auckland	2004
Multi-Region Input-Output (MRIO) Analysis			
City Carbon Footprint Networks	CF MRIO	Adelaide, Brisbane, Melbourne, Perth, Sydney	2016
Comparing a territorial-based and a consumption-based approach to assess the local and global environmental performance of cities	MRIO	Brussels	2016
Transnational city carbon footprint networks - Exploring carbon links between Australian and Chinese cities	CF MRIO	Adelaide, Beijing, Brisbane, Chongqing, Hong Kong: City, Melbourne, Perth, Shanghai, Sydney, Tianjin	2016
Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input-output analysis	CF MRIO hybrid	Melbourne Sydney	2016
Carbon footprints of cities and other human settlements in the UK	CF MRIO		2013
Analyses of water footprint of Beijing in an interregional input-output framework	MRIO WF	Beijing	2011
Towards an Integrated Regional Materials Flow Accounting Model	MRIO	London	2005
Physical Input-Output Table (PIOT)			
Ecological network analysis of an urban metabolic system based on input-output tables: Model development and case study for Beijing	ENA IOA	Beijing	2014

Title	Method	Location	Year
	PIOT		
Comparing urban solid waste recycling from the viewpoint of urban metabolism based on physical input–output model: A case of Suzhou in China	PIOT Scenario analysis	Suzhou	2012
Data Acquisition for Applying Physical Input-Output Tables in Chinese Cities	Method PIOT	Suzhou	2011
Environmentally-Extended Input-Output Analysis (EE-IOA)			
The Concept of City Carbon Maps: A Case Study of Melbourne, Australia	CF EE-IOA	Melbourne	2016
Mercury emissions by Beijing׳s fossil energy consumption: Based on environmentally extended input-output analysis	EE-IOA	Beijing	2015
Environmentally extended input–output analysis on a city scale – application to Aveiro (Portugal)	EE-IOA	Aveiro	2014
An input-output approach to evaluate the water footprint and virtual water trade of Beijing, China	EE-IOA WF	Beijing	2013
Consumption based footprint of a city	CF EE-IOA LCA MFA hybrid	Paris	2013
Analysis of water consumption using a regional input-output model: Model development and application to Zhangye City, Northwestern China	EE-IOA IOA	Zhangye	2009
Hybrid input-output analysis of wastewater treatment and environmental impacts: A case study for the Tokyo Metropolis	EE-IOA Scenario analysis	Tokyo	2009
Applying physical input–output tables of energy to estimate the energy ecological footprint (EEF) of Galicia (NW Spain)	EF EEF EE-IOA	Galicia	2008
Throughflow Analysis			
Evolution of virtual water metabolic network in developing regions: A case study of Guangdong province	ENA Throughflow Analysis	Guangdong (province)	2020
Spatial variation in the ecological relationships among the components of Beijing's carbon metabolic system	ENA Throughflow Analysis	Beijing	2016

Title	Method	Location	Year
Ecological network analysis of an urban energy metabolic system: Model development, and a case study of four Chinese cities	ENA Throughflow Analysis	Beijing Chongqing Shanghai Tianjin	2010
Ecological network analysis of an urban water metabolic system: Model development, and a case study for Beijing	ENA Throughflow Analysis	Beijing	2010
Footprint methods			
Ecological Footprint (EF)			
Incorporating Metabolic Thinking into Regional Planning: The Case of the Sierra Calderona Strategic Plan	EF Energy Accounting MFA	Valencia	2019
A multi-year, multi-scale analysis of urban sustainability	EF	Ra'anana	2016
Assessing urban sustainability of Chinese megacities: 35 years after the economic reform and open-door policy	EF	Beijing, Chengdu, Chongqing, Guangzhou, Nanjing, Shanghai, Shenyang, Tianjin, Wuhan, Xi'an	2016
Surveying the Environmental Footprint of Urban Food Consumption	CF EF MFA		2016
Urban ecological footprint analysis: a comparative study between Shenyang in China and Kawasaki in Japan	EF	Kawasaki, Shenyang	2014
An urban metabolism and ecological footprint assessment of Metro Vancouver	EF	Vancouver	2013
Comparison of energy flow accounting, energy flow metabolism ratio analysis and ecological footprinting as tools for measuring urban sustainability: A case-study of an Irish city-region	EF Energy Balance MFA	Limerick	2012
Applying physical input–output tables of energy to estimate the energy ecological footprint (EEF) of Galicia (NW Spain)	EF EEF EE-IOA	Galicia	2008
Contrasting water footprints of cities in China and the United States	EF WF	Beijing, Chicago, Chongqing, Los Angeles, New York City, San Francisco, Shanghai, Tianjin	2006
Ecological Footprints and interdependencies of New Zealand regions	EF	Auckland	2004

