THE CIRCULAR POTENTIAL OF THE URBAN MINE

A spatial-temporal dynamic stock model for urban systems with a case study of copper in Amsterdam 2018-2050

Thesis

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Abstract

Large material flows are extracted from natural mines in the earth's crust and moved and stored in anthropogenic environments. Extraction processes from natural mines are often harmful for the environment and can cause material scarcity. At the same time governments are formulating ambitions to increase circularity in cities. For these reasons the concept urban mining is becoming increasingly interesting: the process of analysing and recovering or reusing materials from the city. There is still a lot to explore before steps can be taken to implement urban mining. For a lot of materials, data is missing on quantities and precise locations. This research proposes a method to localize material quantities, for estimating the potential of the material mine of a city. This is done with a case study for copper stock dynamics in Amsterdam between 2018 and 2050. Material Flow Analyses up until now seem to have been effective for analysing material stocks and flows in cities. Geographic Information Systems are used for all kinds of geographic research. With a combination of the two, stock dynamics of copper between 2018 and 2050 are modelled on a detailed level. The copper stocks are distinguished on basis of use in the city: buildings, infrastructure, transportation and appliances. Firstly, the current stock density is estimated, resulting in an amount of 150 kilograms of copper per capita, and visualised in a density map. The map demonstrates a high copper density in the centre, and a low density the further away from the centre. Then, the future stock dynamics are modelled. The resulting stock comes down to about 167 kilograms per capita. An energy transition scenario is modelled on top of the model, to gain insights of the impact of the energy transition on the copper stock. This led to an increase of 7%. The stock expands, mainly to areas in around the centre. Several socio-economic variables seem to correlate with the distribution of the copper mine: floor area density and projected population growth. The outcome of the model can be useful for improving logistics of secondary material outflows. The outcome can also support decision making for policy measures that influence the demand of materials that are potentially scarce (such as subsidizing of solar panels). The method was labour and data intensive, python knowledge would be recommended in the future. Another important recommendation is to start a collaboration for a sound database that can be used for prospecting urban mines.

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1. Introduction

1.1. Context

Cities as future mines

Cities are a product of the earth and of time. They reflect centuries of human history: an accumulation of human's efforts of transforming natural resources into temporary structures for protection, comfort and art (Mumford, 1938).

According to the World Urbanization Prospects (2014) 2.5 billion people will be added to the world's urban population until 2050. 66% of our population, against 54% of our population now, will live in urban areas (UNDESA, 2014). As urbanization continues to rise globally, natural resources, extracted from the deep geologic layers of the earth's crust, are transferred and concentrated to areas on top of its crust in the form of buildings, infrastructure, and products, shaping our current urban landscape and lifestyles. Where conventional natural mines often contain mainly one or several types of resources with anthropogenic value, the city can be considered as a complex mine of all types of materials, each entering and leaving the system in their own pace. Some materials flow through the system relatively fast, one could think of packaging materials like plastic, carton or aluminum. Other materials tend to stay relatively long, such as materials used in buildings: cement, bricks, steel or glass. Once the lifetime of products containing these materials is over, some of the materials are recycled. For instance about 30% of the copper that is consumed in Europe originates from secondary sources, and 50% of steel use is secondary (Harper & Graedel, 2004). While the material demands of cities increases, and ore mines deteriorate, an alternative way of extracting materials is becoming increasingly recognized: urban mining (Klinglmair & Fellner, 2010). Urban mining in short is the process where materials are extracted from the anthropogenic stock, not only from waste streams, but from stocks from aged buildings, infrastructure and goods (Klinglmair & Fellner, 2010).

With rising global urbanization trends and scarcity of resources, there is an increasing necessity for a shift towards schemes where the reuse of products and the recycling of materials is optimized.

Copper

Of all materials that are part of a city's metabolism, for this thesis, copper is chosen as material of study. The demand for this metallic element is rising globally mainly due to its great conductive property. Its applications vary from electrical and pipeline infrastructures to electronic devices (Northey et al., 2014). The main uses can be categorized in multiple categories: copper in buildings, infrastructure, transportation and electronic appliances.

The reason that the focus of this thesis is limited to one type of material can be explained by the following findings. Firstly, from an industrial ecology perspective, some characteristics of copper make it an interesting material for a study. The environmental impact for example; for mining a ton of copper, on average 110 tons of copper ore must be processed, which is not only energy intensive, but also leaves millions of tons of gangue and overburden behind (Wallsten et al., 2013)(Bergbäck et al., 2000). Shifting to secondary forms of copper would mean less of these damaging mining practices. Furthermore, in most cases recovery of secondary metals from products/materials is far less energy intensive than their mining (Dodson et al., 2012). Thirdly, mining conditions are expected to become more difficult (lower ore grades, more complexity, greater depths etc.) (Dodson et al., 2012). And technically, metals do not lose intrinsic properties during recycling and thus are very interesting for urban mining (Dodson et al., 2012). Lastly, the international Copper Association estimated that two thirds of the copper produced since 1900 can be found in the anthropogenic in-use stock, which indicates the large potential of secondary copper for keeping up with our future demand.

Knowledge gap

Even though 95% of construction waste is already recycled in the Netherlands, most of it is downcycled. One of the reasons for this is the lack of insight about future secondary resources coming from buildings and infrastructure in cities (Groot & Huizen, 2011). As for copper, 50% of the copper used in Europe comes from recycling (ICSG, 2017). This figure (Mammoth, 2012) clearly demonstrates the fact that not only consumer goods like phones or machines are temporary but eventually, buildings, roads and infrastructure have an end of life as well. When observing this figure, questions arise as, what materials will come out of this? How should we deal with these massive 'new' sources of used materials? How should we rebuild and redesign the city in the face of lowering the cities' impact on climate change? To what extent can cities function as 'new' mines in the future? If urban mining could be adopted by city shapers, further research is necessary to estimate future flows for creating an urban mining plan.

Where are materials located? This is often still a knowledge gap in cities. The importance of filling up this gap depends on which building strategies we adopt in the future (Huele, 2015). One direction of strategies is to aim for building light and modular, resulting in buildings and infrastructure with short lifetimes. The sustainability aspect in this strategy is the fact that materials will not be damaged after deconstruction and can be reused right away. The other strategy is focused on building strong and robust, lengthening the lifetimes. In the first case, accurate geographic and temporal knowledge of materials could be of higher value: as more transportation and movement of materials will be necessary. Assuming this as a possible scenario, it is interesting to experiment with tools and models to improve prediction of stock dynamics.

Some attempts have been made to identify materials, stocks and flows in cities. An example is Madaster, a platform, launched in January 2017, functioning as a public, online library of materials in the built environment. They are currently still working on methods to localize and track materials in buildings. Several studies, based on Material Flow Analysis (MFA) have been performed to estimate current stocks and flows of metals in cities. Chen & Graedel (2012) analysed 350 studies for metal stocks and flows. However, most of these studies are static. They consist of information of current material amounts in cities or countries.

Additionally, there still is a significant gap concerning integration and application of material flow analyses into spatial planning (Kennedy et al., 2011).

For urban planners and policymakers responsible for infrastructure for (urban) mining, production and waste management, more knowledge about spatial and temporal dynamics on past and future stocks and flows could be of high value (Arora, Paterok, Banerjee, & Singh Saluja, 2017)(Arora et al., 2017).When for example designers of a specific building plan in a city know how much of a secondary resource becomes available in the area, they can anticipate and incorporate these materials in their building plan. Thus, for reaching circular goals as proposed by for example the city of Amsterdam, two problems can be expressed: spatial and temporal data of material stocks and flows is not yet collected and visualised in a time lapse about flows and stocks and this way of thinking – optimally reusing materials - is not yet incorporated by city planners and designers (Zhu, 2014). These problems are the motivation behind this thesis.

1.2. Aim of the Research

By extending previous static MFA's done for Amsterdam in a spatial and temporal way, the value of the data can be improved. By adding a spatial dimension, the stock inflows and outflows become visible at very local levels: enabling action on small scales. With the temporal extension, the insights show possible changes in outflows or inflows in the future. This creates a window for anticipation to future changes. And in the context of a transition towards a sustainable state of a city, this is an opportunity to incorporate strategies for improving efficiency or recycling schemes.

The scientific aim of this research is to experiment with the rare combination of Geographic Information Systems (GIS) and MFA. In which steps of an MFA research can GIS be complementary? And is it useful for analysing material stocks and flows on a city level? With this research an attempt is made to create new insights how and when GIS can be useful, or not, in an MFA study.

1.3. Research Questions

The main question of the research is: How can spatial-temporal stock modelling of copper in Amsterdam contribute to reaching circular economy ambitions? The subquestions that follow from this question are:

1. What is the current stock of copper within the built environment of Amsterdam?

2. What socio-economic variables will mainly influence future stock dynamics per copper category?

3. How much copper can be mined each of the coming years from Amsterdam until 2050?

4. How can spatial and temporal information concerning stock dynamics of copper best be visualized and implemented in an action plan to achieve (further) circularity for Amsterdam?

1.4. System Boundary

The case study used in this research is narrowed down in terms of space, time, materials and inventory.

Spatially, the region within the borders of the city of Amsterdam, which is split up in 6 'stadsdelen'or districts: Centrum, West, Westelijk Havengebied, Nieuw-West, Zuid, Oost, Noord and Zuidoost. Within the region, for the sake of the geographical addition to the MFA, the amounts of copper will be modelled per neighbourhood (Appendix 1.1.). The starting year of the model is the current year: 2018. Because multiple national and local ambitions and goals concerning circularity are due 2050, this will be the last year within the scope of the dynamic model. Thus, annual changes of stocks and flows will be modelled for a period of 32 years.

Of all materials that are part of urban metabolism, for this thesis, copper is chosen as material of study. The demand for this metallic element is rising globally mainly due to its great conductive property. Its applications vary from electrical and pipeline infrastructures to electronic devices. Another reason for this choice is the fact that several attempts already have been made for estimating the stock of metals in Amsterdam and can serve a starting point for the dynamic stock model.

The inventory initially was broad: from underground pipelines to the roofs of buildings, all entities that contain a significant amount of copper according to previous urban mining studies, and are owned and maintained by the city of Amsterdam, its citizens or other involved actors, are supposed to be

included. Some exceptions can be made: entities that do not contribute significantly to the amount of copper, such as coins or ATMs, will not be considered. Additionally, the frequency of some entities, such as hibernating stocks, are not known nor estimated. Because of the amount of research that is needed to be able to estimate hibernating stocks, these are left out as well. Since there are so many products containing copper, they are categorized in the way earlier material flow analyses categorized the copper stock for Amsterdam: buildings, infrastructure, transportation and appliances. Appliances can be categorized again in appliances used by households, commercially or industry. These last two categories are left out of the scope as well due to the effort necessary to collect data on these matters, exceeding the extent of this thesis research.

2. Literature Research

This chapter aims at acquiring an understanding of the context in which urban mining activities are unravelling, now and in the future. The main reason behind this subchapter is an attempt to find motivation that research for urban mining is a well-founded focus for a thesis. Then, a brief assessment of past studies is undertaken to get a grasp of the current state of the art of this specific kind of research. Subsequently, more in depth information about the specific case study of focus is set out.

2.1. Scientific and contextual background

2.1.1. Systems, indicators and leverage points

For a complex dynamic system as a city to change to a sustainable state, more is needed then just a change in the way we generate and treat waste or build our houses and infrastructure with primary materials.

In the report 'Indicators and Information systems for Sustainable Development' (1998), Donella Meadows, a prominent environmental researcher and systems thinker, suggests ways of analyzing a system before being able to change the system. Parts in a system can be translated into indicators. She states that stocks and flows should be distinguished because stocks (accumulation of the past history of the system) are indicators of the state of a system and flows could be leading indicators of change. Additionally, stocks are the most countable elements of a system, and thus are a smart source to measure the state of a system. Flows should be measured and monitored, as they say something about the speed and the way the system changes. Thus before creating circular cities, in which cities constantly reuse their resources (Eames et al., 2017), stocks and flows should be revealed and measured (Meadows, 1998).

