DEGREE PROJECT IN ENVIRONMENTAL ENGINEERING,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2020

Assessment of Urban Metabolism of Stockholm Royal Seaport

Through the Enhanced Economy Wide Material Flow Accounting Framework

SINA ABRISHAMI

KTH ROYAL INSTITUTE OF TECHNOLOGY
SCHOOL OF ARCHITECTURE AND THE BUILT ENVIRONMENT

Assessment of Urban Metabolism of Stockholm Royal Seaport

Through the Enhanced Economy Wide Material Flow Accounting Framework

Sina Abrishami

Supervisor
Asterios Papageorgiou

Examiner
ASSOC.PROF.Dr. Miguel Brandão

Degree Project in Sustainable Technology
KTH – Royal Institute of Technology
School of Architecture and Build Environment
Department of Sustainable Development, Environmental Science and Engineering
SE-100 44 Stockholm, Sweden

Preface

This thesis has been written as part of Master's Programme Sustainable Technology in KTH Royal Institute of Technology, Sweden. The study has been developed for the year 2017 under research idea and supervision of Asterios Papageorgiou.

The idea was inspired by the Voskamp et al. (2017) case study in Amsterdam where the application of enhanced Economic Wide Material Flow Analysis (EW-MFA) has been explored. The objectives of the project are to study the full scope of the EW-MFA by extensive literature review, applying the enhanced EW-MFA including water and throughput flows to Stockholm Royal Seaport (SRS) and evaluate the method. Ultimately, the result is validated by comparing this thesis results with other urban areas and also strengths and weaknesses of the enhanced EW-MFA method are assessed for further development.

This thesis project was performed individually with the assist of Asterios Papageorgiou. The bottom-up data has been used for this study by using former research available data considering their validity and reliability. The proper estimations and assumptions have been taken due to lack of an integrated database for SRS.

By adding water and throughput flows, this thesis added new concepts into EW-MFA method showing the necessity of these flows for the Urban Metabolism analysis because of their values. The evaluation of the EW-MFA method itself in this thesis also highlighted further opportunities for completing the method for small-scale urban areas.

Sina Abrishami
Stockholm, August 2020

Abstract

Material flows in Urban Metabolism play a key role for the purpose of building urban areas and growing the economy. There is lack of standard method for accounting of material flows within and across the boundaries of urban systems. This thesis aims to assess the Urban Metabolism of small-scale urban area through the application of the Economic Wide Material Flow Analysis and enhance the scope of the method by adding water flows, which could potentially become a basis for the development of the method in the future. First, the application of the Economic Wide Material Flow Analysis in urban areas was studied through a literature review and then the enhanced Economic Wide Material Flow Analysis was applied to Stockholm Royal Seaport using bottom-up data. Using bottom-up data resulted in detailed information, however, full comparison between urban areas was not possible due to data gaps. The results showed the importance of the method for enhancing Urban Metabolism analysis and amending resource management. Spotting available secondary and recycled resources in the socioeconomic system as a part of application of the method is beneficial to sustain the natural resources use. Since still the method is developing for small-scale urban areas, a mixture of this method and other recommended methods by having focus on data collection is suggested for integrating databases and comprehensive analysis.

Keywords

Urban Metabolism, Economic Wide Material Flow Analysis, Material Flow Analysis, Stockholm Royal Seaport, Circular Economy, Bottom-up data, Top-down data

Sammanfattning

Under de senaste decennierna har stadsområden expanderat snabbare än tidigare. Genom att öka människors tendens att bo i stora städer kommer naturresurser att behövas för att tillgodose stadsområdens växande behov. Materialflöden i stadsmetabolismen spelar en nyckelroll för att bygga miljövänligt och växande ekonomin. Det saknas en standardmetod för redovisning av materialflöden inom och över gränserna för stadssystem. Denna avhandling syftar till att utvärdera stadsmetabolismen genom att använda tillämpning av bred ekonomisk materialflödesredovisning
och förbättra metodens omfattning genom att lägga till vatten- och genomströmningsflöden som potentiellt kan bli bas för utvecklingen av metoden i framtiden. Först studerades tillämpningen av ekonomiskt bred materialflödesredovisning i urbana områden genom litteraturöversikt och sedan tillämpades den förbättrade analysen av ekonomiskt bred materialflöde på Norra Djurgårdsstaden med hjälp av bottom-up data. Att använda bottom-up-data resulterade i detaljerad information, men fullständig jämförelse mellan stadsområden var inte möjlig på grund av dataklyftan Resultaten visade vikten av materialflödesredovisning för att förbättra urban metabolismanalys och ändra resurshantering. Att hitta tillgängliga sekundära och återvunna resurser i det socioekonomiska systemet som en del av tillämpningen av metoden är fördelaktigt för att upprätthålla användningen av naturresurser. Eftersom metoden fortfarande utvecklas för småskaliga stadsområden föreslås en blandning av denna metod och andra rekommenderade metoder såsom, livscykelbedömning, genom att fokusera på datainsamling för att integrera databas och omfattande analys.

Acknowledgements

I would like to express my sincere gratitude to my academic supervisor Asterios Papageorgiou at KTH for this valuable guidance and suggestions throughout the creation of this thesis.

I kindly thank Monika Olsson at KTH for guiding and inspiring me through my study from the beginning.

And at last but not least, I would like to thank my family for their constant supports and encouragements.

Table of Contents

Preface 2
Abstract 3
Sammanfattning 4
Acknowledgements 5
Table of Contents 6
List of Tables 7
List of figures 7
Abbreviations 8
1. Introduction 9
1.1 Background & Problem description 9
1.2 Aim & Objectives 11
1.3 Scope & Limitation 11
2. Literature review 12
2.1 Urban Metabolism 12
2.2 Economy Wide Material Flow Analysis (EW-MFA) 13
2.3 EW-MFA Adapted to Urban Level 16
3. Method 18
3.1 The Enhanced EW-MFA Method 18
3.2 System boundaries definition 20
3.3 Data collection 21
3.4 Validation of the results 22
4. Results 23
4.1 Result from Modified EW-MFA for Stockholm Royal Seaport 23
4.2 Visualization of Material Flow in Stockholm Royal Seaport 28
5. Discussion 30
5.1 Discussion of the results 30
5.2 Validation of the results 32
5.3 Discussion of the method 33
5.4 Recommendations for improving the method 34
6. Conclusions 35
7. References 37
8. Appendix A: Material classification 44
8.2 Appendix B: Description of the data collection process 46

List of Tables

Tables	Page
Table 2.1. Material Flow Accounting indicators' equations and explanation	15
Table 3.1. Apartment spreads in SRS including number of rooms	20
Table 3.2. Used sources for material flow data in the SRS in 2017	22
Table 4.1. Result from EW-MFA for SRS in 2017	23,24,25
Table 4.2. Result from enhanced EW-MFA for SRS in 2017 – Energy	26
Table 5.1 Eurostat EW-MFA results for SRS, Amsterdam, Vienna, and Hamburg	32

List of figures

Figures	Page
Fig 2.1. The EW-MFA model, adapted from Eurostat (2001) and Barles (2009)	13
Fig.3.1. Material flows according to adapted Eurostat method including water flows	19
Fig.3.2. Stockholm Royal Seaport area map (Spatial samples of this study highlighted in the map)	20
Fig.4.1. Construction material flows in Norra1, Norra2, Brofästet and Västra (Tt = 1000t)	28
Fig.4.2. Water and wastewater flow in SRS	29

Abbreviations

CE – Circular Economy

CPA – Statistical Classification of Products by Activity

EU - European Union

EW-MFA – Economic Wide Material Flow Analysis

GDP – Gross Domestic Production

GHG – Green House Gases

GSI – Green Space Index

ICT – Information and Communication Technologies

LCA – Life Cycle Assessment

MFA – Material Flow Analysis

MFCA - Material Flow Cost Accounting

MSW – Municipal Solid Waste

NACE – Statistical classification of economic activities in the European Community

NBS – Nature-based solutions

PIOT – Physical Input Output Table

SCB – Statistical centalbyrån (Statistics Sweden)

SDA - Structural Decomposition Analysis

SEEA – System of Integrated Environmental and Economic Accounting

SRS – Stockholm Royal Seaport

UM – Urban Metabolism

1. Introduction

1.1 Background & Problem description

The world population is growing faster than before, and anticipations shows a 50% of population growth in urban areas by 2030. The Swedish population is anticipated to increase more than one million over the next 10 years from 2018. Statistic in Sweden (SCB) shows an increase in Stockholm population between 70,000 to 80,000 persons per year (SCB, 2018). Studying Urban Metabolism (UM) helps to understand the impact of growing urban areas on increasing natural resources scarcity. UM analysis started more than 50 years ago when the first study of UM was done by Wolman (1965) inspired by solving New York city's drinking water and waste handling problems. Following by studies in the 1970s in Tokyo, Brussel, and Hong Kong focused on improving understanding of UM in different sectors such as energy, industry, and natural industry (Kennedy, et al., 2010). The more UM studies were performed recently, the more the importance of resource management in urban areas was revealed. Strategic sustainable resource management enhance the economy, society, and natural environmental relationships in local, national, and international scales.

Urban areas transform resources that are being extracted locally or imported from external areas for developing the urban built environment and ultimately release emissions and waste to the natural environment (Decker, et al., 2000). Lack of a standard methodology for assessing material flows has been caused applying scattered methods used for assessing material flows in different studies. Eurostat introduced most common used material flow analysis method that has been used by multiple research using available database for national level. In recent years, application of the method was assessed for urban areas considering adapted data originated from national database or bottom-up data collection (Brwone, et al., 2011; Horta, et al., 2017; Bahers, et al., 2019).

The Economy Wide Material Flow Accounting (EW-MFA) is an advanced material flow analysis method for accounting of material flows entering, accumulating in stock, and exiting a socioeconomic system. It considers the socioeconomic system as a ''black box'' where all focus is on imports, stocks, and exports, excluding internal flows. Even though the EW-MFA method has been developed for accounting of material flows at the national level, it has been also adapted for analyzing material flows in different cities (e.g. Amsterdam, Lisbon, and Vienna) (Krausman, et al., 2017; Voskamp, et al., 2017; Barles, et al.,2010). Over the years, the adapted EW-MFA has been further developed by collecting and including more detailed information into it. It was recently enhanced by adding throughput and water flows into the analysis considering modified material classification (less aggregate) for the city of Amsterdam (Voskamp, et al., 2017). Including throughput flows, drinking water and wastewater flows provided not only more detailed findings, but also a deeper understanding of UM. Application of this method considering bottom-up data, which is assumed to be more reliable and relatable data for small urban areas (Papageorgiou, et al., 2019) can provide enhanced insight for deeper and more comprehensive material flow analysis.

The result of the enhanced EW-MFA method can be beneficial for keeping materials for longer period of time. In newly build urban areas, such as the Stockholm Royal Seaport (SRS) recycling and reusing of waste materials is prioritized than the linear economy approach (take-make-dispose), which contributes to over production and accelerating the release of Greenhouse Gas (GHG) emissions. Dematerialization through amending resource management faces challenges that need to be addressed by using

opportunities such as minimizing waste production, increase resource efficiency and productivity (Mayer, et al., 2019). Lack of a standard EW-MFA method for assessing small-scale urban area such as SRS, initiated the idea of possibility of performing the enhanced EW-MFA considering water, air and internal flows. This method enables not only the monitoring of stock changes through material input and outputs, but also improve resource management by highlighting the most resource demanded sectors and responsible for generating waste and emissions to air.

The idea of making a vibrant city, providing a mixture of residential, commercial, and service spaces considering resource efficiency, and being climate responsible started by the Stockholm municipality in Hammarby Sjöstad and continued to the SRS project located at the north-eastern Stockholm. First projects were started in Loudden and Värtahamnen located in the south part of SRS and were continued up north in the residential areas in recent years.

Some of general sustainability goals in the area can be mentioned as saving flora and fauna and its cultural heritage (assessing increasing population impact on origin land utilization), reducing GHG emissions by replacing fossil fuel with renewable energies and targeting fossil fuel free city by 2030. Sustainability goals have been set for not only being fossil fuel free, but also working on energy substitution and human activities adapted to the new system in different sectors from energy, waste, transportation, and water for making more extensive environmental plans for the future. Because of sustainable building environment in SRS, it is estimated that total CO_2 emission reductions for SRS-standard scenario is about 30,000 tonnes CO_2e/year (-60%) and for the progressive scenario 40,000 tonnes CO_2e/year (-80%) by 2030 (Shahrokni, et al., 2015).

Ecological goals in SRS has been established by lowering the use of energy, water, material, and natural resources, and also the sustainable use of energy considering the eco-cycle solutions. For instance, new buildings and transportation system in the area corresponding to the CO_2 emission reductions and saving natural resources. Taking internal material and water flows into consideration in order to maximize secondary sources use within the socioeconomic system is crucial for sustainable resource management in the district (Holmstedt, 2018).

In order to meet the SRS sustainability goals, we need to analyze the material flows from entering to the socioeconomic system, adding to the stock, and exiting the system in order to identify hotspots in resource consumption and provide information that could support the optimization of resource management in the district. The enhanced EW-MFA method could be applied for this task in order to identify sectors with the most resource needs and responsible for the most waste and emission generations. However, the EW-MFA method has not been applied to a small-scale urban area before and its strengths and weaknesses for this type of assessment have not been assessed. Hence, this thesis aims to address two problems. First, the lack of knowledge about the UM of SRS which is necessary in order to improve the resource management in the district and ultimately enhance its sustainability. Second, the lack of knowledge about the potential of the EW-MFA for assessing the UM of small-scale urban areas.