Title	Method	Location	Year
	IOA		
A material flow analysis and ecological footprint of York	EF Energy Balance MFA	York	2002
City Limits. A resource flow and ecological footprint analysis of Greater London	EF	London	2002
The ecological footprint of Cape Town: Unsustainable resource use and planning implications	EF	Cape Town	2002
An ecological footprint of Liverpool	EF	Liverpool	2001
Ecosystem appropriation by Hong Kong and its implications for sustainable development	EF spatial	Guangzhou Hong Kong: City	2001
Carbon Footprint (CF)			
Comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan	CF Emergy Analysis MFA	Kawasaki	2017
City Carbon Footprint Networks	CF MRIO	Adelaide, Brisbane, Melbourne, Perth, Sydney	2016
Surveying the Environmental Footprint of Urban Food Consumption	CF EF MFA		2016
The Concept of City Carbon Maps: A Case Study of Melbourne, Australia	CF EE-IOA	Melbourne	2016
Transnational city carbon footprint networks - Exploring carbon links between Australian and Chinese cities	CF MRIO	Adelaide, Beijing, Brisbane, Chongqing, Hong Kong: City, Melbourne, Perth, Shanghai, Sydney, Tianjin	2016
Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input-output analysis	CF MRIO hybrid	Melbourne Sydney	2016
Analysis of the energy metabolism of urban socioeconomic sectors and the associated carbon footprints: Model development and a case study for Beijing	CF ENA Energy Accounting IOA	Beijing	2014
Carbon footprints of cities and other human settlements in the UK	CF MRIO		2013

Title	Method	Location	Year
Consumption based footprint of a city	CF EE-IOA LCA MFA hybrid	Paris	2013
Implementing Trans-Boundary Infrastructure-Based Greenhouse Gas Accounting for Delhi, India	CF TBIF	Delhi	2012
Greenhouse Gas Emission Footprints and Energy Use Benchmarks for Eight U.S. Cities	CF	Arvada, Austin, Boulder, Denver, Fort Collins, Minneapolis, Portland, Seattle	2010
Twelve metropolitan carbon footprints: A preliminary comparative global assessment	CF	Beijing, Delhi, Jakarta, London, Los Angeles, Manila, Mexico City, New York City, Seoul, Singapore: City, São Paulo, Tokyo	2010
Water Footprint (WF)			
An input-output approach to evaluate the water footprint and virtual water trade of Beijing, China	EE-IOA WF	Beijing	2013
Analyses of water footprint of Beijing in an interregional input-output framework	MRIO WF	Beijing	2011
Contrasting water footprints of cities in China and the United States	EF WF	Beijing, Chicago, Chongqing, Los Angeles, New York City, San Francisco, Shanghai, Tianjin	2006
Life Cycle Assessment method			
Life Cycle Assessment (LCA)			
The Life Cycle Assessment of an Energy-Positive Peri-Urban Residence in a Tropical Regime	LCA	Bangkok	2017
The Efficiency of Informality: Quantifying Greenhouse Gas Reductions from Informal Recycling in Bogotá, Colombia	LCA Scenario analysis	Bogotá	2016
A political-industrial ecology of water supply infrastructure for Los Angeles	LCA PIE	Los Angeles	2015
Consumption based footprint of a city	CF EE-IOA LCA MFA hybrid	Paris	2013