As Meadows also states in her work, there are important leverage points to be found to effectively change a system. A high level of potential change can be found in the functions we appoint to a system. Currently, the city has all kinds of functions, but mainly to serve societies primary and secondary life needs (shelter, food, water, cultural and social values etc) (Arora et al., 2017). After entities and goods that serve these functions degrade and reach their end-of-life, they get disposed. The idea that a city is a potential gold mine (literally), is not yet landed in the mindsets of actors that are part of the constructing and shaping of cities (Arora et al., 2017). When this new function would be linked to cities, more efforts could be stimulated to design a scheme, a playing field, that enables urban mining practices.

A higher level of potential change could be found by looking at the overarching paradigm in which societal agents (i.e. companies, municipalities, scientists, society) act. Kuhn defines a paradigm as an overarching cognitive normative framework, in which societal, institutional and public policy developments are governed and shaped by societal agents (Burns, 2012). Despite the scientific consensus on the matter of climate change, policy decisions up on till now do not seem to be effective enough for tackling the complex problem (Burns, 2012). This indicates the need for a paradigm shift towards a sustainable resource system, a system where extraction from nature can be minimalized and resources can be reused. A system where the concept of urban mining could be applied. And according to many scientists, this shift, or also called a social movement, already started at many levels in society (Du Plessis & Cole, 2011; Moore, 2013). Several thresholds however limit this shift (besides deeply rooted neoclassic economic mechanisms); such as the lack of specific and applicable action plans or incentives by important actors, or lack of data and knowledge on where to start changing things

(Plessis & Cole, 2007). Thus, even though the concept of urban mining (thoroughly introduced later in this chapter) looks promising, in the current system it is complex to realize.

These implications are the motivation behind this thesis: we need more data and knowledge of stocks and flows before, ideally, policymakers, companies, and other actors can actually shift towards a system that allows for a circular concept like urban mining to be successfully applied.

2.1.2. Circular Economy

More than 100 articles on Circular Economy (CE) topics were published alone in 2016. They were useful for both scholars and businesses as it is often interpreted as an operationalization of sustainable development (Kirchherr et al., 2017). A CE definition derived from the most recent thorough study on CE definitions, will be adopted in this thesis:

"A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations" (Kirchherr et al., 2017, p224 and 225).

The article recommends to add an elaborated definition of CE as created by van Buren et al, (2016) because of its completeness and clarity. It includes most dimensions; the R hierarchy, a systems perspective, environmental quality, economic prosperity and social equity.

General criticism towards CE is targeted at its different interpretations and definitions making it a vague concept, with no commonly accepted definition (Kirchherr et al., 2017). Despite that, for operationalizing circularity into our way of designing our surroundings and our lives, many concepts, models and methods have been developed. Of which one is urban metabolism.

> **The R hierarchy**
> (1) Refuse: preventing the use of raw materials;
> (2) Reduce: reducing the use of raw materials;
> (3) Reuse: product reuse (second-hand, sharing of products);
> (4) Repair: maintenance and repair;
> (5) Refurbish: refurbishing a product;
> (6) Remanufacture: creating new products from old products;
> (7) Repurpose: product reuse for a different purpose;
> (8) Recycle: processing and reuse of materials;
> (9) Recover energy: incineration of residual flows.

Box 1. The R hierarchy (Kirchherr et al., 2017)

Signs of Circular economy and urban mining in policy

Several milestones have occurred in the field of policy for stimulating change towards a CE. On the European scale, in 2010 the European Commission introduced a 10 year "Europe 2020 strategy", with the goal to pursue sustainable growth by improving resource efficiency in the European economy (European Commission, 2016). Following from that, a roadmap to a Resource Efficient Europe was published for policy guidance for nations to stimulate decoupling and improve resource efficiency. In 2015, the most central policy action proposal appeared containing a CE package with key focus elements, of which one is metals. The proposal showed that a significant amount of improvement is needed in the way we deal with our metal flows in for example industrial residue streams and end-of-life consumer goods such as vehicles, electronic applications or rechargeable batteries. Additionally, they claim there is a large potential for including secondary metals in our current metal use.

In the meantime, the Dutch government has been setting up some of its own goals and roadmaps for a CE. For example, the 'Nederland Circulair 2050' document, containing for example the goal to use 50% less primary resources (minerals, fossil fuels and metals) in 2030 than in 2015 (Rijksoverheid, 2016). The goals needed more elaboration and guidance to be adopted by actors, which resulted in the 'Grondstoffenakkoord 2016'. A more practical document upon which many economical,

organizational, environmental institutions and companies agreed to play an active role in 5 so-called transition agenda's; 1) Biomass and food, 2) Plastics, 3) Manufacturing industry 4) Construction and 5) Consumer goods. According to the Koninklijke Metaalunie and the FME, who signed the 'Grondstoffenakkoord' in 2017, the main goals for them are to 1) ensure the future supply of metals and 2) create new (circular) business models in which concepts such as environmental impact, resource efficiency and closing of loops should be key (Koninklijke Metaalunie, 2017).

On a city level, Amsterdam has been relatively actively pursuing its own CE goals, especially after setting up the 'Sustainability Agenda of Amsterdam' in 2015. That year, the focus laid on the fundamentals for the transition, ensuring all relevant stakeholders were on the same page and on forming alliances. Recently, a monitor report on the developments was published named "State of Sustainable Amsterdam" (2017). Some successfully implemented circular policy measures (more or less relevant for this thesis) they name are for example the circularity criterium in future tender proposals of housing projects; several accepted plans for large circular building project; enforced optimal reuse of all concrete coming from the city. Additionally, by the end of 2017 the waste recycling plant (AEB) will start running its new high tech separation process thereby improving the post separation of all Amsterdam's municipal waste.

2.1.3. Urban Metabolism

The scientific approach to studying the transformation of the biophysical basis of stocks and flows of society is currently facing two major challenges 1) many aspects in society and the environment are affected, and with that, traditional boundaries between scientific disciplines within this context will need to be ignored; 2) the processes are complex and interconnected and span over different scales (from global scales to cities to local biotopes), different organisations (households, sectors, global communities), and temporal (immediate consequences to long term effects). The smaller the scale the more it represents the typical scope of decision-making: stocks and flows on smaller levels (urban level for example) represent the arena where interventions take place (Pauliuk & Hertwich, 2016).

Scientists are tackling these challenges by taking an interdisciplinary systems approach. This approach is often used for quantification of the impact of transitions, for example the deployment of renewable energy supply. Urban Metabolism is an example of a framework derived from this way of thinking.

Kennedy et al., 2011 performed a meta-analysis concerning the Urban Metabolism framework and its different approaches and applications. The insights of this study and their analyzed studies are the basis for defining Urban Metabolism in this research.

The concept of Urban Metabolism is conceived by Wolman (1965) for which he studied the per capita inflow and outflow rates of water, food and fuel for a hypothetical American city. It has contributed to new insights on system-wide impacts of consumption and the generation of wastes within the urban environment (Kennedy et al., 2007). In 1970 chemical engineers, ecologists and civil engineers started studying the urban metabolism of real cities. Several different additions and approaches were used; energy flows (fuels, electricity and solar) were analyzed and expressed terms of solar energy equivalents; and stocks and flows were analyzed in terms of mass fluxes, often by applying material flow analyses (MFA). The first approach became an urban metabolism school with a focus on linking ecological and economic systems by expressing the different flows in terms of solar energy. The latter approach has become a mainstream school for urban metabolism as it is more practical because they essentially use the units that local governments would use (Kennedy et al., 2011). For the last two decades research and practical applications have been really accelerating. Urban Metabolism researchers looked to key nutrient flows (nitrogen and phosphorus), accumulation processes such as construction materials or nutrients disposed in soils and waste sites, or specific material flow studies

such as the flows and stocks of metals. Urban Metabolism is currently mostly researched within the field of industrial ecology.

The parameters within the urban metabolism approach are representative, responsive, relevant to urban planners and dwellers, based on data that is comparable over time, scientifically valid and thus are good as basis for sustainability indicators of a city (Kennedy et al., 2011). Another application of the Urban Metabolism metrics is accounting of greenhouse gas emissions attributed to cities. Furthermore, mathematical models have been created for determining stocks and flow rates of specific substances within the Urban Metabolism framework. These models have mainly been used for identifying solutions for reduction of environmental impact in earlier stages or phases of substance flows (Kennedy et al., 2011).

Urban Metabolism can be defined as "the total sum of the technical and socio-economic processes that occur in cities, resulting in growth, production of energy, and elimination of waste" (Kennedy et al., 2011). The notion of Urban Metabolism destines from the analogy of the metabolism of organisms in the sense that they both use resources from their environment and both produce excrete waste (Kennedy et al., 2014). Matter and energy are actively and passively used by cities (Decker et al, 2000). A distinction is made, based on time scale, for active inputs: they are either stored or transformed. Transformed materials involve fuel, food and water. They are converted to another form and subsequently turned into waste. Stored inputs are mainly materials that become part of the urban environment, one can think of metals, stone or wood. They are often referred to as stocks. Passive inputs are inputs like water that enter a city without direct anthropogenic interference like waterborne materials from precipitation and surface flow, airborne particulates and solar radiation (Decker et al., 2000).

The perspective and methods applied in this research are derived from the Urban Metabolism framework. Consequently, the material of study, copper, is analysed as a part of the city's metabolism, in the form of stocks.

2.1.4. Urban mining

Since the start of the 21st century, the term urban mining (UM) has been around and used in many forms and different definitions, mainly for describing recovery of in-use metal stocks or future waste flows from anthropogenic sources such as metals in electronic waste. It has often been mixed-up with definitions of recycling. A key difference can be found in the consideration of the stock; quantifying the material in use today can lead to insights in future waste flows. This availability can often be predicted by involving lifetime information of the product (Brunner, 2012).

Baccini and Brunner (2012) define UM broadly: it concerns all activities and processes related to extracting compounds, materials and energy from products, buildings and waste generated from urban mechanisms. Some researchers, like Krook & Baas (2013), narrow down the definition of the term, emphasizing the hibernating metal stocks in the borders of cities, which for some reason have not been adopted back in to anthropogenic material cycles, and have therefore been abandoned in their current urban location. They define it by explicitly not considering metal stocks fulfilling a function right now, and traditional waste handling and recycling challenges. Some researchers only refer to landfills and others apply it to traditional recycling schemes (Brunner, 2011).

A more extensive definition proposed by Brunner (2011) partly fits the scope of this research and will thus be added to the definition as provided by Baccini and Brunner (2012). Brunner included two strategies in to the notion to improve its clearness and further application. One aspect added to the concept is the requirement of a goal-oriented, comprehensive, knowledge database that preserves information and data of material flows from production until recovery. It is important, for deciding

whether the material can be economically mined, to know the quality of the metals that are extracted from the city, their abundance, location and all activities related to it.

The other aspect of Brunner (2011) definition entails that recycling facilities within service-oriented cities should be localized. This aspect is mainly involved for the sake of energy savings; significant advantages can be gained by locating urban mining processes close to the secondary sources. According to Brunner (2011) urban mining performs best, when recycling facilities are located in the city, as big cities can produce sufficient amounts of secondary materials. Secondary materials are used or end-of-life materials that can enter the R hierarchy (box 1). Due to the high capital and environmental costs of a facility that can subtract and recycle copper on a significant scale, this might not be the case now. However, technological innovation or increasing value of secondary sources, or implementation of strategies for modular building, can lead to a logistics system where local facilities for recycling or refurbishing copper are realistic (Xue, Wen, Ji, Bressers, & Zhang, 2017). From that point of view spatial information about copper hotspots in a city is more interesting than a system where most secondary copper is mostly transported and recycled on a global scale. For this reason, the second aspect of Brunner's definition is considered as well.

Because of the novelty of the term, there are still plenty of questions and points of critique. To start with, there are questions about data collection. What kind of data is necessary to enable urban mining? What are good methods to collect, process and visualize the urban mine? How can we arrange and implement urban mining (Huele et al., 2015). Also, researchers haven't yet located the source with the highest resource potential within an urban stock: in electronic waste, in landfills of municipal solid wastes or in tailings and residues from industrial production (Schiller, Müller, & Ortlepp, 2016)? For which cases will urban mining become interesting?