1.2 Aim & Objectives

The aim of this project is to assess the UM of SRS district applying the enhanced EW-MFA framework. By performing the enhanced EW-MFA, the characteristics of SRS UM and their impacts on material flows will be explained. Ultimately, all gathered information will be used to bring suggestions for amending the resource management in the SRS and also enhancing the method in the future.
The objectives of the thesis are:

- To review the full scope of EW-MFA method and identify its applications in an urban context
- To apply the EW-MFA in the SRS
- To analyze and validate the results and evaluate the strengths and weaknesses of the EW-MFA method

1.3 Scope & Limitation

The study of UM can be performed with different methods and tools. In this thesis, the focus is on enhanced EW-MFA considering internal flows for deeper understanding of UM. EW-MFA results is known to be influenced by using a method for collecting data, therefore enhanced EW-MFA has been chosen for reducing inaccuracy of detailed data (Patrício, et al., 2015). The EW-MFA method and its application for urban areas was studied through an extensive literature review, then supplementary information regarding enhanced EW-MFA method was reviewed. The main activities that are considered within the system boundaries are: construction sector, transportation, energy supply chain, as well as waste collection sector.

This method highlights hotspots within the system. However, application of LCA would be needed for achieving comprehensive analysis of each material and product through their life span that ultimately result in better material selection and amending resource management towards sustainability.

Data limitation were planned to be mitigated by an extensive literature review (top-down and bottom-up data collection), and due to data reliability and validity gap, bottom-up data were preferred. A small-scale urban area is considered for this study, which eliminates activities that are included in the study of big cities such as ‘’mining and agriculture”. The year of 2017 is taken as temporal sample due to data, reports, and literature availability, which made it easier for the analysis process. This Master thesis was performed individually with taking available bottom-up data as a basis of estimation process.

2. Literature review

2.1 Urban Metabolism

The UM is similar to a biological organism's metabolism regarding consuming the natural resources and producing waste in different periods of time. A biological organism is capable to utilize energy to transform materials into new shape and forms and also to release wastes and material residues, with the difference from UM that a biological organism is also able to reproduction of its own kind (Graedel & Allenby, 2010, p.42). Materials, products, and services in urban areas are demanded by expanding urban areas, and they are combined with lots of human pressures on the environment such as uncontrolled emissions, resource depletion and waste production. While each city needs materials for its development in different sectors, it is important to supply for needs considering planetary boundaries and natural ecosystem protection (Rockström, et al., 2009). This approach does not mean limiting the city's demands, but affording livability including the human requirement for social amenity, health, and well-being without compromising the natural environement (Newman, 1999).

A holistic assessment approach is required to define the metabolism of urban areas and their connections to environmental boundaries in local and global scales. The study of UM can cover different aspects of life such as livability, employment, education, accessibility to resources, and resource flows and stocks. MFA is counted as an important method to identify urban current and future material needs in order to design better resource management considering urban transformation towards enhancing quality of life without destroying the nature and compromising the ability of future generations to meet their own needs (Browne, et al., 2009; Brundtland, 1987).

Increasing economic wealth and technology provide opportunities for developing cities. As cities become larger, more natural resource will be needed. Different models and methods are deployed to assess urban development pressure on the natural environment by focusing on energy and material flows and their interaction with environment. For instance, Browne, et al. (2010) explained the natural energy and material balance through the first law of thermodynamic (all raw input materials ultimately will end up in waste and it is just a matter of time) to show the material flows in the Irish city (Limerick city) from 1996 to 2002. Application of the EW-MFA provides a holistic assessment of each city's resource consumption and waste production model considering their relationships with regional and global hinterlands focusing on imports and exports (Niza, et al., 2010; Browne, et al., 2011). For instance, Bahers, et al. (2019) used application of EW-MFA for a smaller spatial paradigm (city of Rennes and Le Mans) in France, and the result of the study provided a better picture of intermediate city relationships with their hinterlands for supply chain, material distribution, and waste management.

2.2 Economy Wide Material Flow Analysis (EW-MFA)

EW-MFA aims to analyze material exchanges between a national economy and the natural environment, as well as national economy and other countries' economy (Eurostat, 2013). This method uses the mass balance approach to account inputs (domestic extraction and imports), changes to stocks, and outputs (exports, waste, and emission to nature). It may account unused domestic extraction and indirect flows related to imports and exports considering available data. Material flows refers to all-natural resources either extracted locally or imported to the socioeconomic system as inputs and all materials exports from the current system to other socioeconomic system or the natural environment. EW-MFA assess import and exports flows excluding internal flows emphasizing on city's economic relationships and its dependency on external resources outside the socioeconomic boundary. This method emphasizes on socioeconomic factors to determine resource use pattern and material exchanges in different scales (e.g. nationally or internationally).

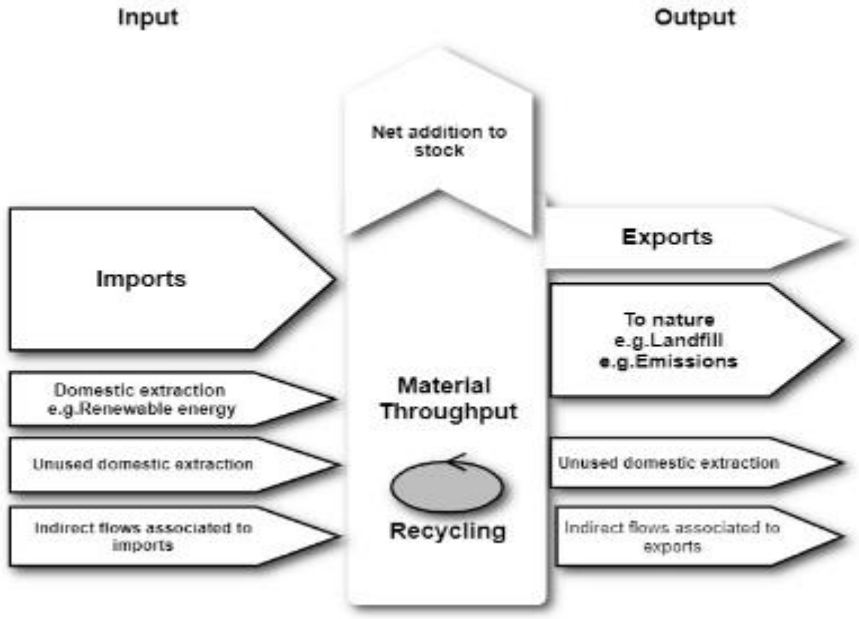

Fig 2.1. The EW-MFA model, adapted from Eurostat (2001) and Barles (2009)

National economic accounting shows how labor, capital and natural resources are used to provide products and services fulfilling the city's requirements in different sectors such as agriculture, clothing, built environment, industries, food etc. Assessing material flows through the socioeconomic system shows the process of turning natural resources like water, land, energy, etc. into emissions to air, waste, sludge, etc. Moll & Watson, 2009). Mass balance is recommended for monitoring the material flow in EW-MFA considering inputs, addition to stock, outputs, and indirect flows and unused domestic extractions.

Indicators can be derived from EW-MFA based accounts. Bringezu, et al. (2003) explains each EW-MFA indicator as below:

Inputs

- Domestic Extraction (DE): Natural materials and sources extracted and harvested within the investigated economical territory and usually the use of these materials has monetary values such as construction minerals (sand, gravel, and crushed stone etc.).
- Unused Domestic Extraction: Refers to all extracted materials in the local area that do not enter the economic system.
- Imports: Raw, semi-manufactured and finished products and materials entered the investigated socioeconomic area from the rest of the world internationally and nationally.
- Indirect Flows Associated with Imports: Upstream material input flows refers to materials extracted and harvested in the rest of the world and required to produce imported materials (used and unused needs to be considered).

Stocks

- Material Accumulation (Net Addition to Stock): Accumulation of materials within the socio-economic system such as buildings, infrastructure, goods etc.

Outputs

- Domestic Proceed Output (DPO): All materials that leave the economic system and enter the domestic environment originating from consumption and production such as waste, used materials and emissions.
- Disposal of Unused Domestic Extraction: Disposal of domestic material locally extracted into the domestic natural environment.
- Exports: Raw, semi-manufactured and finished products and materials exported to the rest of the world.
- Indirect Flows Associated with Exports: Upstream material input flows required to produce export product.

The relationships between the abovementioned indicators are explained by the mass balance approach in Table 2.1.:

Table 2.1. Material Flow Accounting indicators' equations and explanation

	MFA Indicators	Equation / Explanation
Socio-economic system		
	Direct material input	Domestic extraction (DE)+Imports
	Domestic material consumption (DMC)	DE +Imports-Exports
	Total material requirement (TMR)	DE +Unused domestic extraction +Import +Unused extraction in country of origin
	Total material consumption (TMC)	TMR- Exports-unused extraction of exports
	Processed material PM	DMC +Secondary materials
	Net Addition to Stock (NAS)	DMI- (Exports +DPO)
To environmental system		
	Domestic processed output (DPO)	Emissions to air, landfilled wastes from economic activities and households, sludge from wastewater treatment
	Exports	Sent materials to the outside of socio-economic boundary
	Disposal of unused domestic extraction	

Note: Unused materials = waste and residual from natural resource extraction that never entered the national economic system and went straight to the disposal sector after the extraction process; Indirect material ''hidden flows''= Indicate all needed materials along with manufacturing processes

2.3 EW-MFA Adapted to Urban Level

EW-MFA in urban areas provides the detail material flow information corresponding to grow the economy without limit the future needs and disturbing the natural ecosystem (Hammer, et al., 2003). In contrast with EW-MFA at national level, there is no standardized methodology for conducting MFA in urban level (Niza, et al., 2009).Application of adapted method from national to urban scale can be performed by disaggregating material flows using proxy factors such as population, occupied households, and number of workers (Browne, et al., 2011). The adapted EW-MFA shows similarities with the original method, while internal material circulation within the system is excluded from the analysis.

Each city shares unique features and material flow patterns. The EW-MFA at the urban level helps to define these characteristics by monitoring material flows and compare them with other urban areas. For example, a comparison of the Economy Wide Material Flow Accounts of three metropolitan areas in Sweden (Stockholm, Gothenburg, and Malmo) highlights the importance of the method for recognizing each city's economic characterization. Their characteristics are recognized as Stockholm (Consumer-service based), Gothenburg (Industrial based) and Malmo (Service based). These characterizations also explain the reason behind each city's resource management strategy such as absorbing workers, investing on industrial parts, advancing the technology, etc. (Rosado, et al., 2017; Kalmykova, et al., 2015). Each unique UM can also lead the material flows. This metabolism can be temporary, like newly build urban areas in China that caused increase in Total Material Requirement (TMR), or permanent like being dependent to the external resources for supplying required raw materials or processing generated wastes (Barles, et al., 2019; Schandl & Miatto, 2018).

Each material contribution to economic growth can be evaluated by calculating each material share in Gross Domestic Production (GDP). This information also shows to what extent the economy depends on the specific type of material. For example, a case study in Lisbon highlighted the economy's growth dependency to imported fossil fuel over the years (Kovanda, et al., 2012).

Physical exchanges of materials make alteration in accumulation of materials in stock in different sectors. Analyzing of the material accumulation process provides information such as lack of resources, energy demands of moving mass or percentage of specific mass flow and ecosystem disturbances, etc. (Fischer, et al., 2011). A study in the Lisbon metropolitan area performed EW-MFA considering less aggregate classification including each material's life cycle and impact on the dynamic of in-use stocks. Evaluating the dynamics of material stocks over different periods of time highlights the strengths and weaknesses of resource management (Rosado, et al., 2014; Liu, et al., 2020). For example, construction activities transform and modify dynamics of stocks (e.g. extracting raw materials, preparing the land, energy and water consumption, maintenance, demolition). Acknowledging these activities in detail can amend resource management (e.g. using materials with low content, reducing waste generation by sharing surplus with other projects, downscaling bulky materials by reusing them as raw materials) (Schiller, et al., 2017; Migliore, et al., 2020; Wang, et al., 2020).

Studying the application of EW-MFA for UM in different cities provides important information for evaluating the natural resource values properly (e.g. shifting linear production to circular by dematerialization, decarbonization, and closing the material loop within the socioeconomic system) (Barles, 2010). Material specification such as intensity, efficiency, productivity, reusability, and recyclability rank their economical, technical, and environmental performances (Zhang, et al., 2009; Li, et

al., 2010). Enhancing the knowledge of each material specification through application of EW-MFA is beneficial for the dematerialization process by extending material consumption cycle by recycling and using them as secondary and recycled materials in a supply chain (Wiedenhofer, et al., 2019).

Performing EW-MFA brings attention to CE (Mayer, et al., 2019). CE is considering economic growth and environmental protection in parallel by prioritizing recycling, reusing, and reducing than disposal activities that contribute to vast environmental impact reductions (Krausmann, et al., 2017; Virtanen, et al., 2019). Considering natural ecosystems as a model in different sectors improve the material flow circularity. For instance, Nature-based Solutions (NBS) has focus on symbiosis with natural environment by designing and building the urban environment matching the nature around it (Pearlmutter, et al., 2020).

Coupling EW-MFA with other environmental decision-making tools is beneficial to involve other materials' specifications into the analysis and provide more comprehensive results. For instance, coupling EW-MFA with Material Flow Cost Accounting (MFCA) provides detailed holistic information about each material specifications (e.g. including monetary value is equally important as physical values since the extraction and production process might increase or lower the economic and environmental costs of materials, products, and services)(Kovanda, 2019). These detailed databases for each material ultimately result in upgrading former environmental directives and policies towards sustainability.

3. Method

3.1 The Enhanced EW-MFA Method

The lack of standardized and comprehensive EW-MFA method and resource classifications for UM studies required the improvement of the method. Voskamp, et al. (2017) enhanced the EW-MFA method considering less aggregate material classification, and also adding throughput, drinking water and wastewater flow into the analysis. Through this approach, Voskamp provided a more comprehensive and in-detailed information for material flows.

Like other materials, water also can be influenced by the UM. A study of the Korean urban areas (Seoul, Ulsan and Jeju) shows that the city's characteristics impact on the type of water consumption (e.g. Jeju had the highest ground water intensity use because of their intensive agriculture structure) (Jeong, et al., 2020). Assessing water and wastewater flows from their cradle (river, ground, and precipitation) to grave (energy recovery, purification, release to the sea) is vital for enhancing water management (Wendling & Holt, 2020). Enhanced EW-MFA is set to add water and wastewater flows data considering not only storm, rain, and purified water, but also water and wastewater flows from restaurants and commercial areas into the analysis.