Title	Method	Location	Year
Assessment of Environmental Impacts of an Aging and Stagnating Water Supply Pipeline Network	LCA	Oslo	2012
Collaborative Problem Solving Using an Industrial Ecology Approach	F&T LCA MFA SFA	New Jersey New York City	2009
A Demand-Centered, Hybrid Life-Cycle Methodology for City-Scale Greenhouse Gas Inventories	Greenhouse Gas Accounting LCA	Denver	2008
Service Sector Metabolism: Accounting for Energy Impacts of the Montjuic Urban Park in Barcelona	Energy Balance LCA	Barcelona	2007
A Systems Approach to Materials Flow in Sustainable Cities: A Case Study of Paper	LCA		1997
Integrated methods			
Hybrid MFA-LCA			
Combining material flow analysis with life cycle assessment to identify environmental hotspots of urban consumption	Hybrid MFA-LCA	Gothenburg, Stockholm, Sweden	2019
Integrating lifecycle assessment and urban metabolism at city level: Comparison between Spanish cities	Hybrid MFA-LCA	Bilbao Sevilla	2019
A Hybrid Approach for Assessing the Multi-Scale Impacts of Urban Resource Use: Transportation in Phoenix, Arizona	Hybrid MFA-LCA	Phoenix	2017
Urban Metabolism of Recycling and Reusing Food Waste: A Case Study in Taipei City	Hybrid MFA-LCA	Taipei	2015
Combining Material Flow Analysis, Life Cycle Assessment, and Multiattribute Utility Theory: Assessment of End-of-Life Scenarios for Polyethylene Terephthalate in Tunja, Colombia	Hybrid MFA-LCA MAUT	Tunja	2013
Quantification of urban metabolism through coupling with the life cycle assessment framework: concept development and case study	Hybrid MFA-LCA Method	Beijing, Cape Town, Hong Kong: City, London, Toronto	2013
Combined MFA-LCA for Analysis of Wastewater Pipeline Networks	Hybrid MFA-LCA MSA	Oslo	2009
Economic Input-Output Life-Cycle Assessment (EIO-LCA)			
Using Life Cycle Assessment to Evaluate Green and Grey Combined Sewer Overflow Control Strategies	EIO-LCA	New York City	2012
Emergy-LCA			
Sustainability evaluation of e-waste treatment based on emergy analysis and the LCA method: A case study of a trial project in Macau	Emergy-LCA	Macao	2013

Title	Method	Location	Year
Hybrid Emergy-LCA (HEML) based metabolic evaluation of urban residential areas: The case of Beijing, China	Emergy-LCA	Beijing	2009
MFA-Emergy			
Eco-benefits assessment on urban industrial symbiosis based on material flows analysis and emergy evaluation approach: A case of Liuzhou city, China	MFA-Emergy	Liuzhou	2017
Multi-methods			
Incorporating Metabolic Thinking into Regional Planning: The Case of the Sierra Calderona Strategic Plan	EF Energy Accounting MFA	Valencia	2019
Comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan	CF Emergy Analysis MFA	Kawasaki	2017
City Carbon Footprint Networks	CF MRIO	Adelaide, Brisbane, Melbourne, Perth, Sydney	2016
Surveying the Environmental Footprint of Urban Food Consumption	CF EF MFA		2016
The Concept of City Carbon Maps: A Case Study of Melbourne, Australia	CF EE-IOA	Melbourne	2016
Towards a Dynamic Approach to Urban Metabolism: Tracing the Temporal Evolution of Brussels' Urban Metabolism from 1970 to 2010	Energy Balance MFA	Brussels	2016
Transnational city carbon footprint networks - Exploring carbon links between Australian and Chinese cities	CF MRIO	Adelaide, Beijing, Brisbane, Chongqing, Hong Kong: City, Melbourne, Perth, Shanghai, Sydney, Tianjin	2016
Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input-output analysis	CF MRIO hybrid	Melbourne Sydney	2016
Metabolism of Brussels-Capital Region: identification of flows, economic actors and activities on the territory and tracks of reflection for resource optimisation	EW-MFA MFA	Brussels	2015

Title	Method	Location	Year
Urban energy consumption: Different insights from energy flow analysis, input-output analysis and ecological network analysis	ENA EFA IOA	Beijing	2015
Urban metabolism: Measuring the city's contribution to sustainable development	Energy Accounting MFA	Curitiba	2015
Analysis of the energy metabolism of urban socioeconomic sectors and the associated carbon footprints: Model development and a case study for Beijing	CF ENA Energy Accounting IOA	Beijing	2014
Ecological network analysis of an urban metabolic system based on input-output tables: Model development and case study for Beijing	ENA IOA PIOT	Beijing	2014
Urban material flow analysis: An approach for Bogotá, Colombia	Energy Balance MFA	Bogotá	2014
An input-output approach to evaluate the water footprint and virtual water trade of Beijing, China	EE-IOA WF	Beijing	2013
Carbon footprints of cities and other human settlements in the UK	CF MRIO		2013
Consumption based footprint of a city	CF EE-IOA LCA MFA hybrid	Paris	2013
Sustainable design of sanitation system based on material and value flow analysis for urban slum in Indonesia	MFA Scenario analysis SFA	Bandung	2013
Comparison of energy flow accounting, energy flow metabolism ratio analysis and ecological footprinting as tools for measuring urban sustainability: A case-study of an Irish city-region	EF Energy Balance MFA	Limerick	2012
Material Flows and Energy Analysis of Glass Containers Discarded in New Jersey, USA	Energy Accounting MFA	New Jersey	2012