Urban mining implemented: a future scenario

Fast forwarding the time, and combining an envisioned scenario by Eames et al., (2017) and the 'Grondstoffenakkoord 2016' proposal, where the CE strategy would have been largely adopted in a city, the metabolism of a city could look drastically different in 2050. In 2050 the ideal green self-reliant city is described as follows: "*Reduced demand coupled with a mend-and-make-do culture. Small-scale, low capital cost solutions for waste treatment. Focus on optimizing sustainable use of renewable resources, including locally sourced carbon neutral and negative materials*" (Eames et al., 2017). Thus, where currently only 3-4% of the materials used in buildings is secondary, now, a much larger share would be recycled or reused materials, when the goals of the governments would be pursued. Adoption of modular building design principles, secondary material use, material passports for buildings, and a reverse logistics scheme for most of the product and materials has made it possible to reuse components and materials on small and local scales. Where demolishment used to be a process where materials and components degraded in their value, now the value is sustained. Recycling plants are efficiently located throughout the city. As cities lack space for extensive transportation, and also because space and storage is expensive, it is important that logistics in a system like this are optimized. Crucial to planning logistics for urban mining is knowing when and where materials will become available on the one hand and are needed on the other (Müller et al., 2014).

2.1.5. Material Flow Analysis and urban mining

A way to prospect the impact of a system on its environment is by dynamic modelling. It is a forward-looking approach called prospective assessment of transformation strategies (Pauliuk & Hertwich, 2016). These models are currently being developed in several different fields, including industrial ecology (IE).

The current state of the methods designed in the field of IE are not satisfactory enough when it comes to prospective studies of the next socio-metabolic transition according to Pauliuk & Werchner (2016). In the history of IE several attempts have been made for improving these studies by combining different IE methods into new frameworks. This has resulted in a new family of prospective models including the extended dynamic MFA (Pauliuk & Hertwich, 2016). MFA models are a natural starting point for dynamic and prospective modelling (Kleijn, et al., 2000; Van der Voet et al., 2002). In-use stocks of buildings, infrastructure or products are key for understanding transitions of states of regions in the present to their potential future states. They thus are incorporated in prospective MFA models, also named dynamic stock models. They are time series of stocks, broken down into age cohorts,

2.1.6. Useful studies

Similar studies are used as guide for choosing the right approach for this research. Several aspects of exemplary studies were important to look in to: the spatial scale of the dynamic MFA (city/country level) and the temporal focus (prospective). Also, MFA's related to GIS are involved. Up until now only static MFA's were found that used GIS. The inflow and outflow calculation columns are added for insights on what can of variables researchers use for modelling stock dynamics.

Authors	Study focus	Stock model approach	Future Inflow calculation	Future Outflow calculation
(Kleijn, Huele, & Van der Voet, 2000)	PVC stock dynamics in Sweden	Top-down Dynamic SFA, 5 different models	Assumed with a model of linear increase in consumption combined with lifetime and life-time distribution	Output = delayed input approach and a lifespan distribution
(Elshkaki, Van der Voet, Timmermans, & Van Holderbeke, 2005)	Lead in cathode ray tubes in the EU	Top-down retrospective and prospective dynamic stock modelling	Extrapolation of explanatory socio-economic variables in regression model	Leaching and delay
(Muller, 2006)	Concrete in Dutch dwelling stock 1900-2100	Top-down retrospective and prospective generic dynamic MFA model	Demand, population, service stock per capita, lifetime, material intensity per service unit in a a balance eqation	Population, service stock per capita, lifetime distribution and material intensity per service unit
(van Beers & Graedel, 2007)	Zinc in-use stocks, in Australia (urban level as well as countrylevel)	Top-down and bottom-up, snapshot	Proxy indicators (income & population growth)	Constant annual stock growth rates
Bergsdal et al., (2007	dwelling stocks in Norway 1900-2100	Retrospective and prospective MFA	driven by socio-economic parameters	driven by socio-economic parameters

Elshkaki (2007)	Lead stocks in the EU and NL	Dynamic substance flow-stock model	Regression model and projected GDP and population growth	From past and future inflow and lifetime (Weibull)
Igarashi et al. (2008)	Future scrap flows for different Asian countries	Top-down retrospective and prospective dynamic stock modelling	Logistic curve regression analysis with parameters determined with fitting algorithms (eg least-squares method)	Logistic curve regression analysis with parameters determined with fitting algorithms
(Sandberg et al., 2016)	dwelling stocks in 11 European countries	retrospective prospective type-cohort-time stock driven modelling approach	driven by socio-economic parameters	driven by socio-economic parameters
(Bader, Scheidegger, Wittmer, & Lichtensteiger, 2011)	Copper flows in 1840-1860	Bottom-up retrospective mathematical MFA	Extrapolation of past data of the cycles	Extrapolation of past data of the cycles
(Zhang, Yuan, & Bi, 2011)	Household appliances in Nanjing 2009-2050	Top-down stock-based model	Current stock: Mass principle + lifetime (Weibull distribution) Etrapolation: Sigmoid (logistic curve)	Lifetime modelling
(Bellstedt, 2015)	PVC, in Amsterdam 2012	Bottom-up and retrospective in-use stock analysis	Material accounting in urban tissue	
(Sartori, Sandberg, & Brattebo, 2016)	dwelling stock in Norway 1800-2050	Retrospective and prospective MFA	driven by socio-economic parameters expressed in probability functions	driven by socio-economic parameters expressed in probability functions
(Hu et al., 2017)	Beijing's residential building stock 1952-2050	Top-down and bottom-up retrospective and prospective, per capita driven dynamic MFA	Based on floor area, population, GDP, lifetime and concrete intensity	Lifetime of buildings
(Tanikawa, Hashimoto, Tanikawa, & Hashimoto, 2017)	Urban tissues in UK and Japan	Retrospective and prospective MFA of small area	Material accounting with 4d-GIS (including economic variables such as	Demolition curve, specific to the urban tissue

			development plans)	
(Zhu, 2014)	Literature analysis	Spatial and static	GIS modelling	GIS modelling
(Lin, 2016)	Copper stock dynamics in Amsterdam	Prospective, inflow-based MFA	Historic and socio-economic variables	Inflow or historic stock & lifetime

Table 1. Overview of similar studies

2.2. The relevance of copper

In this subchapter, the relevance of the material of focus is assessed. The main question asked, while exploring the phases copper enters and leaves in the environment and economy: why would it be interesting to focus on urban mining of copper?

Copper is a widely distributed metal element, found in approximately 0.01% of the earth's crust. In some deposits the content of copper can reach up to 5% of which one third is currently extracted in Chile (Northey, Haque, & Mudd, 2013). Annual production of primary copper is estimated to be 19.7 million tonnes (Statista, 2017). Copper ores can be categorized in either sulphide (80% of the ores globally) or oxide copper ores. Copper ores are mined with underground or open cut methods and processed in stages including concentrating, smelting and refining. Typically mining operations treat over 50.000 ton per day of ore with copper head below 1%, sometimes reaching levels as low as 0.3% (Nilsson et al., 2017). High amounts of energy, coming from Diesel and electricity, are needed for these operations. For the processing, coal and natural gas are the main energy sources (Mudd et al., 2012).

A growing concern regarding the environment, is the energy, explosives and water requirement and the GHG emissions related to mining and processing of primary copper. This is mainly due to the low ratio of copper in the ore grade (Northey et al., 2013). As the demand increases, the ore grade is expected to decrease, requiring more amounts of ore for a smaller amount of copper, leading to even higher GHG emissions and energy use (Elshkaki, Graedel, Ciacci, & Reck, 2016). The CO_2-eq emissions differ per geographic location, ranging between 2.5 to 8.5 kg CO_2-eq/kg Cu (Mudd et al., 2012). According to the International Copper Study Group, production of copper mines has declined by 2.3% in 2017. This is mainly due to lower ore grades, overall reduced mining rates and mines approaching their end of life (ICSG, 2017).

The world refined production has grown slightly by 0.5%, this is mainly due to increased availability of scrap and countries improving their recycling facilities (mainly China and India and some EU countries). Predictions suggest that production of primary Cu will reach 30 million tonnes during the period 2030-2040. Research has led to predictions that a mine production peak will be reached in 2050 (Nilsson et al., 2017). These numbers have resulted in concern regarding the future availability of copper.

Copper has strong ductility, conductivity, thermal conductivity and corrosion resistance properties (Yang, Li, & Liu, 2017). These unique properties of the element have made it one of the most widely-used metals in construction, transportation, infrastructure, machinery manufacturing and electronic equipment (EEE) (Yang et al., 2017). Copper consumption is closely linked to per capita GDP. It averages between 6 to 10 kg Cu/person/year whereas developed countries have a higher consumption rate than less developed countries (Mudd et al., 2012). Due to population growth and economic growth and the transition to renewable energy sources, the demand for copper has been increasing fast, with approximately 2.2 kg Cu/person/year. This growth has surpassed the supply of secondary copper, which explains the increasing demand for primary copper (ICSG, 2017). Increasing population growth, urbanisation rates and electrification of societies, will lead to an ongoing increase of the demand for copper in the future.

Recycling of copper is universally considered as an effective way to secure future access to the material. Elimination of losses of copper during and after the use is estimated to potentially enable a reduction of global primary copper input of 25% (Ciacci, Vassura, & Passarini, 2017)(Elshkaki et al., 2016). Copper already is one of the most recycled materials, nevertheless the global end-of-life recycling has modest performance. Anticipation to the future outlook of primary copper supply requires improvement in recycling rates (Ciacci et al., 2017). Recycling of copper is a capital and energy intensive process which only some countries, such as China, in the world have invested in. Consequently, secondary copper largely flows at a global scale.

The key stocks of copper are buildings, infrastructure and transportation-mobiles (Bader, Scheidegger, Wittmer, & Lichtensteiger 2011). During the use, emissions occur to soil and aquatic systems due to corrosion and abrasion. When copper products are no longer used, they are dismantled and exported as scrap, recycled or landfilled.

There are many applications for copper. Here, four categories of applications are discussed: buildings, infrastructure, transportation and appliances.

Different types of buildings contain different amounts of copper within their envelope. They can for example be distinguished on basis of their function: industrial, commercial or residential. In buildings copper can be found in hardware such as wiring and plumbing. Also, in built-in equipment such as kitchen sinks, heat pumps, furnaces, individual space heaters, boilers, packaged heating unites or air conditioners. But also in building elements as elevators, escalators, and sometimes roofs and gutters (Rauch, Eckelman, & Gordon, 2007). In this thesis, building elements and materials that are built-in equipment, such as wires for electricity and plumbing for water, are allocated to the building category. Copper that is found in infrastructure includes structures providing distribution of water, railway vehicles, streetlights and electricity. Also energy production, including wind, coal, gas and biomass is involved (Rauch et al., 2007).
Copper in transport modes is found in railway vehicles such as trams and metros, and conventional and electric cars, -trucks, -busses, -motorcycles, and -boats.
Copper can also be found in large amounts in electrical appliances, such as electric and electronic equipment (cookers, refrigerators vacuum cleaners, computers).

To conclude, the mining and processing of primary copper is energy intensive and has a high environmental impact. Additionally, primary copper is becoming increasingly scarce. At the same time, the demand for copper will keep on increasing in the future. Secondary copper will become more and more important. Copper can be 100% recycled by a process that is less polluting and energy intensive than mining and processing copper ores. Thus, it is interesting to look in to stocks of copper to keep up with the demand and at the same time reduce energy use and environmental impacts.

2.3. Case study

A case study is selected for designing a dynamic stock model for material flows in a city. This subchapter is written for generating some basic and urban mining related knowledge about the case before going further into depth during the thesis.

2.3.1. The city of Amsterdam

General information

The main capital of The Netherlands currently accommodates 855.965 inhabitants (CBS, 2018). This is expected to grow to 936.00 in 2030 and 998.000 in 2050 (OIS, 2016). The housing stock reached a total of 426.858 houses in 2017, which is 4000 more than in 2016. Map 1 in appendix 1.1 shows the area of research and the division into districts, which will be used for the model. In appendix 1.2 the population growth per neighbourhood is visualised. Since population growth is an important factor for the future stock behaviour of copper, this map perhaps slightly predicts what the results of the thesis will look like in terms of copper stock development in the future.