There are modifications that were added into method such as including drinking and wastewater flow since they are counted as one of the highest material requirement in each city and it is important to quantify the absorbing water from different resources and water consumption and recycled water within and outside the socioeconomic system. Stormwater and rainwater are two of the main water resources in each city that were considered for this study. Throughput flows, which in previous EW-MFA were excluded, also was considered in the enhanced EW-MFA. Therefore, in this study recovered materials, locally extracted renewable energy and water flows were considered as the most important internal flows with available data and thus they are added into analysis. Moreover, it provides key information for dematerialization and the CE process within the socioeconomic system.

Rosado, et al. (2014) and some other studies analyzed waste categories in detail considering the type of waste and waste treatment for each type. It is important to track the origin and end point of each type of waste to enhance understanding of the waste management in the area. With new material classification (less aggregate), more detailed data are available that resulted in more extensive analysis of the types of material and allowed the comparison of the results with other urban areas.

Adding waste flow and emissions to the nature to the classification not only provided applied information about throughput material flows, but also helped to complete and validate mass balance of materials. For instance, category ''fossil fuel and fossil fuel products'' outputs are estimated based on CO_2 emissions from different sectors.

The following Sankey diagram shows modified Eurostat material flows method including water, wastewater, and throughput flows inspired by Voskamp, et al. (2017). The difference between this resource flow and EW-MFA method is adding water and internal flows such as renewable energies into the analysis of local extraction. Furthermore, waste and emission to nature are also being mentioned in detail. In the original enhanced EW-MFA method by Voskamp, et al. (2017), unused local extraction and indirect flows were also mentioned, but because of data scarcity in SRS, these flows could not be defined and separated from other flows so they are excluded from the final result table.

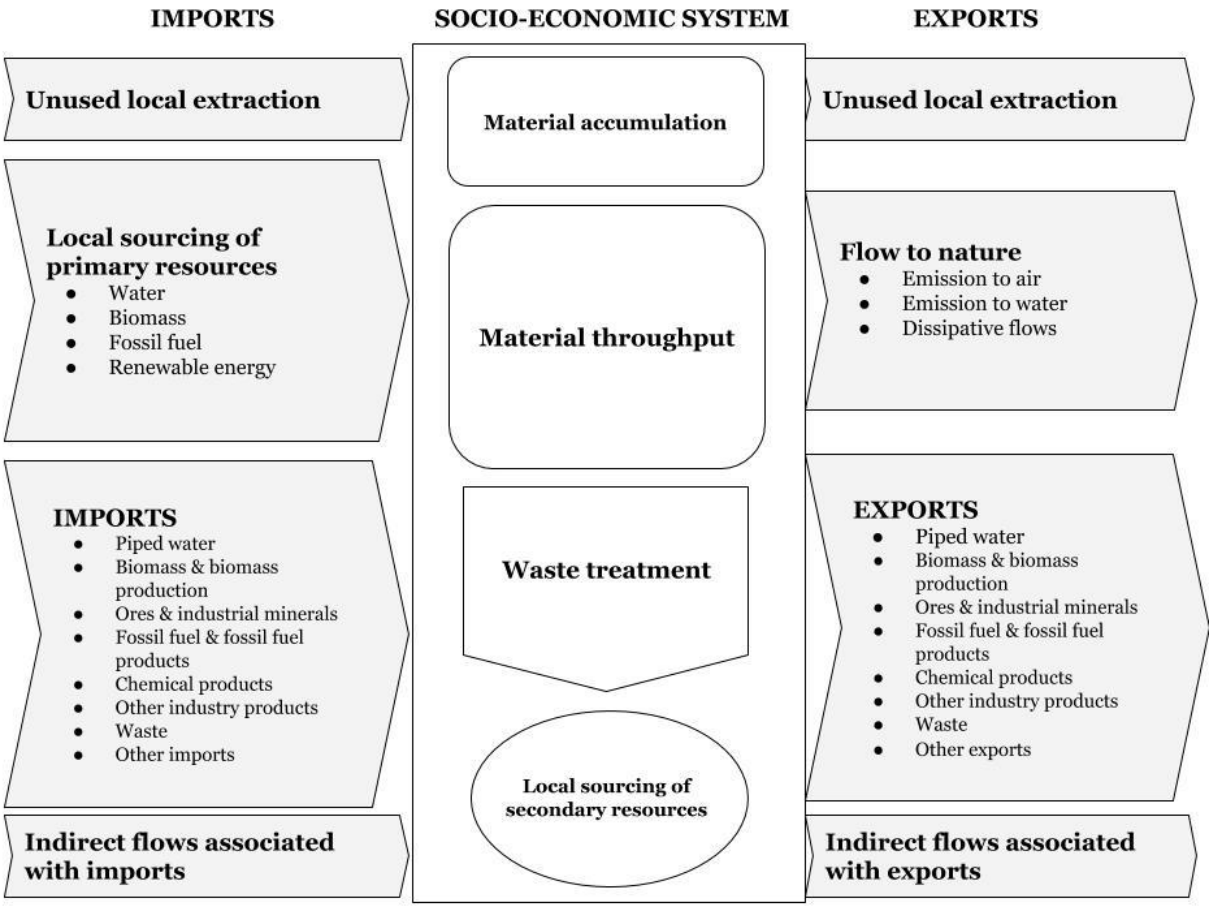

Fig.3.1. Material flows according to adapted Eurostat method including water flows

3.2 System boundaries definition

Defining system boundaries is important as it confines the area of research to desired spatial and temporal boundaries. Closing the boundaries regarding location and time reduces the complexity of urban metabolism analysis. The thesis project is performed in the completed areas of SRS till 2017. These areas are Västra, Norra 1, Norra2 and Brodfästet and are highlighted in Figure 3.2.

Fig.3.2. Stockholm Royal Seaport area map (Spatial samples of this study highlighted in the map)

The following table shows completed apartments spread for estimating residential occupied area in 2017:

Table 3.1. Apartment spreads in SRS including number of rooms

	1 room	2 rooms	3 rooms	4 rooms	5 rooms
SRS Sustainability Report till 2017	315 units	785 units	762 units	585 units	78 units
Of total	12%	31%	30%	23%	3%

Note: Estimation of size and numbers of apartments in SRS, average size for one room unit is around (27 m^2), two rooms (44 m^2), three rooms (74 m^2), four rooms (120 m^2), five rooms (150 m^2), six rooms (300 m^2)

The spatial sample of this study was estimated based on occupied area in SRS in 2017. The size of households and commercial areas is estimated using data from Statistics in Sweden (SCB) and SRS Sustainability reports (2017). In total, around 183325 m^2 are occupied by household areas (2 525 units) and 20 500 m^2 are occupied by commercial areas (Total 203825 m^2). Population is estimated 4 800 residents considering 1.9 residents per dwelling (SRS roadmap, 2017). Most of data are modified considering proper proxy factors such as population and occupied apartments and area. Each material ratio is used to fill the data gap for materials with similar functionality such as cement and concrete in construction sector. According to mass balance principle, materials cannot be created nor destroyed within the urban system, therefore all input materials into the system equal all outputs over the same period plus the stock changes in the system. Mass balance is used for estimating materials inputs and outputs.

3.3 Data collection

Data was collected from available data sources with proper modifications considering the case study's spatial and temporal boundaries. In the Table 3.2, the data sources are described, considering their type of data and year mentioned specifically. Most of the data extracted or adapted to 2017. Moreover, bottom-up data preferred to top-down data due to its higher accuracy. The modifications that were made in this study are described next.

The modified material classification was inspired by methods taken from different studies and Statistical Classification of Products by Activity (CPA) (2nd level) (Rosado, et al., 2014; Browne, et al., 2011; Niza, et al., 2009). In case of data availability, the (3rd level) of CPA was also considered to provide more detailed information (e.g. ''non-metallic minerals'' has been described for available material data such as cement, clay and glass and the rest is considered as ''other non-metallic minerals'') (see Appendix A). This material classification approach leads data collection to selecting detailed bottom-up data considering this study system boundaries.

Including drinking water and wastewater flows based on data source and estimation of each sector's fresh water consumption and wastewater production was performed. Stormwater and surface water data also was available and was added into data collection.

Waste materials were sent to the outside the SRS district for the further treatment process, except recovered materials that were used as recycled resources, such as excavated materials in construction sector. Excavated materials are mentioned in internal flows and are considered as recycled resources, the mass balance principle has been used for estimating construction waste considering 2% of material inputs became waste and the rest accumulated in the stock or shared with ongoing construction projects.
Data for recovered and landfilled materials was collected from different construction activities in the area. Construction waste materials from open public place construction were divided considering reported data from Stockholm Stad (2017) (77.41% material recovery,12.79% landfill, 9.08% energy recovery and 0.72% reuse) (see Appendix B)

Energy needed for the district heating and cooling and electricity was taken based on standard data from SRS roadmap (2017) (see Appendix B). Then the proper modification for energy resource fractions are considered (Exergi Sustainability report, 2017), and further energy consumption forecast in the district was discussed (see Appendix B). Fuel consumption for transportation is estimated based on available data

from Swedish Transport Analysis (Trafikanalys) and Swedish Traffic Agency (Trafiksverket). Units were also is normalized based on validated and reliable sources.

Detailed emissions data was available for energy plants located in the area (Värtaverket and Giggen) from Naturvardsverket (2017) and also Statistics yearbook for Stockholm (2019). CO_2 emissions are calculated considering energy production, transportation, good and services and maintenance, in addition to the amount of CO_2 saved from recycling waste. CO_2 emissions data was taken from the SRS roadmap standard because of its accuracy and reliability of data compared to other data sources (Stad, S., 2017). While for emissions that no other data was available like Dinitrogen oxide (N_2O,) Nitrogen Oxide (NOx) and Sulphur Oxide (SOx), the Naturvardserket data was adjusted and used. Waste treatment process also released GHG emissions and at the same time provided emission savings, and both amounts were considered in the calculation process.

Table 3.2. Used sources for material flow data in the SRS in 2017

Material Category	Type of data	Base year	System boundary	Source
Local sourcing (Primary & secondary)	Local	2017	Stockholm Royal Seaport (SRS)	Royal Seaport Roadmap
	Local	2016	SRS	Papageorgiou, et al. (2019) supporting information
	National	2017	SRS	Svergieavfallhantering
Import/Throughput/Exports	Local	2017	SRS	Papageorgiou, Royal Seaport Roadmap, Stockholm Exergi Trafikanalysis (2018) Trafiksverket (2017)
Waste treatment	Local	2017	SRS	Stockholm Royal Seaport Sustainability report, Papageorgiou, Roadmap
	National	2016	Stockholm	Stockholmvattenochavfall
Emissions	National	2017	Stockholm	Statistics Årsbok Stockholm (2019)
	Local	2017	SRS	Stockholm Royal Seaport Sustainability Report Royal Seaport Roadmap
	Local	2017	SRS	Naturvärdsverket

3.4 Validation of the results

Because of lack of comparable data for other urban areas, results from this study aggregate and units normalized to being able to compare with other urban areas. For instance, GDP was found in million SEK per capita from official statistics in Sweden (Sveriges officiella statistik, 2018) for Stockholm, the proper modification based on SRS population and currency exchange rate to million Euro was done in order to normalize the SRS GDP unit to be comparable with other urban areas. Values for Amsterdam, Vienna, and Hamburg was extracted from Voskamp, et al. (2017).

4. Results

4.1 Result from Modified EW-MFA for Stockholm Royal Seaport

The result from the application of the modified EW-MFA to SRS are presented in Table 4.1. Almost all needed material was imported from external resources (national and international) except renewable energies such as solar energy, energy produced by local power plants, and recycled water and construction materials. Just around 58 kt (kilotonne) construction materials such as rock, gravel, metal and 3.6 GWh (Gigawatt hours) energy are estimated to be reused and recovered from demolition, excavation activities, and biogas production.

Table 4.1. Result from EW-MFA for SRS in 2017

		Inputs	Internal flows	Outputs
	Material: kilo tonnes (kt)			
	Local sourcing of primary resources (inputs) & Secondary resources (internal flows)			
Water				
	Purified water	-	7.80	-
	Respiration	-	0.80	-
	Storm runoff	-	8.00	-
	Total	-	16.6	-
Recovered Materials from waste				
	Construction	-	13.8	0.27
	Rock	-	26.7	-
	Recycled waste	-	0.78	-
	Total	-	41.2	0.27
	Import/ Throughput/ Export			
Piped water				
	Household water	-	263	-
	Commercial water	-	79.0	-
	Restaurants	-	3.40	-
	Water in food	2.00	-	-
	Wastewater (from restaurants)	-	-	3.40
	Total	2.00	354	3.40

Table 4.1 (continued).

	Import/ Throughput/ Export	Inputs	Internal flows	Outputs
Non-metallic minerals				
	Article of concrete	275	-	7.00
	Glass	0.23	-	0.004
	Clay	2.30	-	0.05
	Cement, lime, and plaster	8.70	-	0.18
	Other non-metallic	23.0	-	0.46
	Total	309.2	-	7.69
Biomass & biomass products				
	Crops	0.88	-	-
	Plants & animal products	2.59	-	-
	Other food	0.10	-	-
	Beverage	0.64	-	-
	Textile & wearing apparel	0.10	-	-
	Wood, cork & rubber	0.05	-	-
	Paper & board	0.44	-	-
	Total	4.80	-	-
Ores & industrial minerals				
	Metallic manufacture products	13.1	-	0.26
	Metal ores	3.34	-	0.06
	Other fabricated metal products	0.14	-	0.002
	Total	16.58	-	0.32
Fossil fuel & fossil fuel products				
	Asphalt	12.44	-	-
	Plastic products	6.60	-	-
	Total	19.04	-	-
Chemical products				
	Chemical products	1.83	-	-
	Total	1.83	-	-
Other industry products				
	Other goods	0.10	-	-
	Total	0.10	-	-
Waste				
	Rock and shaft (recycled)	-	-	18.0
	Metal recycled	-	-	1.80
	Hazardous waste (landfill)	-	-	0.37
	Total	-	-	20.2
	Local waste treatment			
Municipal solid waste				
	Household waste	-	-	0.54
	Commercial waste	-	-	0.10
	Commercial waste(powerplants)	-	-	0.45
	Chemical waste	-	-	0.02
	Construction waste (landfilled)	-	-	4.53
	Vacuum collection system (paper & plastics)	-	-	0.13

Table 4.1. (continued).