Title	Method	Location	Year
	Scenario analysis		
Analyses of water footprint of Beijing in an interregional input-output framework	MRIO WF	Beijing	2011
Analysis of water consumption using a regional input-output model: Model development and application to Zhangye City, Northwestern China	EE-IOA IOA	Zhangye	2009
Collaborative Problem Solving Using an Industrial Ecology Approach	F&T LCA MFA SFA	New Jersey New York City	2009
Combined MFA-LCA for Analysis of Wastewater Pipeline Networks	Hybrid MFA-LCA MSA	Oslo	2009
A Demand-Centered, Hybrid Life-Cycle Methodology for City-Scale Greenhouse Gas Inventories	Greenhouse Gas Accounting LCA	Denver	2008
A method for regional-scale material flow and decoupling analysis: A demonstration case study of Aichi prefecture, Japan	IOA MFA Method	Aichi	2008
Applying physical input–output tables of energy to estimate the energy ecological footprint (EEF) of Galicia (NW Spain)	EF EEF EE-IOA	Galicia	2008
The energy and mass balance of Los Angeles County	Energy Balance MFA	Los Angeles	2008
Service Sector Metabolism: Accounting for Energy Impacts of the Montjuic Urban Park in Barcelona	Energy Balance LCA	Barcelona	2007
The Changing Metabolism of Cities	Energy Balance MFA	Brussels, Cape Town, Hamburg, Hong Kong: City, Sydney, Tokyo, Toronto, Vienna	2007
Contrasting water footprints of cities in China and the United States	EF WF	Beijing, Chicago, Chongqing, Los Angeles, New York City, San Francisco, Shanghai, Tianjin	2006
Ecological Footprints and interdependencies of New Zealand regions	EF	Auckland	2004

Title	Method	Location	Year
	IOA		
Long-term Coordination of Timber Production and Consumption Using a Dynamic Material and Energy Flow Analysis	Energy Accounting MFA	Swiss lowland region	2004
Estimating the urban metabolism of Canadian cities: Greater Toronto Area case study	Energy Accounting MFA	Toronto	2003
A comparison of the sustainability of public and private transportation systems: Study of the Greater Toronto Area	Energy Accounting Greenhouse Gas Accounting	Toronto	2002
A material flow analysis and ecological footprint of York	EF Energy Balance MFA	York	2002
Escalating trends in the urban metabolism of Hong Kong: 1971-1997	Energy Balance MFA MSA	Hong Kong: City	2001
Energy and material flow through the urban ecosystem	Energy Balance MFA	Bangkok, Beijing, Buenos Aires, Cairo, Delhi, Dhaka, Jakarta, Karachi, Kolkata, Lagos, London, Los Angeles, Manila, Mexico City, Moscow, Mumbai, New York City, Osaka, Rio de Janeiro, Seoul, Shanghai, São Paulo, Tehran, Tianjin, Tokyo	2000
The metabolism of a city: the case of Hong Kong	Energy Balance MFA MSA	Hong Kong: City	1978

CityLoops is an EU-funded project focusing on construction and demolition waste (CDW), including soil, and organic waste (OW), where seven European cities are piloting solutions to be more circular.

Høje-Taastrup and Roskilde (Denmark), Mikkeli (Finland), Apeldoorn (the Netherlands), Bodø (Norway), Porto (Portugal) and Seville (Spain) are the seven cities implementing a series of demonstration actions on CDW and soil, and OW, and developing and testing over 30 new tools and processes.

Alongside these, a sector-wide circularity assessment and an urban circularity assessment are to be carried out in each of the cities. The former, to optimise the demonstration activities, whereas the latter to enable cities to effectively integrate circularity into planning and decision making. Another two key aspects of CityLoops are stakeholder engagement and circular procurement.

CityLoops started in October 2019 and will run until September 2023.

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