The city of Amsterdam has a good and relevant platform of public data. Several potential sources with spatial and temporal information are: OIS, CBS, Structuurvisie 2020 and Koers2025.

Spatial plans

To be able to keep up with the fast growth of the city of Amsterdam, the city has set up the Koers 2025, a selection of areas and design criteria in which the growth can occur. The freshly formed college of the city of Amsterdam has set some concrete goals in terms of future development for buildings and infrastructure – both relevant categories when looking into trends of copper use. For example, for the next five years the goal has been set to develop 7500 apartments per year (whereas no concrete plans have been formulated for development of non-residential buildings). In the areas Houthavens, Zeeburgereiland, Zuidoost and across the IJ-oevers, mainly high and compact buildings will be built. An impression of the building style that will be adopted (high and compact), is demonstrated in the visualised plans for Zeeburgereiland (figure 1). In the past, the city grew horizontally. Now, for the sake of green areas and landscapes, and for stimulating social integration compact and vertical building design will be the new building strategy (Koers 2025, 2017). It seems, according to Laurens Ivens, city councillor of 'living' (wonen), initially, development plans were more ambitious. But due to material and labour scarcity in Amsterdam it resulted in the current plans (Parool, 2017).

Figure 1. An impression of possible design for a new neighbourhood on Zeeburgereiland (Parool, 2017)

A desktop research to circular goals and strategies that actors (policymakers, companies, research institutes) in the city of Amsterdam have set, leads to a handful of documents and platforms in which many CE related topics are addressed. Some leading actors in the field seem to be the city of Amsterdam, the Amsterdam Economic Board, Amsterdam Smart City, Metabolic, TNO, Circle Economy, Rabobank and Amsterdam Metropolitan Solutions Institute. An attempt is made below to find a leading thread in these sources.

- In 2011 Amsterdam translated its sustainability ambitions in a four-year comprehensive programme called "Amsterdam Definitely Sustainable 2011-2014". Broad goals were formulated for four pillars; climate and energy, mobility and air quality, sustainable innovative economy and materials and consumers.

- In 2015, the city of Amsterdam commissioned a research to measure the CE potential of the city, with emphasis on the opportunities this discourse would bring the city and its business community. Worldwide it was the first such research on this scale.

- A guiding report resulted from this research called "Circular Amsterdam, a vision and action agenda for the city and metropolitan area"

- Ambition of the region is broadly formulated: for 2025 Amsterdam aspires to be precursor on a global scale in the field of solutions dealing with the scarcity of resources. They will do this by redesigning and closing energy-, water- and material loops while at the same time realizing innovation and new business opportunities in their own region.

- Actions that have been undertaken are mainly orientation of markets and supply chains and attempts to involve relevant actors concerned with important material flows (potentially) circulating through the region. The highest listed materials were all building- and construction waste materials (Amsterdam Economic Board, 2017). For several important supply chains an analysis was done of the most important material flows. Subsequently, feasible options for recycling these flows were elaborated.

In 2016 AEB separated 1380 tons of copper from waste flows from Amsterdam. Much scrap copper, which can be reused 100%, is recycled from this. In 2016, separation of electronic cables resulted in 37,8 tons of copper (AEB, 2016). A lot of scrap copper is exported to larger recycling facilities in the world. Thus, currently the flows of secondary copper flow at a global scale.

Policy visions that will form a basis for future dynamics of copper products are listed in the table 2.

Category	Vision in 2050	Source
Population	7.2% growth compared to 2018	OiS, 2018
Building stock	80.000+ buildings added	Amsterdam housing plan
Solar Energy	1600 MW	Sustainable Agenda
Wind Energy	500 MW	Sustainable Agenda
Coal fired energy	0 MW	Hemweg 8

Gas	0 MW	Hemweg 8
Electricity distribution	70% capacity growth	Lin. 2016
EV charging stations	23000 charging stations	Lin. 2016
Cars	100% EV	Sustainable Agenda
E-bikes	Ownership doubles	CBS. 2018
Boats	100% electric since 2020	Sustainable Agenda
Trucks	All vans (<12 t) electric	Sustainable Agenda
Busses	100% electric	GVB
Rail vehicles	All day and night operation	Metronews

Table 2. Policy visions for 2050 used in dynamic stock model

REPAiR

Because one main aim of this thesis is to contribute to filling up data gaps concerning material stocks related to geography, it will largely adopt some steps behind the geodesign approach. Geodesign is, in short, defined as 'design in geographic space' with the purpose to 'facilitate life in geographic space'(Miller, 2011). It is the overall concept of a large project by which this thesis is largely inspired. The REPAiR project, led by TU Delft, and another 18 partners, among which Amsterdam Metropolitan Solutions (AMS), is a large project focussing on revealing space-specific challenges of waste and resource management on a local scale (REPAiR Project, 2018). REPAiR adopts the idea that Urban Metabolism facilitates the shift towards seeing waste as a resource, but to achieve this there are some implications they aim to tackle. REPAiR hopes to contribute to this shift 'by including technological and social developments, both up and downstream, and by defining if, when and where waste becomes a resource' (REPAiR Project, 2018). By integrating life cycle thinking and geodesign they aim to operationalize Urban Metabolism. To conclude, this project is of relevance because it includes steps for localizing and prospecting (future) waste flows by combining spatial analysis and adopting the Urban Metabolism approach in Amsterdam. The aim of this research is, partly, to localize local potential 'waste' or 'resource' flows, important steps before being able to design a plan around how to deal with these flows in the future.

PUMA and additional MFA's of Amsterdam

Prospecting the Urban Mines of Amsterdam (PUMA), is a completed project that was commissioned as well by AMS Institute, while executed and elaborated by Metabolic, CML Leiden University, Technical University of Delft and De Waag Society. The PUMA framework for prospecting an urban mine is proposed and elaborated by Van der Voet et al., 2015 and is aimed at improving estimations about the size of the urban mine of the city of Amsterdam, the locations of the concentrations but also how the stock can be accessed best.

The collaboration between the research groups resulted for example in a density map of copper stocks in residential buildings in Amsterdam in 2015, as can be seen in figure 2.

The company Metabolic assessed the viability of the assumptions made during the PUMA research, with a sample research of several buildings. Consequently, several assumptions needed revision. These adaptations will be considered in this thesis.

Figure 2. Density map of copper in residential buildings made by Waag Society

Later, students of industrial ecology quantified other stocks of metals in Amsterdam in a student project group. Also, several students at different universities in The Netherlands (Elshkaki, 2007; Lin, 2012; Bellstedt, 2015) did their thesis or doctoral research on exploring stocks and thereby added new relevant insights to not only stock dynamics but also to the bottom-up or top-down methods and policy aims and plans for the city of Amsterdam.

Several rough but useful conclusions that have been made after the execution of the PUMA project are;

- the urban mine is vast and still growing, the demand will not decrease anytime soon,
- resource or circular policies could be contradictory to decarbonisation polices,
- UM contributes to shifting the focus on increasing recycling rates and the share of secondary production,
- for this, a detailed information base is necessary and plenty of work for the coming years, and,
- the PUMA method is easily up scalable to the whole country (Lecture van der Voet & 't Zelfde, 2017).

Some next steps according to van der Voet (2017) are the inclusion of other stocks and to larger geographical boundaries, to put it in a larger MFA framework and to explore the usefulness of GIS for fixed and mobile objects (Lecture, van der Voet & 't Zelfde, 2017). Mainly the last step is addressed in this thesis.

3. Methodology

3.1. Dynamic and spatial material flow analysis

The approach in this study is two-phased: the first assessment concerns a bottom-up characterization of the copper stock in terms of product category, size (kg) and location (district or neighbourhood). The second assessment will combine place specific and product specific conditions related to the product category and model the stock inflow and outflow starting from the point that the stock estimations were done (2018), until 2050. Per category different conditions can be revealed that play a large role in future stock dynamics. These will be handled in 3.2. First, the basics of a (spatial) dynamic stock model will be elaborated that will form the basis for the models.

3.1.1. Principles of the dynamic stock model

Bottom-up MFA

Quantification of stocks and flows in material flow analyses can be approached in two ways; top-down or bottom-up. A top-down approach derives in-use stock from the net flow by using the balance of masses. A bottom-up approach derives the stock at a certain time by quantification and summation of all entities containing copper in a specific area or system (Hilty et al., 2014). The latter approach will be applied in this study. Spatial data will form the basis for the estimations of the initial stock. It is assumed that in the production, manufacturing and waste management processes there is no significant storage of copper. They can be seen as static, hence only the use phase will be considered in the approach.

In the first step, an inventory is made of the most common anthropogenic entities containing copper in a city. The entities are categorized on basis of use and dynamic stock behaviour. Then, the average copper content for each entity is estimated and multiplied by the estimated or documented frequency of entities per area. This frequency can depend on number of households, number of buildings, demographic or socio-economic data retrieved by the city of Amsterdam, or data retrieved form estimations done by Baz et al., (2016) or Huele et al., (2016).

The mathematical formula, proposed by Graedel et al., (2010) used for estimating the current stock is:

$$S_t = \sum_i^A N_{it} m_{it} \ (1)$$

Where St = is the current stock; A = number of different types of goods; N=number of certain good; m = metal content; it = in-use at time t. Thus, the steps taken are:

- Estimating the amount of a product in Amsterdam per district on basis of data provided by the city and literature
- Assessing the average weight of that product
- Assessing the metal content of that product, in the form of a percentage
- Multiplying these three steps above for estimating the total stock of metal in the product of subject per area

Geographic allocation of the stock

Since the stock estimation in this research is approached geographically, the Geographic Approach is applied. The Geographic Approach is a way of thinking and problem solving that allows to create geographic knowledge by measuring spatial elements, organizing the data and analyses and modelling of processes and their relationships. The Geographical Approach is the underlying method for data collection, examination, analysis and production of maps for each stock category.
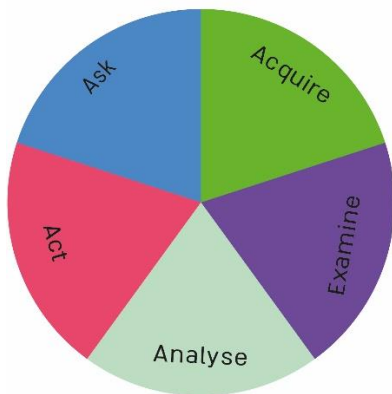
The Geograpical Approach

Figure 3. The Geographical Approach

Eventually the resulting copper amounts per address, household or entity are summed, resulting in a map containing the total amount of copper per area. Per category a different spatial scale is chosen for visualization of the stock. This choice is based on the availability of data. One would assume that addresses are available in a public spatial database (= a database involving coordinates/spatial information for mapping in GIS). This is however not the case yet. Thus, the scales for visualisation will be pc6 areas, neighbourhoods, or districts.

The stocks are mapped with ArcGIS 10.2. Spatial data on neighbourhoods or districts is saved in layers in the form of raster or vector data. A collection of vector data (for example the frequency and location of streetlights) contains an attribute table. This table can be edited, enabling the user to combine it with other tables and add columns with calculations, this way the estimated amounts of copper can be visualized per area. Then, based on this relative frequency of copper, a colour code is linked to the neighbourhood resulting in coloured maps revealing the hot spots: which neighbourhoods are the largest potential copper (gold)mines?

Eventually, for each copper category a map will be created by applying this method. These will be summed, resulting in a final map with copper stock totals for 2018. The economic value of scrap copper will be involved, resulting in an extra map showing the economic value of every neighbourhood in terms of scrap copper. For extra details about how the data was retrieved, Appendix 2 can be viewed.

Prospective stock modelling

Two types of modelling for prospecting future in- and outflows of the stock can be chosen: flow driven, or stock driven. With a flow driven model, data about the inflow is used for estimating the stock. In a stock driven model the future inflow and outflow is estimated on basis of the state of the stock. The flow-driven method is applied for most products in this research. However, sometimes historic and/or future data of the stock is available (such as the amounts of buildings and their age per neighbourhood), then a stock-based approach is applied. The stock approach is also applied when there is no data available besidese the current stock. Then an average lifetime is applied (the amount is divided by the lifetime).