	Waste room	-	-	1.35
	Mixed waste	-	-	1.90
	Recycled	-	-	0.35
	Dry matter of wastewater	-	-	1.20
	Total	-	-	10.6
Flow to nature				
Emission to air				
	Carbon dioxide (CO_2) total (Residential)	-	-	10.5
	CO_2 total (Construction)	-	-	7.00
	Nitrous oxide (Nox)	-	-	0.24
	Dinitrogen oxide (N_2O,)	-	-	0.11
	Sulphur dioxide (Sox)	-	-	0.05
	CL_2, HCL inorganic	-	-	0.01
	Ammonia (NH_3)	-	-	0.0006
	Dust	-	-	0.001
	Total	-	-	17.9

The mass balance principle has been used for estimating outputs. Because of volume of ongoing construction activities in the area only 2 % of construction material inputs was considered as outputs and the rest was considered to be added to the stock. Waste materials either exited the SRS for further treatment processes or recovered within the system. ‘’biomass & biomass products’’ outputs were expected to be counted in municipal solid waste, but no disaggregated data was available for each fraction. In total 351.58 kt inputs and 56.9 kt outputs excluding water flow and energy has calculated and following the mass balance principle 84 % of materials has been added to the stock.

By including water flows into analysis, a significant amount of material is added to the result which shows the importance of water flows in the EW-MFA (31% of whole input materials). 1034 liters of water are consumed by each restaurant per day, and 140.4 liters of wastewater per person are produced from households (equivalent to 263 kt total wastewater per year). Including these water flows into the analysis shows not only water consumption and wastewater production levels in the area, but also reveals the strategic plans for recycling water by removing pollutants from storm run offs and using them through waste-to-energy process for the energy recovery purpose. The SRS district is planned based on strategic plans to maximize rain and storm water capture rate and recycling water, such as implementing technologies such as Green Space Index (GSI), vacuum collection system and structured tree with biochar (see Appendix B). Wastewater in the sewage system from household and restaurants is sent to the power plant for energy recovery and wastewater procurement site for purification purposes. It is estimated that more than 90 % of wastewater is recycled or processed for energy recovery in the area.

One of the biggest material consumers is the construction sector because of the construction of buildings and roads, and the open area project completion process. 90% of disposed materials in this sector is expected to be reused, recovered, and recycled depending on material durability in the system. In the construction sector, considerable amounts of material were excavated or demolished, and the goal is reusing and recycling them as much as possible. From Stockholm Royal Seaport Sustainability Report

2017 (Stockholm Stad, 2017) it was found that 13 kt out of 50 kt construction waste are recycled considering construction waste from open public places, and also 26 kt rock is reused in Norra2 (see Appendix B). The category ''non-metallic mineral'' such as concrete, cement, concrete blocks include 76% of whole material inputs showing the importance of alterative renewable materials replacement instead of conventional materials in the construction sector in order to ultimately reduce material input mass in this sector.

Reused and recovery material and energy from construction waste and disposal is higher than landfill, but still because of the high volume of waste in this sector landfilled materials added 4.5 kt (12.79% of total disposed waste) to the municipal solid waste outputs (see Appendix B). Recycled construction materials (rock, shaft, and metal) are considered as output materials since the closest waste treatment site located outside the SRS district. While these materials and other recovered materials are assumed to be estimated and included in the recovered construction materials by adding throughput flows into analysis.

Table 4.2. represent energy flows regarding amounts of reported renewable energy resources and recovered energies in the area, plus energy that were consumed in transportation and supplying energy process in a form of fossil fuels.

Table 4.2 Result from enhanced EW-MFA for SRS in 2017 – Energy

Energy: GWh		Inputs	Internal flows	Outputs
Local sourcing of primary resources (inputs) & Secondary resources (internal flows)				
Renewable Energy				-
	Solar energy	-	0.40	-
	Thermal	-	1.20	-
	Solid & Liquid fuel	-	5.10	-
	Waste fuel	-	4.90	-
	Total	-	11.6	-
Recovered Materials & energy from waste				
	Energy recovery from households	-	1.00	-
	Energy recovery from construction waste	-	3.20	-
	Biological recovery	-	0.36	-
	Biogas combustion	-	0.12	-
	Total	-	4.68	-
Import/ Throughput/ Export				
Fossil fuel				
	Gasoline	-	0.07	-
	Diesel	-	0.03	-
	Energy supply	-	0.12	-
	Total	-	0.22	-

Produced energy from renewable sources such as waste and biofuel were increased compared to reduction in fossil fuel consumption, announced by Stockholm Exergi and Statistical yearbook for Stockholm (2019)

(see Appendix B). Energy for heating and cooling and electricity were supplied mostly from renewable resources. More than half of the energy are supplied from ‘’solid & liquid biofuel” and ‘’waste fuel” by 66%, while ‘’fossil fuel” was used as an energy supply by 11%. High material needs in construction sector caused increase in energy recovery from disposed waste. Only in public open space construction, it was estimated that 9% of the disposed materials were used for energy recovery (3.2 GWh). However, this amount was reported higher in Norra 2 and Västra compared to the public open space (Stockholm Stad, 2017).

Estimated CO_2 emissions for residential area are emissions from energy, transportation, goods and services, and maintenance. Previous studies show that total construction waste is reduced by 40% in 2017 compared to its previous year, something that indicates progress in controlling waste production (SRS Sustainability Report, 2017). However, CO_2 emissions from construction activities considering concrete, steel, and asphalt in Norra 1 are two times higher than energy recovery from the same sector. Another construction activity with high material demands is building roads (e.g. asphalt and fuel). Reduction in CO_2 emissions from building roads and maintenance activities in the area compared with its baseline figures is considerable. Strategic plans such as energy efficiency, renewable fuel substitution, and amending supply and logistics were influential to reduce transportation related emissions in the district (SRS roadmap, 2017).

GHG emissions emitted from power plants located in the area (Värtaverket & Giggen) stood at the highest by 1903 kt. GHG emissions are also measured for the completed residential area (10 kt) and construction area (7 kt) in 2017 (SRS sustainability report, 2017; SRS roadmap, 2017). Emissions were estimated considering baseline emissions from buildings and infrastructure (including heating, cooling and electricity and biogas), transportation, maintenance and goods and services and waste management, which they shared GHG emissions from the highest to lowest, respectively.

In the households, waste strategy is to sort the waste as much as possible by providing sorting waste guidelines for residents and facilitating area with accessible waste room near each building, therefore waste were produced 27 kg less per apartment compared to 2016 (SRS sustainability report, 2017). New in-sink grinder installed in all household and restaurants’ kitchen connected to vacuum collection system cause massive reductions in food waste accumulation in waste room and increasing energy recovery (see Appendix B). For instance, 65% of household waste is recycled (0.35 kt out of 0.54 kt) considering metals, glass and collection of paper, plastics, and street litter by vacuum system. Mixed waste is estimated higher compared to other waste fractions found in the waste room such as packaging, glass, paper, metal. etc. that are described as waste room in the result table. This difference shows the importance of clarifying mixed waste fractions for sorting and treating them properly. Since, the closest waste treatment site is located outside the socioeconomic system boundary, all wastes are considered to be exported outside the socioeconomic system, except those used for energy recovery by local power plants. 96% of waste is recycled or used for energy recovery and the rest is sent for disposal and landfill process (Exergi Sustainability report, 2017).

4.2 Visualization of Material Flow in Stockholm Royal Seaport

The information from the result table supported the creation of the Sankey diagram shown in Figure 4.1. which depicts the construction material flows in SRS. The difference between inputs and outputs is expected to accumulate in the system (314,34 kt). The category ‘’article of concrete” includes considerable part of ‘’non-metallic minerals” followed by ‘’other non-metallic minerals” and ‘’cement”, lime”, and ‘’plaster”. The category ‘’other non-metallic minerals” is mentioned aggregated because of data gaps, considering the fact that the most important materials already were mentioned in the result table. Based on literature review, 56% of total ‘’other non-metallic minerals” (23 kt) is considered as ‘’wood and wood products” used in construction sector (NCC annual report, 2017). The category ‘’metallic manufactured products” referred to basic metals, fabricated metal products, and machinery and equipment. Outputs are mentioned below excluding throughput materials such as recovered materials and including disposed materials and emissions to nature. In nutshell, 94% of total construction inputs are considered to be added to the stock considering SRS construction activities.

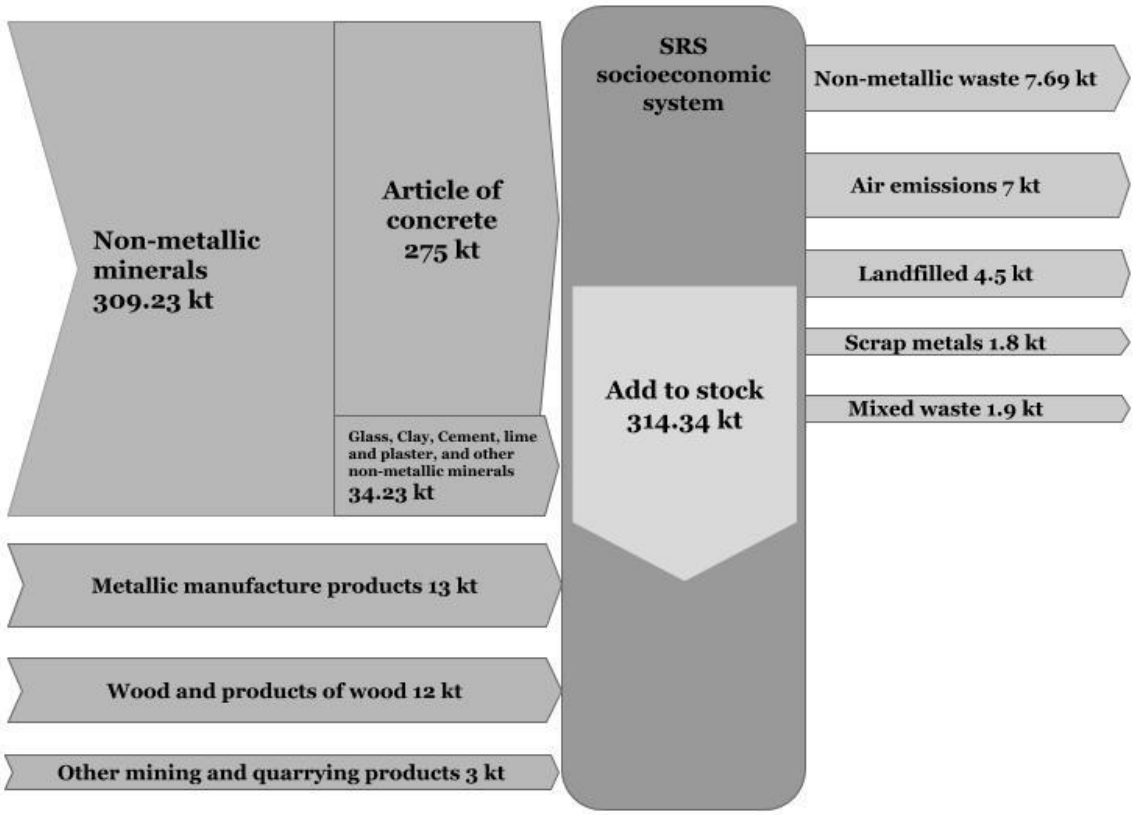

Fig.4.1. Construction material flows in Norra1, Norra2, Brofästet and Västra (kt = 1000t)

The detailed information for water consumption and wastewater production is taken from validated sources and simulations (Stockholm Stad, 2017; Papageorgiou, et al., 2018) (see Appendix B). Storm water also is considered based on (SRS Sustainability report, 2017). Water use in household and restaurant sector was added quite equal amounts of material as total construction materials showing the key role of water flows in EW-MFA. All data are presented in thousands-tonne for better assessment of the flows. In the wastewater treatment section, energy recovery and purification functions are expected to take a place for most of the collected wastewater. High household wastewater production (263 kt) highlights the importance of energy recovery projects such as biogas production from the collected wastewater in vacuum collection system (see Appendix B). Wastewater from restaurants is based on 377 t wastewater production per year for each restaurant and data modified for nine restaurants in the system boundary (see Appendix B). 529 kg per capita water in food on average was reported for SRS that was considered in the Figure 4.2. More than 90% of the water intake in restaurants is expected to end up in sewerage system and food, and the rest is accumulated in the system.

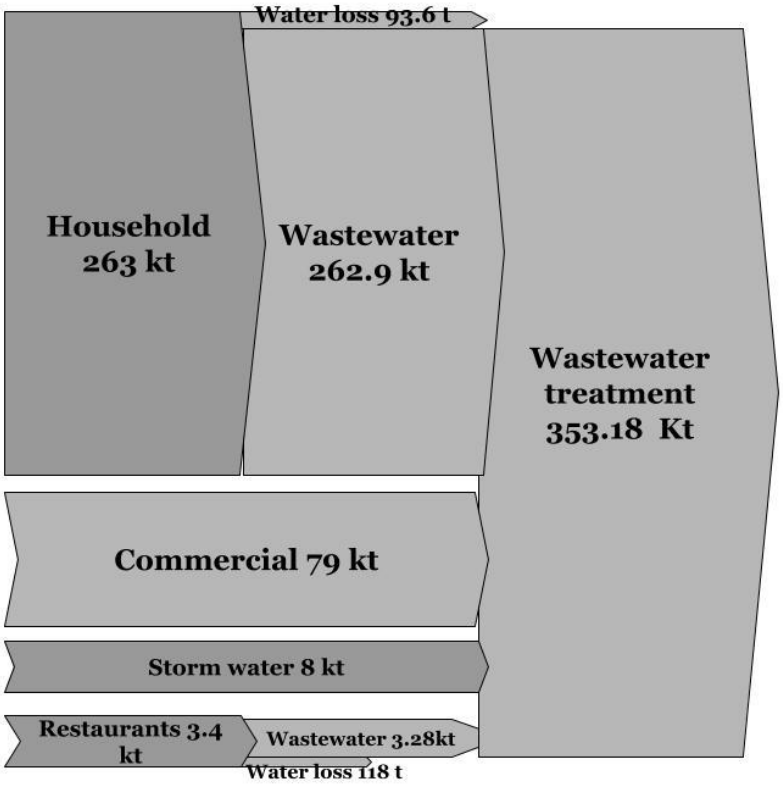

Fig.4.2. Water and wastewater flow in SRS

5. Discussion

5.1 Discussion of the results

MFA has focus on flows aiming to identify sectors with the most resources demands, while LCA estimate the potential environmental impacts within the resource life span (extraction, production, manufacture, use and end of life stages) (Kalmykova, et al., 2019). The application of the enhanced EW-MFA for small-scale urban areas provides deeper understanding of the area's infrastructure and metabolic material flow processes. Less aggregate material classification including throughput material flows provides detailed information about material flow origins and destinations that enable us to highlight the hotspots regarding material need within the system. And gain a better picture of material circularity within the socioeconomic system such as recovered materials and renewable energies extracted locally. In addition, with new detailed material classification comparison between urban areas is possible, revealing each city's unique characteristic impact on material use. Furthermore, the result can be transferred as an exemplary model for other new urban areas with similar economic, social, and environmental status, whereas MFA itself might need be combined with application of other method's result such as LCA to draw comprehensive conclusion regarding amending resource management.

Using bottom-up data provided detailed information regarding material flow in sectors where material was required more than other sectors due to the SRS metabolism in 2017. For instance, massive construction activities in the area resulted in experiencing increase in ''non-metallic minerals'' inputs to the socioeconomic system. On the other hand, new material classification provided detailed information regarding SRS strategic plans to not only reduce CO_2, but also save carbon underneath trees and absorbing CO_2 with investing on GSI projects.

Adding water and wastewater flows into the analysis, which resulted in adding considerable amounts of material flows, including stored stormwater and purified water within the socioeconomic system. Different strategies considering capturing storm, and surface water and recycling wastewater has increased understanding of the city's metabolism for water recycling and energy recovery from wastewater.
Some of these strategies in SRS are counted as below:

- GSI which refers to green structure of the buildings by building green country yards and roofs to avoid storm water run offs.
- Vacuum collection systems were installed in every buildings, restaurants, and commercial units to grinding waste foods in the sink and send them to the power plants for energy recovery purposes.
- Structured tree with biochar defines new structural tree plant that can ssequester CO_2 in the biochar underneath the tree plant and also capturing and save stormwater run offs from the surface inside the inlets where the supply of air and water to the tree happens

One of strategic plans for capturing storm water in the SRS is mentioned green buildings which refers to gardens on the roof and open areas to save the storm water runoffs as much as possible. Capturing and filtering storm water was highlighted by Wendling and Holt (2020) with using nature-based solutions (e.g. absorbing surface water by application of permeable pavements was assessed). This strategy is

implemented in SRS by planting trees with biochar bringing solution to capturing and filtering the surface water.

It is predicted by SRS roadmap that with the completion of the rest of residential areas (12 000 apartments) and commercial areas (more than 100 000 square meters) by 2030, water use will increase but at lower degree than the rest of Stockholm by performing the above mentioned strategic plans for reducing water consumption and increasing capturing and recycling water. The same result from adding water flows into the analysis of Amsterdam confirms the significant role of water and wastewater flows for enhancing understanding of city's metabolism (Voskamp, et al., 2017).

Locally generated renewable energies such as thermal and solar energies have increased the local renewable resources production rate that sustains the energy supply chain and lessens the environmental impacts. Nevertheless, LCA of renewable energy technologies in the local context that will consider production, installation, and maintenance processes is needed to distinguish pros and cons of these technologies and provide more accurate and comprehensive evaluation.

Involving internal material flows emphasized on recovered materials and locally produced renewable energies. Involving recovered materials from the construction sector, added considerable amounts of materials. Produced energy from wastewater and waste materials have also been responsible for most of the energy coverage. However, energy recovery from waste is associated with releasing uncontrolled toxic emissions that need to be monitored, for comparing waste fuels with fossil fuels regarding their environmental impacts (Virtanen, et al., 2019). Adding power plants data, added massive amounts of waste and CO_2 emissions to the result. Nevertheless, due to lack of detailed classification regarding powerplants energy resource origins, they mentioned separately in the result table and estimated bottom up data is preferred for the analysis process.

Analyzing buildings and road construction waste treatment methods or conversion of biogas derived from wastewater sludge shows to what extent SRS strategic plans help to reuse materials, recovers energy, and reduce the GHG emissions. Moreover, it prevails the roadmap for the future opportunities regarding increasing reuse, recycle and recover rates by explicating sourcing of recycled and secondary resources from internal waste treatment process. Developing this knowledge base helps to identify the share of material inputs and consumption of renewable and nonrenewable resources which ultimately provides deeper understanding of metabolic process in the system. The amount of material use in construction and waste statistics are not fully consistent to the mass balance principle because of each material unique durability and end of life within the system.

In SRS, the recorded recovered materials in the construction sector and their calculated share to GDP shows their noticeable contribution to economic growth. Choosing materials, product, and services considering their quality, efficiency, productivity, and recyclability could enhance the SRS circular economy. Moreover, spotting useable and recyclable materials in the system and studying the dynamics of material physical exchanges in the stock could enhance reusing and recycling considerably. These recovered materials in SRS includes mostly materials from construction and demolition activities such as rock, sand, and metals. Clarifying landfilled material fractions also could be beneficial for increasing recycling due to massive amounts of landfilled construction materials.

Household's waste data was available from different data sources. The comparison of the differences between the collected data allowed the fair and accurate analysis of SRS strategic plans for reducing waste production and increasing sorting waste materials (see Appendix B). However, quality of waste statistics needs to be improved. For instance, mixed waste production is reduced in the area compared to other

regions in the Stockholm, but due to its high amounts more data regarding waste fractions is needed for handling them better by proper sorting process and choosing the right waste treatment for each material than them using conventional methods such as incineration.

5.2 Validation of the results

Less aggregated material classification considering internal flows describes the city's characteristics and provides opportunity to compare detailed material flows with other urban areas. These comparisons can be exemplary for amending resource management (Hammer, et al., 2003; Rosado, et al., 2014). A comparison of the SRS aggregated results with other urban areas (Amsterdam, Vienna, and Hamburg) considering material share in GDP is considered for validating the result. The comparison presented in Table 5.1.

Table 5.1 Eurostat EW-MFA results for SRS, Amsterdam, Vienna, and Hamburg

Characteristics	SRS		Amsterdam	Vienna	Hamburg
Base year of study	2017		2012	2001	2003
Population	4800		790,000	1,726,0000	1,590,000
Land area	203 (km^2)		219 (km^2)	755 (km^2)	415 (km^2)
GDP (million euro)	290.56		56,912	70,994	56,728
Material flows	t	(t/GDP)	(t/GDP)	(t/GDP)	(t/GDP)
Inputs					
Total local extraction					
Biomass	-	-	0.4	2.1	3.8
Minerals	8000	27.50	-	-	1.8
Metal	-	-	-	-	-
Fossil fuel & fossil fuel products	-	-	-	0.4	-
Total Imports					
Biomass	4818	16.50	179	235	51
Non-metallic minerals	309839	1066.50	-	-	-
Total ores & industrial minerals	16633	57.25	222	352	132
Fossil fuel & fuel products	20594	70.89	844	294	153
Chemical products	1834	6.31	102	113	10
Other industry products	102	0.35	78	318	-
Other imports			20	104	98
Outputs					
Total exports					
Biomass & biomass products	-	-	177	217	32
Non-metallic minerals	7570	26.05	-	-	-
Total ores & industrial minerals	332	1.14	169	282	91
Fossil fuel & fossil fuel products	17546	60.39	745	183	89
Chemical products	-	-	35	146	17
Other industry products	-	-	74	295	-
Other exports			22	95	80
Physical balance					
Biomass & biomass products	4818	16.50	1.65	18	19
Non-metallic minerals	302269	1040.50	52.48	-	-
Total ores & industrial minerals	16301	56.11	98.50	70	41
Fossil fuel & fossil fuel products	3048	10.49	67.45	111	64
Chemical products	1834	6.31	5.86	-33	-7
Other industry products	102	0.35	-2.12	23	-
Other exports				9	18

Note: since modified material classification was not available for other cities, Eurostat material classification is used for comparison.

The above-mentioned data was taken from Voskamp, et al. (2017) who used the EW-MFA method for describing each cities material share to GDP and then compare them together. Reduction in fossil fuel

consumption in SRS by investing on renewable energies is noticeable, while consuming asphalt in the district was added considerable amounts of fossil fuel in the district temporarily. Whereas ‘’fossil fuel’’ stood at highest or one of the highest among other material inputs for other urban areas. On the other hand, construction related materials such as ‘’total ore & industrial minerals’’ and ‘’non-metallic’’ are consumed more in SRS, while other cities had different material consumptions based on their unique metabolisms. Voskamp, et al. (2017) explained that renewable energy generation is quite low in Amsterdam, particularly energy produced from ‘’biomass’’, but wind energy is relatively high. In Vienna energy sources depend on hydropower due to its access to infrastructure and natural resources (Voskamp, et al., 2017). Whereas in SRS solar and thermal energy from biofuel are the most common renewable sources and they are quite higher (11.7 GWh) than the estimated energy from fossil fuels (1.4 kt).

Studying UM through material flow shows each unique UM that can be defined by its location, extraction facilities and geographic accessibility. High construction activities in SRS such as excavation and demolition projects caused considerable increase in ‘’non-metallic’’ outputs compared to other materials. In Vienna, where industry stood at the center of the economic activities, most of the outputs were related to ‘’total ores’’ and ‘’industrial minerals and products’’ confirms the importance of these types of material for the Vienna’s economic growth. Physical balance calculation for SRS could not be done properly because of material’s output data gaps and lack of waste material fractions, while construction materials such as ‘’non-metallic minerals’’ and ‘’total ores’’ are expected to stand out from other types of material due to their high mass and versatility in the area.

5.3 Discussion of the method

Analyzing the material flows in a less aggregate classification provides key information revealing the UM and city’s characteristics influence on materials use. For instance, some temporary economic activity like developing the built environment cause an increase in specific types of material consumption. Another reason for increasing specific type of material is city’s economic activity dependency on specific material for maintaining economic growth, such as importing food products from other areas. Detailed material classification helps to extensively understand the relationship between economy and material flows. Nevertheless, since the method is still new more comparable data from other urban area needs to be investigated in the future for having full comparison between urban areas.

Adding water flows added a massive amount of materials into the analysis shows that the importance of freshwater consumption and wastewater production. Also studying different water resources and urban metabolism impacts on using specific water resource is necessary to understand water management in the urban area (e.g. most of the drinking water in SRS was supplied from surface water procurement process) (Stockholmvattenochavfall, 2018; Statistics Sweden, 2015).

Dematerialization in the socioeconomic system can be progressively increased by adding internal flows and improve the material productivity, efficiency, reproducibility, and ecological efficiency, etc. depending on the type of material and economic activity. The application of the enhanced EW-MFA has increased understanding of material value which consequently may reduce overproduction of primary resources. However, recycling itself may require new facilities and consume more energy than primary resource production that needs to be addressed (Geyer, et al., 2016; Krausmann, et al., 2017; Mayer, et al., 2019).

Both bottom-up and top-down data were taken from the literature, and it was found that bottom-up data is more reliable than top-down, as it is more detailed and could improve the analysis of UM, ultimately. Data gaps could partly overcome with the application of the mass balance principle, especially in the construction sector. Furthermore, fractions of disposed material in the construction sector need to be identified since most of them were reported as mixed waste or landfilled. Since excavated materials are

found in specific projects, more comprehensive data and fractions will be needed for a more accurate analysis of the district. Mass balance principle was taken for addressing data gaps considering the fact that SRS is a new built area and most of the material inputs were considered to be added to stock and in longer period of time, outputs can be specified.

Benchmarking SRS metabolism with other cities through the study of material flows is another important application of enhanced EW-MFA method. For instance, Amsterdam is known for product trade activities and SRS is considered as developing in building an environment under lots of construction activities. After completion of construction, the SRS district's performance is expected to be service-based following Stockholm characteristic as a bigger scale model. Enhancing understanding of UM as a part of application of performing enhanced EW-MFA method, is useful for amending city's interactions within and outside its administrative boundaries, directly and indirectly.

5.4 Recommendations for improving the method

Coupling EW-MFA method with other environmental decision-making tools could provide a more holistic view of each material. For example, combining LCA and EW-MFA is recommended, since the EW-MFA result can provide inventory for an LCA (Brunner & Rechberger, 2017). Moreover, life cycle thinking indicating environmental impacts of each material, product, and service from cradle to grave (extraction of raw materials to the residual of waste) is beneficial to enhance the EW-MFA model (Lavers, et al., 2017). Another example is combining this method with Material Flow Cost Accounting (MFCA) to evaluate the monetary value of each material (Westin, et al., 2019). The application of Physical Input and Output Tables (PIOT) is also important for calculating input, stock, and output indicators contribution to not only economic progress, but also reducing environmental impacts.