The principles of a flow-driven model are used for calculating the current stock inflows and outflows are:

$$F_t^{in} = (S_t - S_{t-1}) + F_t^{out} \qquad (1)$$

$$F_t^{out} = \sum_{k=1}^{M} F_{t-k}^{in} \times d_k \qquad (2)$$

F_t^{in} and F_{t-k}^{in} are product inflows entering society in year *t* and year *t-k*.

F_t^{out} is the outflow of obsolete product in year *t* and year *t-1*.

M is the maximum lifetime of a product.

d_k is the lifetime distribution value which is normally represented in a probability density function. In this research however, the focus is on spatial distribution, less on annual change. And so average lifespans will be used as determination of the outflow instead of a probability density function.

Data needed is the stock of 1 year. Preferably there is data about the inflow of a year, otherwise it can be assumed that the product inflow of year 0 is 0 ($F_t^{in} = 0|t < 1$ and $F_t^{out} = 0|t < 1$).

Forecasting of the stock can be done by 1) modeling the product life time distribution 2) extrapolating the stocks based on past information and 3) determining the initial year.

Depending on the data available, in this research a flow driven, or a stock driven approach is chosen. The model is visualized in figure 4.
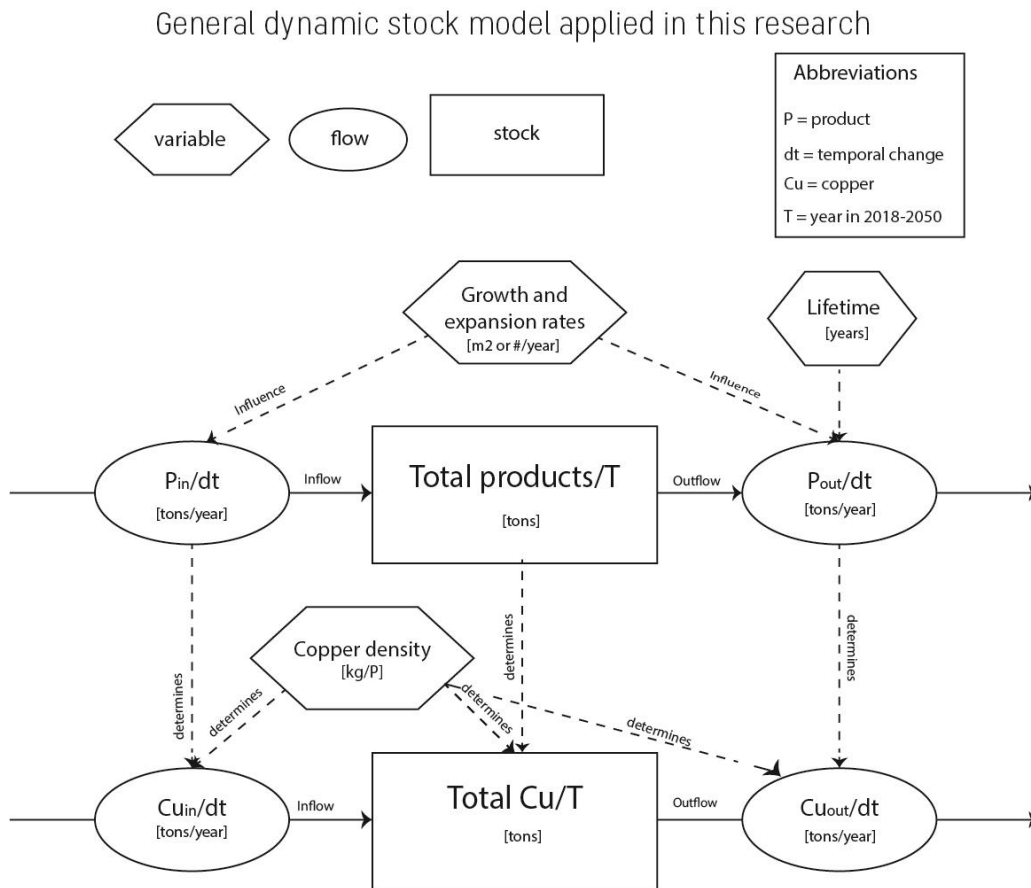
Figure 4 Basic dynamic stock model used in this research

Lifespans

Many studies have shown that the lifetime of a product can be expressed best with a Weibull statistical distribution function. However, in this study for each category or subcategory an average lifetime and historic inflow or stock information will be used for modelling the annual outflows.

Acquiring data

Data collection is needed for knowing how much copper there is, where it is located and when they might come available for extraction (Huele et al., 2015). Types of information that are required are.

1. The products, appliances, types of infrastructure or buildings that contain copper
2. The location or spatial distribution of these products
3. The copper content of the products
4. The life span of these appliances, their present lifetime and future variables that influence their availability (such as development plans

Categorization

Since copper can be found in many kinds of products, each with their different dynamic behaviour, categorization of product types is necessary. The categorization is based upon the following traits: type of use by humans and average length of the in-use phase. This leads to the following six categories; buildings, infrastructure, transportation, household-, corporate- and industrial appliances (figure 5). These categories are divided in subcategories, each containing a set of (assumedly the most common) products that will be used for modelling the stock dynamics. Depending on the data, the spatial scales are selected per category. Service appliances and industrial appliances seemed more difficult to locate and predict, and thus are left out of the scope, because of lack of data and time.

	Subcategory	Products	Spatial Scale
Buildings	Residential / Service / Industrial	Apartments (m2) / Service buildings (m2) / Industrial buildings (m2)	neighbourhood
Infrastructure	Water distribution / Electricity distribution / Telecommunication / Railway	Distribution pipes / Grid, public lighting / Copper cables / Rail system	neighbourhood/ city
Transportation	Automobiles / Water / Rails / Motorcycles / Bicycles	Busses, trucks, cars; conventional/hybrid/electric / Private boats, ferries, canal cruise boats, cargo / Train, metro, tram / Conventional, electric / Conventional, electric	neighbourhood/ city
Household appliances	Kitchen appliances / Electronics / Lighting	Refridgerators, washing machines, ovens, microwaves, other / Televisions, PC's, laptops, printers, phones / Lamps	neighbourhood
Service appliances	Kitchen appliances / Electronics / Lighting	Refridgerators, washing machines, ovens, microwaves, other / PC's, printers, phones / Lamps	neighbourhood
Industrial appliances	Agricultural equipment / Construction equipment / Energy production / Other	Tractors, machinery / Cranes, vehicles / Windmills, solar panels / Small machinery, large machinery	district

Copper stock product categories

Figure 5. The copper product categories

3.1.2. Steps for modelling copper stock in buildings

1. Acquiring data

Four types of information are required for visualising the current urban mine (Huele et al., 2015).

> ➤ The buildings that contain the metals
> ➤ The location of the buildings
> ➤ The metal content of the buildings
> ➤ The lifespan distribution

Various databases are available that contain information about buildings, their spatial locations, size and lifetime. The main database used in this research is the BAG (Basisregistratie Adressen en Gebouwen) and BGT (Basisregistratie Grootschalige Topografie). The relevant information that is found in this database are; addresses and postal codes, the year the building was built, the function of the building and the amount of floor area. The information is maintained by the Cadastre, Land Registry and Mapping Agency (Kadaster) and accessible at www.pdok.nl. The data can be converted to editable layers for GIS by downloading it via QGIS, a software for reading spatial data in WFS or WMS format.

Spatial planning data for Amsterdam can be found at maps.amsterdam.nl. All known development plans and strategic areas for possible later development plans are provided there in json format which can be converted via mapshaper and directly imported in ArcGIS.

The use of metals in residential buildings was estimated by Huele et al. (2016) via the PUMA method, as this is not registered yet by any organisation. They used some exemplary studies such as Wallsten (2013) and building data provided by TU Delft. A distinction was made in parts within the building envelope that contain metals; in casco (referring to bars and beams or reinforcements), on the surface, in frames, in gutters and pipes, water and sewage pipes, heating systems, and wiring and cables. The findings are translated to contents per square meter of floor surface area. This information was combined with the BAG database and applied by Koutamis et al., (2016) and refined by Blok & Roemers (2016).

In the PUMA method these aspects are generalised per building type, mainly based on the size and age of the buildings. In this research, the PUMA method was changed a little according to other studies that included functional buildings in their stock estimations.

2. Mapping the current stock

Estimating the copper content of residential buildings has been done with the PUMA method. The data received from the PUMA project contained a range of copper contents per residential address in Amsterdam. Additional information per address is the surface area in square meters, the building height and the function of the building object.

What is left to get an idea of the whole copper mine in buildings is the copper content of buildings with other functions. For this, the PUMA method is applied to the residential buildings, resulting in average amount of copper per floor area. This amount will be applied to all the other buildings. The current stock is expressed in m2 floor area and found with BAG maps in ArcGIS.

Figure 4 illustrates the dynamic stock model used as basis for modelling the stock dynamics. The inflow is modelled by combining information about the amount of buildings added per year (appendix 2) with the spatial development areas (appendix 1). The outflow is modelled by combining historic stock data with lifetime of buildings and renovation rates (appendix 2). The stock is modelled by summing the inflow to the stock of the year before minus the outflow. The copper dynamics are modelled by multiplying the previous stock and flow data with the copper density per m2 floor area.

In ArcGIS, by reading attribute tables, the surface area of every destination plan will be revealed. By applying the calculate geometry tool, the number of square meters that will change annually can be calculated.

In GIS and excel several steps are taken to model the future in and outflow of copper. The steps are translated to flowcharts (below).

As far as the spatial plans of Amsterdam go, they are used for estimating future demand of copper. After 2035, strategic spatial areas (appendix 2.1.2) are the next areas where most new buildings will be added. The prospects of this research (until 2050) exceed the timespan for which the development plans are determined. For estimating copper supply and demand after 2030, a map is used that was retrieved by an interview with Maurits Hoog, a manager at the city of Amsterdam (email communication in appendix 3). In the map, called 'Strategic Development Plans' areas are highlighted that will probably be changed in the future. What will happen is not yet determined and thus they are called strategic areas. For this study they are split up in 4 timespans: 2030-235 until 2045-2050.

Because Amsterdam contains historic buildings which are not likely to be demolished anytime soon, mainly building plans (provided online until 2035) will be used for estimating future demolishment of buildings and thus future copper flows. But, according to Hoog (2018), renovation cycles happen to buildings in Amsterdam after more or less 25 years. During these renovation cycles, wires and cables incorporated in the construction of the buildings are monitored. When the state of these cables is below a certain level they will be replaced during renovation cycles unless they are broken before the cycle.

For estimating future outflows, spatial data of age of buildings (appendix 2.1.2) was combined with the statement of Hoog (2018) that every 25 years buildings are renovated. If an outflow is missing due to lack of data for a certain year, an average renovation rate of 0,25% is assumed (Sartori et al., 2016). Additionally, it is assumed that during renovation not all copper is replaced, but half of the copper in the building envelope. This renovation rate is combined with lifespan data of the buildings: the renovation number is applied to the total number of buildings that turn 25 years old in the specific year.
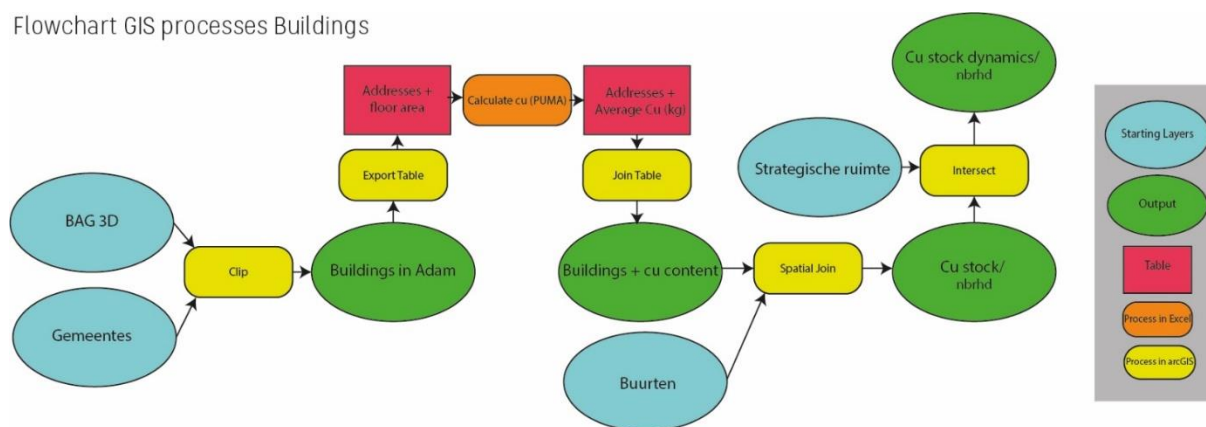
Flowchart 1. Spatial analysis steps for assessing copper dynamics in buildings

3.1.3. Steps for modelling copper stock in infrastructure

1. Acquiring data

For each category a different approach is taken, depending on the availability of data.

- Water distribution

Waternet has been contacted for accurate spatial information about location of the waterpipes. This data is not available. Instead, an excel file was shared with the total length of copper pipelines for Amsterdam. As a solution this is combined with a road map of Amsterdam (appendix 1).

- Telecommunication

Data concerning telecommunication is out there (CLIKViewer) but attempts to convert it to ArcGIS or QGIS for free have failed up un till now. Since it is unclear to what extent glass fiber has replaced telecommunication, and no one was interviewed for extra information, the part of telecommunication that is not in buildings is left out of the scope.

- Electricity distribution

Alliander will not share spatial nor temporal data about the grid underneath Amsterdam that they are responsible of. An alternative way of modelling this is assuming the amount of MW per neighborhood strongly corresponds to the number of roads in the neighborhood. The average amount of copper in kg/MW is known (48,000) (Zhang, 2011). A roads map (appendix 1) will be used as proxy.

- Power generation

For solar panels and wind turbines precise spatial vector maps with watt per entity are available in the geodatabase of the city of Amsterdam (2018). For these entities the stock of copper per neighborhood can thus easily be mapped.

Other forms of generation (biomass, coal-fired powerplant, waste to energy) occur centrally. The locations of these plants will be located and their copper content (found by Lin, 2016) will be linked to the neighborhood where it is located.

- Public lighting

A vector map with all streetlights and traffic lights is publicly available in the geodatabase of the city of Amsterdam (2018). An average copper content is linked to these lights and mapped.

- Railway

All railways are found in WFS data in the geodatabase of the city of Amsterdam (2018). With ArcGIS the total length of the rail can be calculated with a calculation tool. The average amount of cu per type of railway is linked to the length resulting in a graph with the total cu for Amsterdam. Additionally, a map can be made calculating the amount of cu stock in railways per neighborhood.

2. Mapping the current stock

The current stock is mapped by combining the sums of copper in tons of all categories per neighborhood and joining them in the neighborhoods layer in ArcGIS. The stock in 2018, summed inflows and outflow (2018-2050) are divided by the number of hectares of the area, resulting in a density map.

3. Mapping the stock dynamics

Flowchart 2 shows the general steps done in excel and ArcGIS for modelling the stock dynamics of infrastructure.
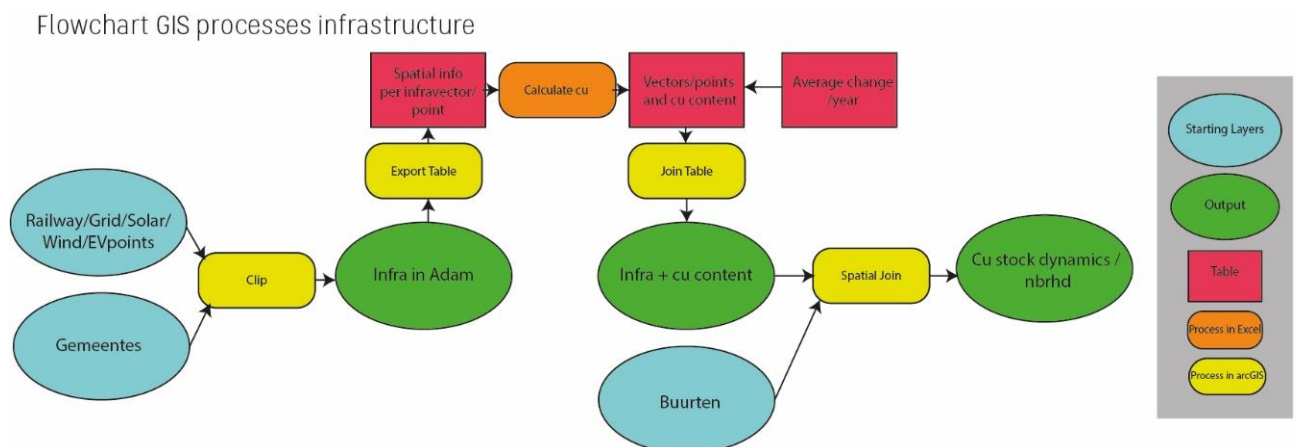
Flowchart 2 Spatial analysis steps for assessing copper dynamics in infrastructure

Figure 4 illustrates the dynamic stock model and the way the variables are generally are found. The current stock is found by sourcing information about the amount and size of infrastructure elements (rails, pipes, cables, streetscape, energy producing elements) at OiS and CBS and the weight in scientific literature. This is linked to proxy data (such as a roads map, or roof surface map) to map the distribution of the stock. The inflow is modelled by assuming that growth occurs at areas that grow (visualized in this strategic development map in appendix 1) combined with renovation cycles (appendix 2). The outflow is also linked to the lifespan and/or renovation cycles. The stock is determined by the inflow and the outflow. The copper dynamics are found by multiplying the previous stock and flows with the copper density of the infrastructure elements.

3.1.4. Steps for modelling copper stock dynamics in transportation

1. Acquiring data

The products in this category can be split up in public and private. Private transport involves cars, motorcycles, e-bikes and boats. Public/commercial transport includes metro's, trams, busses and

trucks. A lot of data in this category is known: CBS, OiS, GVB and city of Amsterdam each have provided data about the number of mobiles per capita or, in the case of public transport, the total amount of mobiles in the city.

2. Mapping the current stock

All mobiles that can be linked to capita (cars, motorcycles, ebikes), in ArcGIS a map is visualised per neighbourhood. Public transport mobiles are allocated to a neighbourhood in which they are stored or parked when they are not used.

3. Mapping the stock dynamics

The lifetimes, population growth, and policy goals about future aspired ways of transporting people will be used for modelling the future copper stock in the transportation. Flowchart 3 and 4 show the processes that are used in GIS and excel to model the stock dynamics. A different method is needed for private and public transport because private transport can be linked to capita while public transport is linked to parking areas.
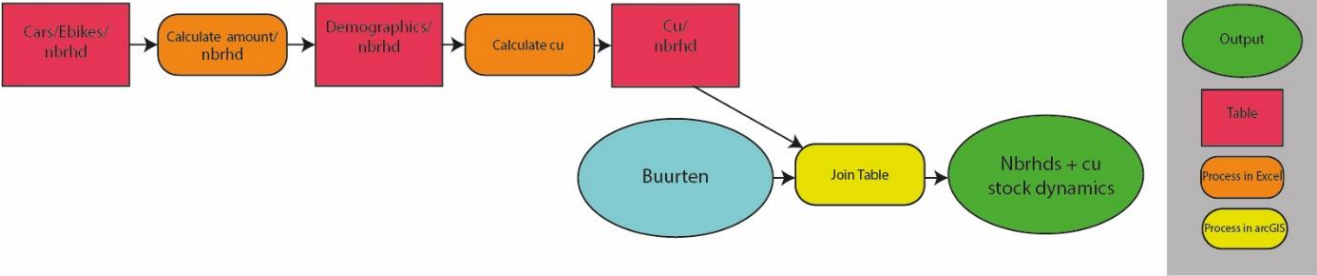
Flowchart 3. Spatial analysis steps for assessing copper dynamics in private transport
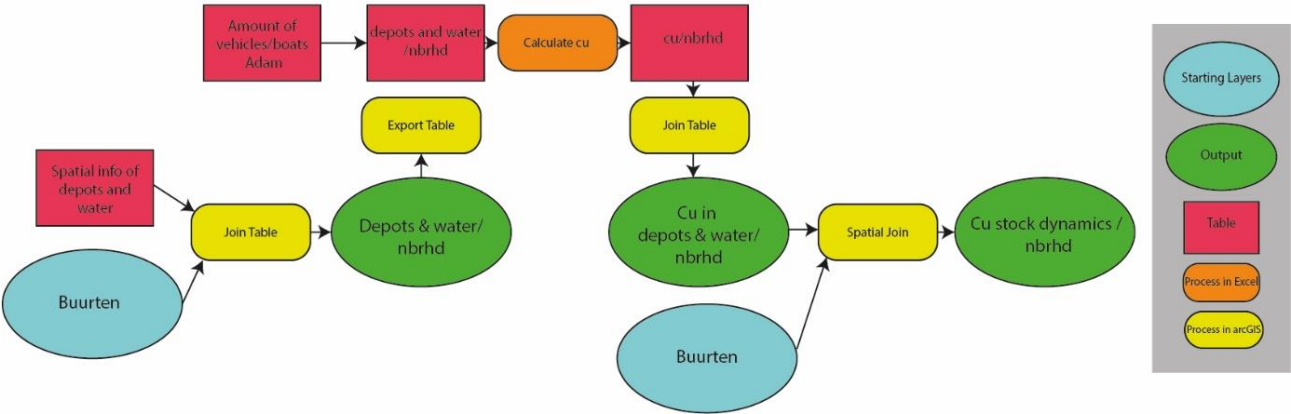
Flowchart 4. Spatial analysis steps for assessing copper dynamics in public transport

For private transport the inflow of vehicles is determined by population change and the average amount of vehicles per capita. The outflow of vehicles is determined by historic data about the stock of vehicles per neighbourhood provided by the OiS (2016) and the lifetime of the vehicle (appendix 2), according to equation 2 in chapter 3.1.1. The stock is determined by historic data provided by OiS (2016) and by the inflow of vehicles and outflow. The copper inflow, stock and outflow are found by multiplying the number of vehicles by the copper density.

For public transport the number of mobiles (trams, busses, metros), flowing into the stock in the future are provided by GVB (2018). The historic and current stock is provided by OiS (2016) and GVB (2018). The outflow is determined by the lifetime of vehicles (appendix 2) and plans about replacement provided by GVB (2018). The copper inflow, stock and outflows are found by multiplying the copper density (appendix 2) of the products by the total amount of products in Amsterdam.

3.1.5. Steps for modelling copper stock dynamics in household appliances

1. Acquiring data

The following data is collected and structured for modelling the current stock; households per neighbourhood (OiS, 2018), the average amount of household appliances per household (Rauch et al., 2007; Ardente et al., 2015; and Lin, 2016), the average copper content per appliance (Baz et al., 2016; Lin, 2016). The combination of this data results in an average copper content per household. This results in a copper density per neighbourhood (in tons/hectare).

2. Mapping the current stock

For each neighbourhood the current number of households is mapped in GIS. In excel, for each product in this category a copper content is found and the average amount of the product per household (HAPH). The HAPH rate is multiplied by the copper content to know the amount of copper per household. Then, this is joined in the household neighbourhood layer in ArcGIS and multiplied by the number of households. To reduce the effect of size (the larger the neighbourhood the higher the amount of copper), the final amount is divided by the surface area of the neighbourhood resulting in a density map.

3. Mapping the stock dynamics

For each neighbourhood the demographic change and prospects are mapped from 2008 to 2050 Appendix 1.

The following data is collected for the demand: growth of households per neighbourhood and average lifetimes of household applications. With a lifetime distribution and/or an average disposal rate for every year an amount of cu can be modelled as outflow.