Identifying the location of countries where the export products are produced is important to avoid misleading information result from outsourcing of material, energy, and emission-intensive economic activities by high-income countries. Comprehensive material database indicating each material's resource origins in the future remarkably reveals environmental and social impacts of extracting material resource from their actual origins (e.g. environmental impacts depending on the location are varied such as deforestation, biodiversity loss, land-system change) (Krausmann, et al., 2017).

Data availability is still problematic in the data collection process, having a standard estimation and assumption for each sector can be beneficial for reducing errors and inaccuracy. Standard estimation can be prepared from the study of the similar material functionality in other urban areas to make an exemplary model applied for newly built areas. Using an exemplary model from previous EW-MFA results are useful to estimate general material classification, especially when no detailed data is available, such as mixed waste. The EW-MFA method is normally limited to have an empirical focus on annual flows of materials and energy. Working on the dynamic of the method to be expandable over time is recommended for the future.

A smart sustainable city is an innovative city using the application of information and communication technologies (ICTs) for providing quality of life and efficiency of urban operation and services. It ensures present and future needs by employing concepts such as dematerialization, demobilization, mass customization, intelligent operation, and soft transformation within the decision-making process (Cavada, et al., 2014). ICT-aided urban metabolism is the new concept which resulting in collecting high-resolution evaluation of data by completion, data reliability, validity and most importantly availability (Shahrokni, et al., 2015; Holmstedt, 2018; Hämäläinen, et al., 2020).

One of the challenges for the future is preparing information with employing new technologies and artificial intelligence (AI) to simulate the material flow model in order to specify spatial and temporal dynamics of resource flows based on its background and system's behavior. In this way we are able to locate where and when resources are present in the system (primary and secondary) which increasingly amend resource management system.

6. Conclusions

The extensive literature review that was conducted in this study showed that there is lack of a standardized method for material flow accounting in urban systems, and usually different studies have different focus on specific sectors, materials, products, and services, according to their aims. Therefore, this thesis applied the enhanced EW-MFA method considering throughput flows, water and wastewater flows for monitoring material flows, which could potentially become a basis for UM analysis in small-scale urban areas. The application of the enhanced EW-MFA for analyzing the UM in small-scale systems such as SRS, has the following strengths and limitations:

- Strengths
    - It can account for wastewater and water flows, which adds a considerable amount of materials into the analysis.
    - Bottom-up data collection approach brought detailed insight to the city's material flows.
    - Throughput flows consideration in the result helps to have better picture of intersectoral flows within the socioeconomic system.
    - It provides origin and destination of the material inputs.
    - Less aggregate material classification provides detailed information for each material.
    - Enhanced EW-MFA can be performed in different scale of urban areas.
- Limitations
    - Data availability, reliability, validity, and relevancy.
    - The need to normalise collected data units in order to being comparable.
    - Lack of comparable data for enhanced EW-MFA from other urban areas.

The data limitation could be overcome by using application of the mass balance principle. However, more detailed data in the waste sector will be needed for more accurate analysis in the future. For instance, mixed waste fractions need to be identified. The new material classification used in enhanced EW-MFA method is not common material classification for EW-MFA. Therefore, the EW-MFA Eurostat classification should be used for comparing and validating results.

The application of the modified EW-MFA in a small-scale urban area with its modification to include water flows, revealed the importance of water flows for a more comprehensive material flow analysis. Gaining in-depth and more complete knowledge about the SRS's metabolism and its strategic plans for resource management in different sectors, such as construction, waste, and water management etc., is part of the application of the enhanced EW-MFA. Because of different scales, full comparison between SRS and other urban areas was not possible. Nevertheless, the SRS approach towards material and energy use and recycling compared to Amsterdam, Hamburg and Vienna is assessed and revealed unique characteristics of each urban metabolisms. Internal flows assessment within the socioeconomic system boundary also emphasized the amount of energy, waste and water circulated within the system by being recycled, recovered, and reused. Assessing flows to nature in detail for each sector's emissions and wastes

and comparing them with material inputs in each sector or recovered energy and materials provided a holistic analysis of UM.

Most of the city's sustainable strategic plans contribute to a circular economy by closing the material loop activities such as reusing used materials, recycling secondary resources or energy recovery (e.g. waste fuel and biofuel). This approach is taken seriously and intensively in SRS by not only implementing green strategic plans in different sectors (waste collection, transportation, energy, and construction), but also shaping user's behavior toward sustainability in the future.

Choosing the right materials with right specification for developing the built environment is necessary for protecting the natural environment and avoiding heavy material transportations. Construction materials are heavier than other materials and normally hard to recycle. Therefore, replacing common construction materials, such as concrete and steel, with timber is recommended to avoid using environmentally destructive materials for developing the built environment in the future. Timber is not only renewable and efficiently absorbs carbon dioxide, but also requires less energy in production and has better insulation properties than steel.

Despite the fact of limitations, especially in data availability, still results provide a good information and the main purpose of studying the UM of SRS through the application of enhanced EW-MFA is achieved. The comparison of UM of the SRS with the UM of other urban areas revealed not only the importance role of SRS's strategic plans towards climate change mitigation, but also the importance of each city's characteristics toward its resource management. Dematerialization in different sectors, such as construction and waste management, can provide massive financial and environmental benefits for the socioeconomic system. More research for improving the availability and developing of the bottom-up data and collaboration between local actors and stakeholders is recommended for mitigating the limitations of this study in the future especially in the data collection process.

7. References

Augiseau, V. and Barles, S., 2017. Studying construction materials flows and stock: A review. *Resources, Conservation and Recycling*, *123*, pp.153-164.

Ayres, R.U. and Ayres, L.W., 1997. Use of materials balances to estimate aggregate waste generation in the United States. *Measures of environmental performance and ecosystem condition*, pp.96-156.

Bachner, G., 2017. Assessing the economy-wide effects of climate change adaptation options of land transport systems in Austria. *Regional Environmental Change*, *17*(3), pp.929-940.

Bahers, J.B., Barles, S. and Durand, M., 2019. Urban Metabolism of Intermediate Cities: The Material Flow Analysis, Hinterlands and the Logistics-Hub Function of Rennes and Le Mans (France). Journal of Industrial Ecology, 23(3), pp.686-698.

Bai, X., 2016. Eight energy and material flow characteristics of urban ecosystems. Ambio, 45(7), pp.819-830.

Barles, S., 2010. Society, energy, and materials: the contribution of urban metabolism studies to sustainable urban development issues. Journal of Environmental Planning and Management, 53(4), pp.439-455.

Bringezu, S., Schütz, H. and Moll, S., 2003. Rationale for and interpretation of economy-wide materials flow analysis and derived indicators. Journal of Industrial Ecology, 7(2), pp.43-64.

Browne, D., O'Regan, B. and Moles, R., 2009. Assessment of total urban metabolism and metabolic inefficiency in an Irish city-region. Waste Management, 29(10), pp.2765-2771.

Browne, D., O'Regan, B. and Moles, R., 2011. Material flow accounting in an Irish city-region 1992–2002. Journal of Cleaner Production, 19(9-10), pp.967-976.

Brunner, P.H. and Rechberger, H., 2016. *Practical handbook of material flow analysis* (Vol. 1). CRC press.

Buyle, M., Braet, J. and Audenaert, A., 2013. Life cycle assessment in the construction sector: A review. *Renewable and sustainable energy reviews*, *26*, pp.379-388.

Cavada, M., Hunt, D.V. and Rogers, C.D., 2014, November. Smart cities: Contradicting definitions and unclear measures. In *World Sustainability Forum*, pp. 1-12).

Conversion of units, 2020. [online]
Available at: https://ec.europa.eu/energy/en/content/housing-space-person
[Accessed 15 April 2020].

Converting energy unit to mass unit, 2020 [online]
Available at: https://www.convertunits.com/from/MWh/to/tonne+of+oil+equivalent
[Accessed 15 May 2020].

Decker, E.H., Elliott, S., Smith, F.A., Blake, D.R. and Rowland, F.S., 2000. Energy and material flow through the urban ecosystem. Annual review of energy and the environment, 25(1), pp.685-740.
Deetman, S., Marinova, S., van der Voet, E., van Vuuren, D.P., Edelenbosch, O. and Heijungs, R., 2020. Modelling global material stocks and flows for residential and service sector buildings towards 2050. *Journal of Cleaner Production*, *245*, p.118-658.

Dhar, S. and Marpaung, C.O., 2015. Technology priorities for transport in Asia: assessment of economy-wide CO 2 emissions reduction for Lebanon. *Climatic change*, *131*(3), pp.451-464.

Dos Muchangos, L.S., Tokai, A. and Hanashima, A., 2017. Application of material flow analysis to municipal solid waste in Maputo City, Mozambique. Waste Management & Research, 35(3), pp.253-266.

Eurostat. 2001. *Economy-wide material flow accounts and derived indicators: A methodological guide*. Luxembourg: Eurostat, European Commission, Office for Official Publications of the European Communities.

Eurostat, 2018. Economy-wide material flow accounts handbook.

Eurostat, 2008c. *Glossary: Statistical classification of products by activity (CPA).* [Online]
Available at:
http://ec.europa.eu/eurostat/statisticsexplained/index.php/Glossary:Statistical_classification_of_products_by_activity_(CPA)
[Accessed 14 April 2020].

Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H. and Weisz, H., 2011. Methodology and indicators of economy-wide material flow accounting: State of the art and reliability across sources. Journal of Industrial Ecology, 15(6), pp.855-876.

Geng, Y., Fu, J., Sarkis, J. and Xue, B., 2012. Towards a national circular economy indicator system in China: an evaluation and critical analysis. *Journal of cleaner production*, *23*(1), pp.216-224.

Gerland, P., Raftery, A.E., Ševčíková, H., Li, N., Gu, D., Spoorenberg, T., Alkema, L., Fosdick, B.K., Chunn, J., Lalic, N. and Bay, G., 2014. World population stabilization unlikely this century. Science, 346(6206), pp.234-237.

Geyer, R., Kuczenski, B., Zink, T. and Henderson, A., 2016. Common misconceptions about recycling. *Journal of Industrial Ecology*, *20*(5), pp.1010-1017.

Graedel, T.E. and Allenby, B.R., 2010. *Industrial Ecology and Sustainable Engineering: International Edition* (p. 425). Pearson Education Inc., Upper Saddle River, Prentice Hall.

Haberl, H., Wiedenhofer, D., Erb, K.H., Görg, C. and Krausmann, F., 2017. The material stock–flow–service nexus: A new approach for tackling the decoupling conundrum. Sustainability, 9(7), p.1049.

Hämäläinen, M., 2020. A Framework for a Smart City Design: Digital Transformation in the Helsinki Smart City. In *Entrepreneurship and the Community* (pp. 63-86).

Hammer, M., Giljum, S. and Hinterberger, F., 2003, October. Material flow analysis of the City of Hamburg. In workshop Quo vadis MFA.
Hoffrén, J., Apajalahti, E.L. and Rättö, H., 2009. Pilot Study on Economy-wide Material Flow Accounting (MFA) with Hidden Flows in Finland.

Holmstedt, L., 2018. Evaluation of Sustainable Urban District Developments: The Case of Stockholm Royal Seaport (Doctoral dissertation, KTH Royal Institute of Technology).

Holmstedt, L., Brandt, N. and Robèrt, K.H., 2017. Can Stockholm Royal Seaport be part of the puzzle towards global sustainability? –From local to global sustainability using the same set of criteria. Journal of Cleaner Production, 140, pp.72-80.

Holmstedt, L., Shahrokni, H. and Brandt, N., 2018. How to Evaluate Sustainable Urban District Developments.

Horta, I.M. and Keirstead, J., 2017. Downscaling aggregate urban metabolism accounts to local districts. *Journal of Industrial Ecology*, *21*(2), pp.294-306.

Huang, S.Y., Chiu, A.A., Chao, P.C. and Wang, N., 2019. The Application of Material Flow Cost Accounting in Waste Reduction. *Sustainability*, *11*(5), p.1270.

Huang, C.L., Vause, J., Ma, H.W. and Yu, C.P., 2013. Urban water metabolism efficiency assessment: Integrated analysis of available and virtual water. *Science of the Total Environment*, *452*, pp.19-27.

Jacobi, N., Haas, W., Wiedenhofer, D. and Mayer, A., 2018. Providing an economy-wide monitoring framework for the circular economy in Austria: status quo and challenges. *Resources, Conservation and Recycling*, *137*, pp.156-166.

Jeong, S. and Park, J., 2020. Evaluating urban water management using a water metabolism framework: A comparative analysis of three regions in Korea. *Resources, Conservation and Recycling*.

Johansson, S., Shahrokni, H., Kristinsdóttir, A.R. and Brandt, N., 2015. Summary of the Business-as-Usual and Green Development Greenhouse Gas Baselines and Roadmaps for the Stockholm Royal Seaport in Accordance with the Methodology Supplied by the Clinton Climate Initiative.

Kalmykova, Y., Rosado, L. and Patrício, J., 2015. Urban economies resource productivity and decoupling: metabolism trends of 1996–2011 in Sweden, Stockholm, and Gothenburg. Environmental science & technology, 49(14), pp.8815-8823.

Kalmykova, Y., Rosado, L. and Patrício, J., 2016. Resource consumption drivers and pathways to reduction: economy, policy, and lifestyle impact on material flows at the national and urban scale. Journal of Cleaner Production, 132, pp.70-80.

Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z. and Djurovic-Petrovic, M., 2010. A review of bottom-up building stock models for energy consumption in the residential sector. *Building and environment*, *45*(7), pp.1683-1697.

Kennedy, C., Cuddihy, J. and Engel-Yan, J., 2007. The changing metabolism of cities. Journal of industrial ecology, 11(2), pp.43-59.

Kennedy, C., Pincetl, S. and Bunje, P., 2011. The study of urban metabolism and its applications to urban planning and design. Environmental pollution, 159(8-9), pp.1965-1973.

Kovanda, J., 2019. Use of physical supply and use tables for calculation of economy-wide material flow indicators. *Journal of Industrial Ecology*, *23*(4), pp.893-905.