Flowchart GIS processes Household Appliances
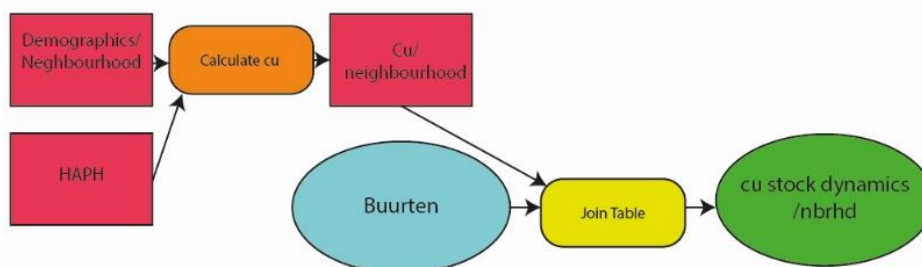
Flowchart 5. Spatial analysis steps for assessing copper dynamics in Household Appliances

The stocks and flows of household appliances are found by linking an average amount of household appliances to the number of households per neighbourhood, which is expressed in tons. The inflow of household appliances is modelled multiplying the HAPH with the household growth rate. The current stock is modelled by multiplying the HAPH with the number of households in the specific year. For the first couple of years the outflow modelled with a disposal rate. Then function 2 in chapter 3.1.1. is

applied for the outflow. The copper stock and flows are modelled by multiplying the copper density with the numbers of household appliances in the stock or flows of the specific year

3.2. Scenario modelling

Electrification of the city could mean a high increase of the demand for copper. For insights on the potential impact of electrification measures, some potential scenarios of the energy transition are modelled. By adding new input data in the attribute tables of stock layers in ArcGIS: the difference between the copper stock in 2050 after a business as usual scenario and an energy transition scenario can be observed. Additionally, changes in copper demand or secondary copper supply can be modelled. Many pathways for decreasing Amsterdam's consumption of fossil fuels are possible Several steps are currently high on the agenda: EV's, Solar panels, and moving away from gas. For these products, many scenarios are possible. For EVs an energy transition scenario constructed by Ecofys (2015) will be used as input for the scenario model. For solar panels, data is provided by the city of Amsterdam in the form of the potential energy production for each roof in Amsterdam if a solar panel would be installed. And lastly, according to the newest national plans, in 2050 all houses will have to be disconnected from the gas grid. It is assumed that gas will be substituted by heat pumps. Heat pumps contain much copper, what will be the effect of this on the copper demand of Amsterdam?

Eventually these three scenarios will be combined and visualised in a GIF (moving map) showing the difference between the stock of copper in 2050 in a BAU scenario and an energy transition scenario.

4. Results

In this chapter, the results of the bottom-up quantification of the copper stock and its dynamics in Amsterdam are set out. The multiple dimensions of the research result in a deeper understanding of the behaviour of the stock, the inflows and outflows of copper. The temporal dimension enables us to see when large amounts could be discarded or needed, and the spatial dimension tells us where in the city we can find these future sources of secondary copper or new demands for copper. Additionally, this analysis leads to insights of what kind of products, entities and services require the highest amount of copper or provide us with the largest amounts of secondary copper in the future.

For each category the spatial and temporal aspects of copper and its behaviour are visualised in the same way. Different governmental-, demographic or technology factors such as changing demand, governmental goals and strategies, or innovations, are considered for modelling the copper behaviour per category. When a factor significantly changes the stock behaviour in the future, it's mechanism and its influence is involved in the results as well.

The second part of this chapter takes a closer look at some of these important factors by applying a scenario analysis. It was found that mainly for infrastructure and transportation, several factors can lead to large changes of the stock behaviour. And so, these categories are selected for the scenario analysis.

4.1. The stock dynamics in Amsterdam

4.1.1. The total stock

The copper contents of all categories involved in the research; buildings, infrastructure, transport and appliances, were summed per neighbourhood and translated into a density map (tons/hectare) (map 1). In total the stock of copper in 2018 in this research is estimated to be approximately 130 000 tons. This is about 150 kilos of copper per capita. The map tells us that the distribution of copper is mainly concentrated in the centre areas of the city, and less in the industrial and outer areas. The neighbourhoods with the highest densities are not directly located in the centre. These are Houthavens, Nieuwendammerdijk/Buiksloterdijk and Tuindorp Buiksloot. Further in this chapter we will discuss which categories contribute to this distribution.

For the next 32 to years the stock is estimated to increase to a total of 167000 tons. When considering population growth for 2050, a total of 167 kg of copper per capita will be reached. This is an increase of 17 kg per capita. In the map below, the areas that will change most can be visualised by **double clicking** on the map.

Total stock density of copper (tons/ha) in 2018

StockDensity 2018 (ton/ha)

Cu density (ton/ha)

- 1 - 4
- 5 - 6
- 7 - 8
- 9 - 10
- 11 - 12
- 13 - 14
- 15 - 16
- 17 - 18
- 19 - 20
- 21 - 22
- 23 - 24
- 25 - 26
- 27 - 28
- 29 - 32
- 33 - 32

0   1,75   3,5   7 Kilometers

Total stock density of copper (tons/ha) in 2050. BAU scenario

StockDensity 2050 BAU (ton/ha)

Cu density (ton/ha)

- 4
- 5 - 6
- 7 - 8
- 9 - 10
- 11 - 12
- 13 - 14
- 15 - 16
- 17 - 18
- 19 - 20
- 21 - 22
- 23 - 24
- 25 - 26
- 27 - 28
- 29 - 30
- 31 - 135

0   1,75   3,5   7 Kilometers
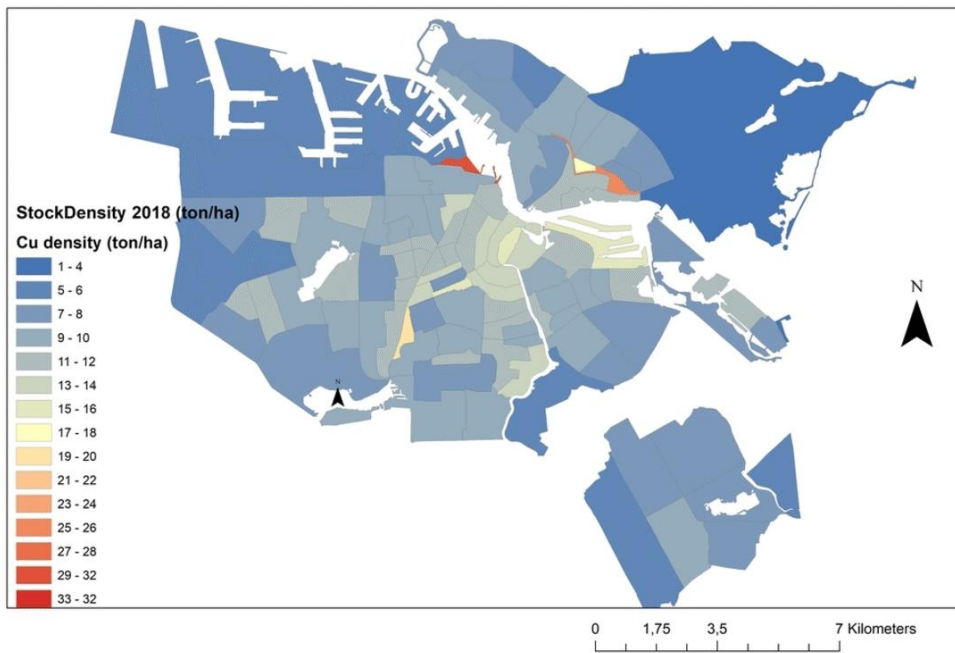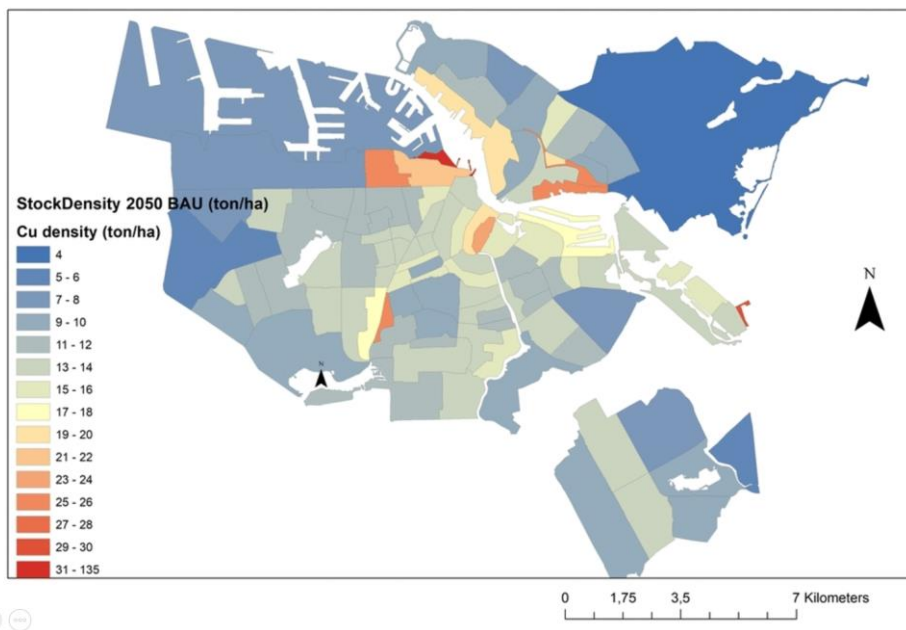
Map 1. (DOUBLE CLICK FOR ANIMATION) Total stock of copper (ton/ha) in Amsterdam 2018 and 2050

Highest stock	ton/ha	Highest inflow	ton/ha/year	Highest outflow	ton/ha/year
Houthavens	31.8	Houthavens	4.9	Houthavens	1.5
Nieuwendammerdijk/Buiksloterdijk	21.7	IJburg Oost	2.3	IJburg Oost	0.95

Tuindorp Buiksloot	20.4	Noorderlijke IJ-oevers Oost	0.9	Van Lennepbuurt	0.6

Table 3. Areas with highest stock, inflow and outflow

4.1.2. The total potential mine

In total, in the period of 2018-2050, about 128600 tons can be mined from the city. This is an average annual outflow of 4019 tons. The highest annual outflow per hectare will be in Houthavens, followed by IJburg-Oost and Noorderlijke IJ-oevers. Map two strongly corresponds with two variables that are mapped in <u>appendix 1</u>: the floor area density and the building plans.

Average annual outflow of copper (tons/ha) between 2018-2050
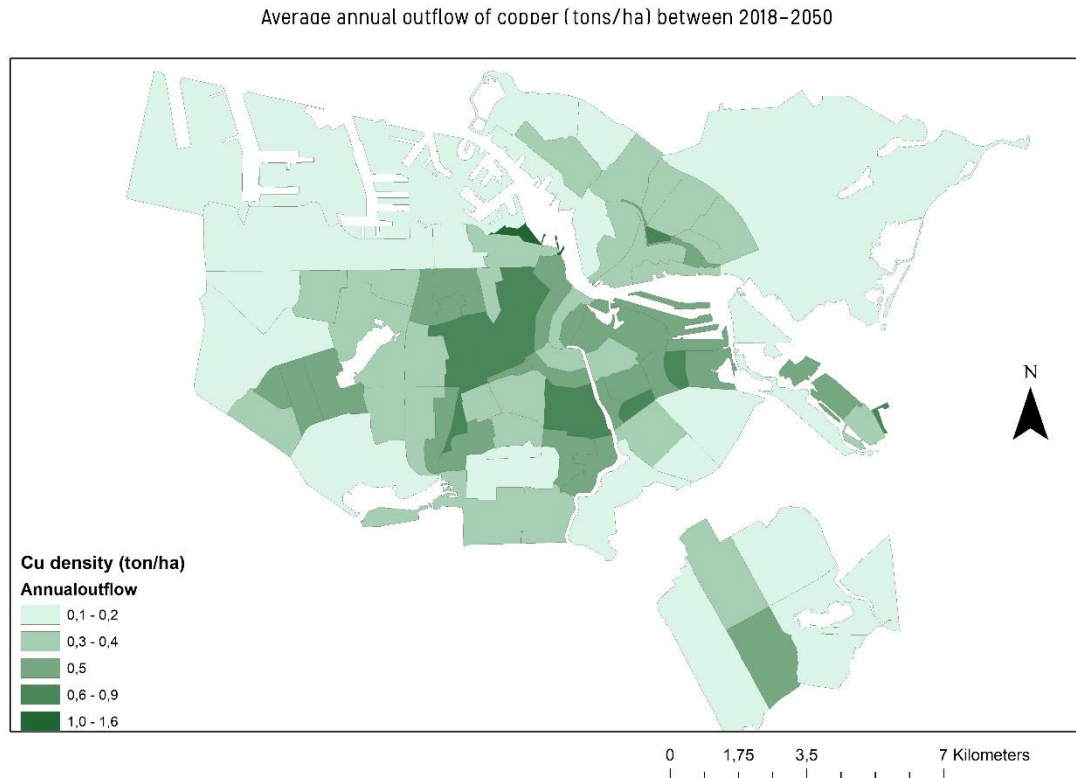
Map 2 Average annual outflow between 2018-2050

4.1.3. The future demand

The total cumulative inflow for the next 32 years is estimated to be about 185000, or 5782 tons of copper per year. This is about 56400 tons higher than the copper outflow. This means that the total demand of the city of Amsterdam will not be in balance with its supply, and thus copper will need to be imported from elsewhere. The highest demand comes from Houthavens and IJburg-Oost. Many compact development plans will occur in these areas.