Kovanda, J., van de Sand, I., Schütz, H. and Bringezu, S., 2012. Economy-wide material flow indicators: Overall framework, purposes and uses and comparison of material use and resource intensity of the Czech Republic, Germany, and the EU-15. *Ecological Indicators*, *17*, pp.88-98.

Krausmann, F., Schandl, H., Eisenmenger, N., Giljum, S. and Jackson, T., 2017. Material flow accounting: measuring global material use for sustainable development. *Annual Review of Environment and Resources*, *42*, pp.647-675.

Laner, D., Feketitsch, J., Rechberger, H. and Fellner, J., 2016. A novel approach to characterize data uncertainty in material flow analysis and its application to plastics flows in Austria. *Journal of industrial ecology*, *20*(5), pp.1050-1063.

Lavers, A., Kalmykova, Y., Rosado, L., Oliveira, F. and Laurenti, R., 2017. Selecting representative products for quantifying environmental impacts of consumption in urban areas. *Journal of Cleaner Production*, 62, pp.34-44.

Liu, M., Tan, S., Zhang, M., He, G., Chen, Z., Fu, Z. and Luan, C., 2020. Waste paper recycling decision system based on material flow analysis and life cycle assessment: A case study of waste paper recycling from China. *Journal of Environmental Management*, *255*, p.109859.

Li, M., Zhang, H., Li, Z. and Tong, L., 2010. Economy-wide material input/output and dematerialization analysis of Jilin Province (China). *Environmental monitoring and assessment*, *165*(1-4), pp.263-274.
Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P. and Blengini, G.A., 2019. Measuring progress towards a circular economy: a monitoring framework for economy-wide material loop closing in the EU28. Journal of industrial ecology, 23(1), pp.62-76.

Miatto, A., Schandl, H., Wiedenhofer, D., Krausmann, F. and Tanikawa, H., 2017. Modeling material flows and stocks of the road network in the United States 1905–2015. *Resources, Conservation and Recycling*, *127*, pp.168-178.

Migliore, M., Talamo, C. and Paganin, G., 2020. Construction and Demolition Waste. In *Strategies for Circular Economy and Cross-sectoral Exchanges for Sustainable Building Products* (pp. 45-76).

Moll, S. and Watson, D., 2009. Environmental Pressures from European Consumption and Production. A study in integrated environmental and economic analysis, ETC. SCP working paper 1.
Moriguchi, Y. and Hashimoto, S., 2016. Material flow analysis and waste management. In *Taking stock of industrial ecology* (pp. 247-262).

Moriguchi, Y., 2007. Material flow indicators to measure progress toward a sound material-cycle society. *Journal of Material Cycles and Waste Management*, *9*(2), pp.112-120.
Mostafavi, N., Farzinmoghadam, M., Hoque, S. and Weil, B., 2014. Integrated urban metabolism analysis tool (IUMAT). Urban policy and Research, 32(1), pp.53-69.

Mulalic, I., 2005. Economy-wide Material Flow Accounts for Denmark.

Müller, E., Hilty, L.M., Widmer, R., Schluep, M. and Faulstich, M., 2014. Modeling metal stocks and flows: a review of dynamic material flow analysis methods. Environmental science & technology, 48(4), pp.2102-2113.

National Research Council, 2004. *Materials count: The case for material flows analysis*. National Academies Press.

Newman, P.W., 1999. Sustainability and cities: extending the metabolism model. Landscape and urban planning, 44(4), pp.219-226.

Niza, S., Rosado, L. and Ferrao, P., 2009. Urban metabolism: Methodological advances in urban material flow accounting based on the Lisbon case study. Journal of Industrial Ecology, 13(3), pp.384-405.

Papageorgiou, A., Sinha, R., Frostell, B. and Sundberg, C., 2019. A new physical accounting model for material flows in urban systems with application to the Stockholm Royal Seaport District. Journal of Industrial Ecology.

Patrício, J., Kalmykova, Y., Rosado, L. and Lisovskaja, V., 2015. Uncertainty in material flow analysis indicators at different spatial levels. *Journal of Industrial Ecology*, *19*(5), pp.837-852.

Pearlmutter, D., Theochari, D., Nehls, T., Pinho, P., Piro, P., Korolova, A., Papaefthimiou, S., Mateo, M.C.G., Calheiros, C., Zluwa, I. and Pitha, U., 2020. Enhancing the circular economy with nature-based solutions in the built urban environment: green building materials, systems and sites. *Blue-Green Systems*, *2*(1), pp.46-72.

Petrol unit convertor, 2020 [online]
Available at: https://www.thecalculatorsite.com/conversions/substances/oil.php
[Accessed 1 June 2020].

Ranhagen, U. and Frostell, B., 2014. Eco-cycle model 2.0. for Stockholm royal seaport city district: Feasibility study-final report. KTH Royal Institute of Technology.

Renouf, M.A., Serrao-Neumann, S., Kenway, S.J., Morgan, E.A. and Choy, D.L., 2017. Urban water metabolism indicators derived from a water mass balance–Bridging the gap between visions and performance assessment of urban water resource management. *Water research*, *122*, pp.669-677.

Rosado, L., Kalmykova, Y. and Patrício, J., 2016. Urban metabolism profiles. An empirical analysis of the material flow characteristics of three metropolitan areas in Sweden. Journal of Cleaner Production, 126, pp.206-217.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J. and Nykvist, B., 2009. Planetary boundaries: exploring the safe operating space for humanity. *Ecology and society*, *14*(2).

Rosado, L., Niza, S. and Ferrao, P., 2014. A material flow accounting case study of the Lisbon metropolitan area using the urban metabolism analyst model. Journal of Industrial Ecology, 18(1), pp.84-101.

Schandl, H. and Miatto, A., 2018. On the importance of linking inputs and outputs in material flow accounts. The Weight of Nations report revisited. *Journal of cleaner production*, *204*, pp.334-343.
Schiller, G., Gruhler, K. and Ortlepp, R., 2017. Quantification of anthropogenic metabolism using spatially differentiated continuous MFA. *Change and Adaptation in Socio-Ecological Systems*, *3*(1), pp.119-132.

Schütz, H., Moll, S. and Bringezu, S., 2004. Globalisation and the shifting environmental burden: material trade flows of the European Union.

Shahrokni, H., Årman, L., Lazarevic, D., Nilsson, A. and Brandt, N., 2015. Implementing smart urban metabolism in the Stockholm Royal Seaport: Smart city SRS. Journal of Industrial Ecology, 19(5), pp.917-929.

Shahrokni, H., Lazarevic, D. and Brandt, N., 2015. Smart urban metabolism: Towards a real-time understanding of the energy and material flows of a city and its citizens. *Journal of Urban Technology*, *22*(1), pp.65-86.

Stad, S., 2017. *Stockholm Royal Seaport Road Map-The Journey Has Begun*. Version 2017-09-27.

Stec, A., 2020. The Impact of Rainwater Harvesting on a Drainage System and a Catchment. In *Sustainable Water Management in Buildings* (pp. 131-139). Springer, Cham.

Stockholm population and statistics, 2018. [online]
Available at : https://www.macrotrends.net/cities/22597/stockholm/population
[Accessed 15 April 2020].

Sweden population & economy statistics, 2019. [online]
Available at: https://www.ceicdata.com/en/sweden/population-and-urbanization-statistics/se-population-density-people-per-square-km
[Accessed 25 May 2020].

Van Berkel, R., Fujita, T., Hashimoto, S. and Geng, Y., 2009. Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006. *Journal of Environmental Management*, *90*(3), pp.1544-1556.

Vignani, D., 2012, April. Efficiency in the use of natural non-renewable resources from mining and quarrying in Italy. Time series analysis and Economy-wide Material Flows Accounts. In *46TH SCIENTIFIC MEETING OF THE ITALIAN STATISTICAL SOCIETY*.

Virtanen, M., Manskinen, K., Uusitalo, V., Syvänne, J. and Cura, K., 2019. Regional material flow tools to promote circular economy. *Journal of Cleaner Production*, *235*, pp.1020-1025.

Voskamp, I.M., Stremke, S., Spiller, M., Perrotti, D., van der Hoek, J.P. and Rijnaarts, H.H., 2017. Enhanced performance of the Eurostat method for comprehensive assessment of urban metabolism: a material flow analysis of Amsterdam. Journal of Industrial Ecology, 21(4), pp.887-902.

Wang, Z., Lv, J., Gu, F., Yang, J. and Guo, J., 2020. Environmental and economic performance of an integrated municipal solid waste treatment: A Chinese case study. *Science of The Total Environment*, *709*, p.136096.

Wein Vienna statistics, 2018. [online]
Available at: https://www.wien.gv.at/english/administration/statistics/vienna-in-figures.html
[Accessed 25 February 2020].

Wendling, L.A. and Holt, E.E., 2020. Integrating engineered and nature-based solutions for urban stormwater management. In *Women in Water Quality* (pp. 23-46).

Westin, A.L., Kalmykova, Y., Rosado, L., Oliveira, F., Laurenti, R. and Rydberg, T., 2019. Combining material flow analysis with life cycle assessment to identify environmental hotspots of urban consumption. *Journal of cleaner production*, *226*, pp.526-539.

Westöö, A. & C. Jensen. 2018. Matavfall i Sverige. Naturvårdsverket. Retrieved from
Wiedenhofer, D., Fishman, T., Lauk, C., Haas, W. and Krausmann, F., 2019. Integrating material stock dynamics into economy-wide material flow accounting: concepts, modelling, and global application for 1900–2050. *Ecological economics*, *156*, pp.121-133.

Wolman, A., 1965. The metabolism of cities. Scientific American 213 (3), 179e190.
World population review, 2017. [online]
Available at: http://worldpopulationreview.com/world-cities/stockholm-population/
[Accessed 12 March 2020].

World Commission on Environment and Development and Brundtland, G.H., 1987. *Presentation of the Report of the World Commission on Environment and Development to the Commission of the European Communities, the EC and EFTA Countries... 5 May 1987, Brussels*. World Commission on Environment and Development.

Zhang, Y., Liu, H., &Chen, B. (2013). Comprehensive evaluation of the structural characteristics of an urban metabolic system: Model development and a case.

Zhang, Y., Yang, Z. and Yu, X., 2009. Evaluation of urban metabolism based on emergy synthesis: A case study for Beijing (China). Ecological modelling, 220(13-14), pp.1690-1696.

8. Appendix A: Material classification

The material classification inspired by mix of classification used in a report by Voskamp et al. (2016) and 2nd level of Statistical classification of economic activities in the European Community (CPA) used by Papageorgiou et al. (2019). Since, the 3rd level CPA was used by Papageorgiou, et al., (2019) aggregated data was adjusted and considered for this study. Some of classifications were not considered because of not being applied for this study system boundaries such as ''Products of agriculture", ''Mining & quarrying", etc. In the following table, the classification of products is explained.

Table A 1. Classification of materials

1st level	2nd level	3rd level
Manufactured products		
	Food products	
		Crops
		Plants & animal products
	Beverages	
	Tobacco	
	Textile	
	Wearing apparel	
	Leather products	
	Wood and products of wood, cork, and furniture	
	Paper and paper products	
	Chemical & Chemical products	
	Rubber & plastic products	
	Other non-metallic	
		Article of concrete
		Clay
		Glass
		Cement, lime, and plaster
		Rock
	Basic metals	
	Fabricated metal products	
Natural water		
	Drinking water	
	Commercial waster	
Secondary materials		
	Metal	
	Non-metallic raw materials	

Table A 1. (continued).

Classification of natural inputs	
Mineral & energy resources	
	Solid & liquid fuel
	Waste fuel
	Solar energy
	Thermal
	Oil resources
Inland water resources	
	Surface water
	Storm water
Other water resources	Perspiration
Classification of residuals	
Solid waste	
	Household waste
	Mixed household waste
	Commercial waste
	Construction waste
	Recyclable
	Landfilled
	Food waste
	Sludge
Wastewater	
	Wastewater from households
	Wastewater from restaurants
	Stormwater
Air emissions	
	Carbon dioxide (CO_2)
	Dinitrogen oxide (N_2O_2)
	Sulphur dioxide (Sox)
	Nitrous oxide (Nox)
	Ammonia (NH_3)
	Dust

8.2 Appendix B: Description of the data collection process

Waste and emission full material flow data collection are brought in detail as below, due to varied data from different sources for the same category, all used sources and extracted data specifically from each source is mentioned as below. Some of big differences were expected due to different data collection methodologies.

Table B.1. Detailed material outputs (waste and emissions) mentioning the sources

	Export		(kt)	
Waste		Inputs	Internal flows	Exports
	Frihamnen			
	To be landfilled	-	-	50.0
	To be recovered	-	-	50.0
	Gasklockan demolition			
	Metal	-	-	1.80
	Hazardous waste to landfill			0.37
	Demolition Gasverksvägen Hjorthagsgaraget			
	Rock			18.0
	Norra Djurgårdsstaden			
	Rock & shaft recycled	-	-	600
	Local waste treatment			
Municipal solid waste				
	Household waste (Sustainability report)	-	-	0.54
	Household waste (Estimated from available data for Norra1)	-	-	0.51
	Household waste (Matfall Naturvårdsverket)	-	-	0.47
	Household waste (Stockholmvattenochavfall)	-	-	2.99
	Commercial waste (Matfall Naturvårdsverket)	-	-	0.11
	Commercial waste(powerplants)	-	-	0.45
	Chemical waste	-	-	0.016
	Construction waste (Recovered)	-	41.5	-
	Construction waste (Energy recovery)	-	3.21	- -
	Vacuum collection system (paper & plastics)	-	-	0.13
	Vacuum collection system (estimated)	-	-	0.56
	Waste room (roadmap)	-	-	1.34
	Waste room(estimated)	-	-	0.42
	Waste room(årsbok)	-	-	0.26
	Mixed waste (roadmap)	-	-	1.89
	Recycled (estimated)	-	-	0.35
	Recycled(årsbok)	-	-	0.25
	Recycled (power plants)	-	-	9.20
	Landfilled (construction open space)	-	-	4.52
	Landfilled (remediation estimated)	-	-	1.55
	Bulky waste (roadmap)	-	-	0.80
	Dry matter of wastewater (estimated)	-	-	1.20

Table B.1. (continued).

Flow to nature				
Emission to air				
	CO_2 total (Residential)	-	-	10.58
	CO_2 total (Construction)	-	-	7.03
	CO_2 total (Transportation Stockholm stad)	-	-	1082
	CO_2 total (power plants)	-	-	1903
	CO_2 total (årsbok)	-	-	1956
	Nox	-	-	0.24
	N_2O_2	-	-	0.11
	Sox	-	-	0.05
	CL_2, HCL inorganic	-	-	0.01
	NH_3	-	-	0.0006
	Dust	-	-	0.001

Construction waste from projects (Frihamnen & *Norra Djurgårdsstaden*) was briefly mentioned, while they did not count in the result table due to their ambiguous locations and the period of extractions. Different data was found for municipal solid wastes from different sources considering hotspots in waste management and bottom-up data was preferred in this thesis. Therefore, data from the SRS sustainability report and roadmap (2017) was considered as a basis of data collection for the final result table , while other collected data from other sources helped to compare SRS with its upper scale (Stockholm) for analyzing the SRS strategic plan outcomes in the waste management sector.

CO_2 for residential area was estimated from taken from available data for SRS roadmap (2017) baseline CO_2 emissions data for heating, cooling and electricity for buildings, transportation, good and services and maintenance. However, CO_2 data for construction sector was only available for concrete, steel and asphalt for Norra 1, therefore collected data was adjusted considering proper proxies corresponding to this study system boundaries. Top-down CO_2 emissions data was also available for Stockholm and power plants located in the SRS district that due to bottom-up data preference for this study, they are just mentioned above and excluded from result table. Other emissions data like Nox and N_2O_2 was taken from available data from Naturvardsverket.

During the data collection process in different sectors, there are sources with high influence on material aggregation such as powerplants and energy supply company. Table B.2. shows a complete emission list provided by Naturvardsverket for the two power plants located in Hjorthagen (Västaverket & Giggen) in tonnes for 2017.

Table B.2. Emissions originated from power plants located in SRS

Emissions Värtaverket & Giggen tonne (Naturvardsverket)	Tonnes
CO_2 total	1903597,15
CO_2 biogenic	1419494
CO_2 fossil	448970,15
NOx	243.7
N_2O	111,78
SO_2	53,22
Cl 2, HCL inorganic	9,55
Dust	1,825
NH_3	0,61
CH_4	26,6

Construction municipal solid waste

Excavation and remediation activities in the area are inevitable since the area is under construction. Some of the excavated materials were reused directly within the system such as a 26,70 kt rock in Norra2 and some of them were sent to the landfill or exported outside the SRS district for further treatment process. In order to avoid missing consideration of landfill and recovered materials in the construction sector, the SRS Sustainability Report, (2017) for construction waste data was preferred than specific project's construction waste. However, energy recovery from Norra 2 and Västra was reported higher than public open space but due to data gaps could not be considered in the final result table.

Excavated materials from construction activities in total in 2017 mentioned 49 kt from open public spaces which except 13,84 kt that were reused, the rest were treated considering construction waste and disposal percentages (77.41% material recovery,12.79% landfill, 9.08% energy recovery and 0.72% reuse) (Stockholm Stad, 2017). Waste exports referred to demolition for the specific projects and because of materials such as rock and shaft being extracted from the area and are sent to be landfilled or recycled as unused extraction outside the district. Therefore, no imports allocated and just exports mentioned in the final result table. Former studies recommended considering (2 %) of construction materials as outputs which was taken into consideration for calculating outputs in this sector (Papageorgiou, et al., 2018).

Household & Restaurants waste

Different data was available corresponding to household, commercial and total waste production per capita from Food Waste Agency in Sweden (Matavfall) and Stockholm Food and Waste Organization (Stockholmvattenochavfal). However, the SRS Sustainability Report (2017) was preferred. It reported 215 kg household waste is assumed to be produced per apartment per year which is counted as a basis of household waste calculation. Paper and plastic waste collected with vacuum collection system was mentioned separately in the result table for emphasizing on the new collection system impacts, while the amount is already counted in recycled waste. Food waste, paper and plastic collected from the vacuum collection system and collected waste from the waste room, commercial and mixed waste also were considered without further categorization due to data gaps regarding waste material fractions.

Restaurant food waste was assumed to be added into collecting waste with considering vacuum collection data since all restaurants and households were equipped with in-sink grinder (Stockholm Municipality officials). Estimated waste in the SRS roadmap for waste room was preferred (the estimation based on Norra 1), because of its accuracy. Commercial and recycled waste from power plants were just mentioned in the result table but was excluded from analysis.

Vacuum collection system

The vacuum collection system has been installed by a company called Envac crossing 236 hectares and ranging from Hjorthagen in the north to Loudden in the south. Not only is collecting grinded food waste from households and restaurants but also collecting papers, glass and street litter are included. This new method removes conventional waste loading waste trucks transportation causing GHG emissions reduction. In the SRS, the new waste collection system was installed for 6000 residential units plus stationery collections for paper, plastic, and street litter, and over 400 more inlets are planned to be installed by 2027. The new vacuum collection system has lots of environmental benefits such as reducing waste collection lorry by 90%, using green fuels to run the vacuum collection system, increasing biofuel production, and increasing reuse and recycling materials etc. Table B.3 shows the recycling material percentage difference between SRS and rest of Stockholm highlighting the SRS strategic waste management plans such as vacuum collection system. This new system has been collected 32.8 kg paper and 20 kg plastics per apartment considering Norra 1 and Norra 2 districts, in addition 116 kg residual collected waste per capita was reported by Stockholm City's inventory.

Table B 3. Waste comparison between Stockholm Royal Seaport and rest of the Stockholm

	SRS	Rest of Stockholm
Food waste	22.6%	30%
Packaging	30%	30.9%
Hazardous waste	0.06%	0.11
Purity for the newspaper and recycled paper fraction	91.5%	

Source: SRS sustainability report, (2017)

Energy

Energy supply source ratio described as (Solid & Liquid fuel 39%, Waste fuel 27%, Fossil fuel 11%, Electricity 11%, Waste energy from wastewater 7%, Waste energy from seawater 4%, Waste energy recovery from district heating 1%) (Exergi sustainability report, 2017). Bottom-up data was used from the SRS Sustainability Report, (2017), demanded energy for hot water and heat considered 47 kWh/ m^2 and for electricity 8 kWh/ m^2, which is corresponding to this study's system boundaries. Whereas the city's aim is to reduce this amount to 45 kWh/ m^2/year (=20 for hot water, 18 for heating and 7 for operational electricity) in the future.

Total SRS completed areas including households and commercial areas were 203825 square meters, Energimyndigheten and SCB released energy indicators for 2016 and based on total energy use considering hot water, and other electricity usage in Sweden calculated as mentioned below:

Table B.4. National energy consumption data per square meters

Total energy use (2015)	kWh/ m^2
Total energy usage, one and two dwelling buildings	156
Total energy use, multi-dwelling buildings	221
Total energy usage, non-residential premises	258
Average	211.667

These are top-down data extracted from a national based data source, while SRS started with 110 kWh/ m^2 and had decreased the amount of total demanded energy to 80 kWh/ m^2 as Stockholm Royal Seaport reported for 2016. In the new buildings total energy had been reduced by 55 kWh/ m^2 which claimed to be lower than current National Building Code.

The SRS Report in 2017, measured energy consumption for Norra2 and Brofästet 55 kWh/ m^2, and 69 kWh/ m^2 and 41 kWh/ m^2 for Norra1 and Västra respectively. On average 55 kWh/ m^2 was consumed in 2016 which is lower than Swedish building code (BBR). Wastewater heat is planned to be added to the system in case of extra demanded energy emergency. Locally generated energy from solar panels, photovoltaics, solar thermal energy, and hydropower estimated as solar PVs (2 kWh/ m^2) and solar heat (6 kWh/ m^2) for Norra1 and Västra (Holmstedt, L. et al. 2018). Energy needed for construction is reported less than 4000 kWh per office and less than 5000 kWh per worker in a year in 2017. There are other energy consumptions in the area which were considered like road and street lights, water management, consumed energy for energy supply and recovered energy from biogas combustion (120 kWh/person) (SRS roadmap, 2017).

Consumed energy in transportation in the form of fuels is counted as one of the biggest sectors, for allocating energy, therefore bottom-up data originating from dependent variables such as type of car and fuel base, number of trips per day and average distance of each trip all are assumed and calculated based on this study spatial and temporal boundaries. Some of the assumptions were taken from the Swedish Transport Analysis (Trafikanalys) regarding the number of cars running on specific types of fuel. It is assumed that most of the workers and residents' cars run with diesel and gasoline, while public transportation was planned to be replaced with more renewable and green fuels such as electric and biofuel-based buses in the SRS area. Number of cars with different fuels was assumed based on available data for Stockholm and average distance and number of trips were taken from Papageorgiou et al. (2018). The number of trips is assumed 2 trips per day and 2 km distance each trip in the area. Number of cars was taken based on Norra 1 and was expanded to the occupied residential area till 2017, plus gasoline and diesel fuel consumption calculated based on Trafiksverket (Swedish Traffic Agency).

The units are normalized for gasoline and diesel from liter to ton by following reliable sources such as Convertunits, (2020), Thecalculatorsite, (2020) equivalence ratio (1 liter gasoline = 0.78 kg, 1 liter Diesel = 0.83 kg) and for energy supply MWh equivalence equation (1MWh = 0.086 tonnes of oil) were considered.

Table B.5. shows energy estimation for the district and their supply sources (Exergi, 2017). Energy data was taken from baseline data (SRS roadmap, 2017).

Table B.5. Electricity resource allocations based on exergi reported fractions

	MWh	Total needed energy	
Electricity	1630,6	13132.37	
Wastewater management	1166		
Heat and cold	9579,77		
Road & Street lights	756		
Biogas combustion		577	
Total needed energy		13132.37	
Energy supply sources			MWh
		Solid & liquid fuel (39%)	5122
		Waste fuel (27%)	3546
		Fossil fuel (11%)	1445
		Electricity (11%)	1445
		Other Waste energies (11%)	1445

Data from energy company in SRS shows increase in waste and biofuels, while the fossil fuel-based fuels has been reduced from 2018 to 2019.

Table B.6. Exergi (energy company located in Norra Djurgårdsstaden) released in detail information regarding energy supplies for year 2018 and 2019

Input in own operation		2018	2019
Renewable & recycled fuels			
	Waste fuels (tonne)	859772	877207
	Liquid fuels (Nm^3)	54571	45586
	Solid biofuels (tonne)	1115064	1155659
	Biogas (Nm^3)	0	0
	Fossil fuels		
	Coal (tonne)	187074	111883
	Fossil oil (Nm^3)	35143	24372
	Urban gas (Nm^3)	0	0
	Additives and chemical (tonnes)	47371	42470

Source: Exergi, Sustainability report 2019

Water

Most of the water demands are assumed to be supplied by recycling and surface water collected from treatment plants called Löveverket and Norsborgs Vattenverk located around 20 km far away on the west side of Stockholm. Around 90% of used water is predicted to be recycled from sewage system water collection, which is connected to the street drainage and vacuum collection system to maximize the water recycling flow. SRS Sustainability Report, (2017) explained 7800 m^3 water was purified from wastewater treatment plants plus 8000 m^3 stored storm water runoffs. Water and wastewater flow data from water intake to wastewater from each restaurant was inspired by Papageorgiou et al. (2018) water flow data collection.

Reviewing top-down data from statistic in Sweden (SCB) shows people with a freshwater connection, each consume 157 liter of water per day and in Statistical yearbook for Stockholm (Årsbok, 2019) this amount reported 283 liter per day for each person in 2017. The SRS road map detailed water consumption by 150-liter household use and 45-liter commercial use, therefore 195 liter per person per day, including restaurant water use are considered for freshwater consumption adjusted to the estimated population by 2017. Result of wastewater per person from the household shows (150 L/person/day), whereas for wastewater calculation wastewater from commercial areas and restaurants also needs to be considered (377 t wastewater assumed to be exported per restaurant and there are 9 restaurants in the area, and 1034 L/day average water consumption, 302 L/day out of total 1034 L/day referred to cooking considered as internal flows). Water find in food products such as meat, fish, fruit, dairy products, etc. was considered for calculation of water in food (Papageorgiou, et al., 2018).

Statistics yearbook for Stockholm (2019)

Table B.7. shows water consumption in Stockholm in total, per day and per person reported from water treatment plants called Löveverket and Norsborgs Vattenverk where around 20km far away on the westside of Stockholm.

Table B.7. Water consumption in Stockholm supplied by Norsborg and Lovöverket from 2000 to 2017 per capita

Water consumption etc	2000	2005	2010	2015	2016	2017
Water treatment plant						
Production water million m^3	79,1	78,0	87,9	90,6	89,0	90,4
Norsborg agency	49,3	51,6	58,3	57,7	58,0	56,6
Lovöverket	128,4	129,6	146,2	148,3	147,0	147,0
Total						
Charge water million m^3						
Inside the city	85,0	81,5	80,0	89,0	83,0	81,7
To the neighboring municipalities	24,4	27,0	33,7	36,0	37,0	38,0
Birth pattern	19,0	21,1	32,5	23,0	27,0	28,0
Total	128,4	129,6	146,2	148,3	147,0	147,7
Water consumption in Stockholm						
Total million m^3	104,0	102,6	112,5	112,0	110,0	109,7
Per day 1000 m^3	285,0	281,0	308,2	306,0	301,0	300,5
Per person and day, litre	342,0	328,0	327,0	289,0	288,5	283,0
Avloppsreningsverket						
Purified total million m^3	162,1	143,6	137,6	158,3	140,2	154,0

Source: Årsbok 2019, Stockholm water and Avlopp/Sweco

TRITA TRITA-ABE-MBT- 20710