Cu density (ton/ha)
AnnualInflow
- 0,1 - 0,4
- 0,5 - 0,7
- 0,8 - 1,2
- 1,3 - 2,1
- 2,2 - 5,2

0   1,75   3,5   7 Kilometers

Map 3 density map of the sum of the demand of copper between 2018-2050 (ton/ha)

4.1.4 Important variables

As figure 6 demonstrates, in the stock of 2018, copper is mainly found in buildings (about 84000 tons), then infrastructure (32000 tons), transport (9000 tons) and household appliances (5400 tons). However, when the totals of all estimated outflows are summed for each category, the shape changes. Especially the size of the copper outflow in household appliances increases. The average annual outflow of household appliances for the next 32 years is estimated to be about 1500 tons. The copper outflow of buildings follows with 1440 tons, transport 800 tons and infrastructure is now the lowest with 265 tons.

The size of the annual copper demand per category is as follows (from large to small), annual copper demand in household appliances amounts in 1800 tons per year, buildings about 1700 tons per year, transport about 1300 tons and infrastructure about 1000 tons. All the demands for copper are higher than the outflows of copper.

Figure 7 shows the change per category between 2018-2050 for every 10 years. The growth strongly differs per category. By 2050 the stock in transport will have grown with 288%, HHA with 169%, infrastructure with 68% and buildings with 7%.

STOCK SHARE 2018

transport 4%
hha 4%
Infra 26%
buildings 66%

DEMAND

Infra 17%
HHA 31%
transport 23%
buildings 29%

OUTFLOW

Infra 7%
HHA 37%
transport 20%
buildings 36%
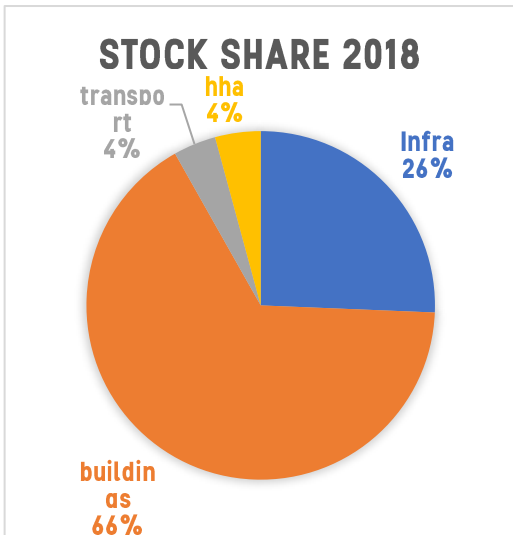
Figure 6 Share of categories in the stock, outflow and demand

Stock behavior per category (tons) 2018-2050

Legend: 2018, 2025, 2035, 2050
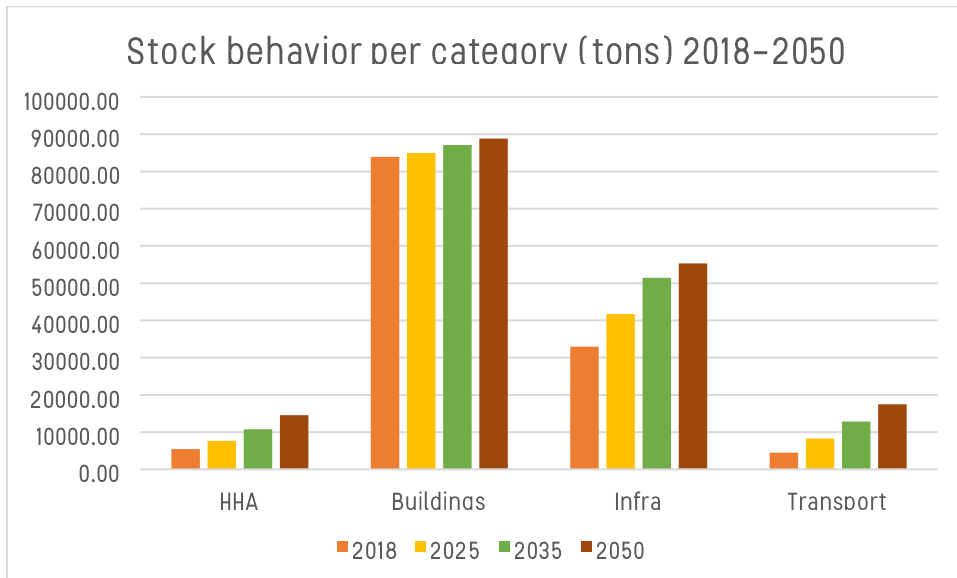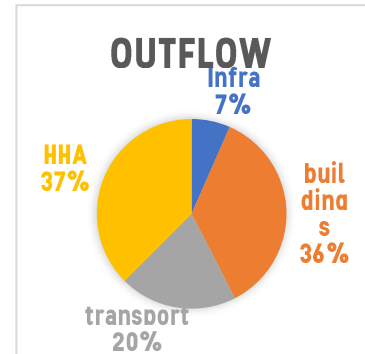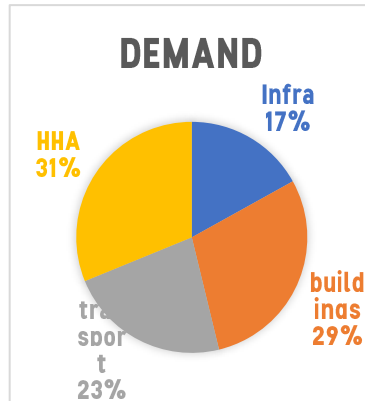
Figure 7 Stock dynamics over the years per category

4.2. Stock dynamics per category
4.2.1 Buildings

The current stock

The average amount of copper found when the PUMA method was applied to the building stock (an average of 0,3 kg copper/ m2 of floor area) was used for estimating copper contents in all types of non-residential buildings. For comparison there are some methods found in literature used earlier to estimate copper composition in buildings in other countries, further elaboration can be found in appendix 2.

Public databases containing data on building level combined with the extended version of the PUMA method to functional buildings, lead to an estimation of the copper stock in buildings of **83900 tons** in 2018. As can be seen in map 4, the pattern of distribution of copper in buildings is not typically in the form of central high and outer circle low, what could have been expected. When relating the map showing the average heights of buildings per neighbourhood (appendix 1), there is a high correspondence visible. This shows that the floor area density is an important variable for the copper density in this category.

Stock of copper (ton/ha) in buildings 2018
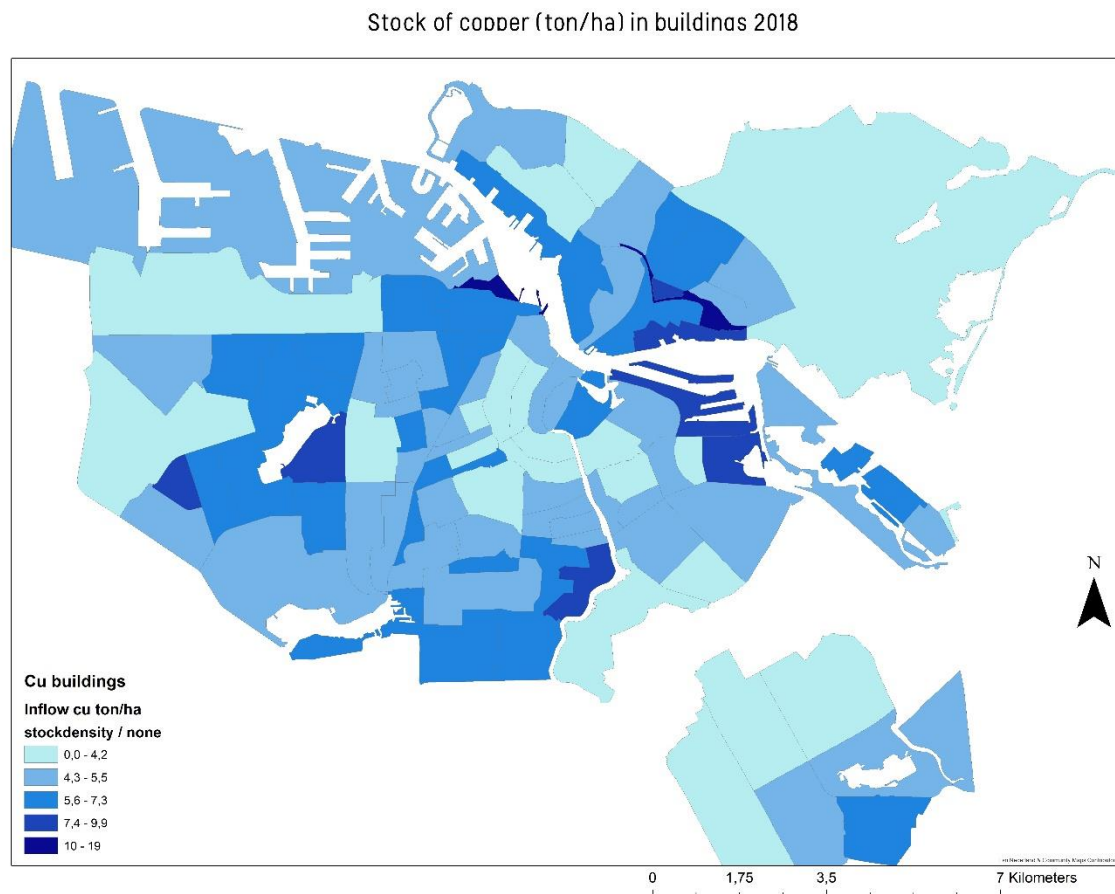
Map 4 density map of stock of copper (ton/ha) in buildings 2018

The potential mine

The total stock is expected to increase from 83900 tons to 90330 tons. This is an increase of approximately 7%. The growth is based on the most recently published developing plans and by the assumption that after 2035 the building stock will increase with about 5000 units per year.

The inflow of copper into the building stock seems to stay steady, the variables that determine the inflow are the used renovation rate of 25 years (assuming that half of the copper in the building envelopes is replaced), and the building plans. In the first ten years the building plans are known to a detailed level. After 2035 it is assumed that 5000 unit are added annually in the strategic areas (appendix 1). The new buildings are mainly built in the Houthavens, Zeeburgereiland, Zuidoost and the IJ-oevers.

The average annual inflow is estimated to be about 2000 tons of copper and will mainly flow to areas around the centre of the city and the edges of the city as well.

The annual outflow of copper is estimated to be about 700 tons and seems to be especially large for areas that already contain many buildings but are involved in the ambitious developing plans (appendix 1).

Highest stock 2018	Ton/ha	Highest annual inflow	ton/ha	Highest annual outflow	ton/ha
Houthavens	19.4	Houthavens	0.596875	Houthavens	0.55
Nieuwendammerdijk/Buikslo terdijk	15.4	Noordelijke IJ-oevers Oost	0.34375	Nieuwendammerdijk/Buikslo terdijk	0.26875
Oostelijk Havengebied	9.9	Nieuwendammerdijk/Buikslo terdijk	0.26875	Oostelijk Havengebied	0.171875

Table 4. The geographic hotspots

When observing figure 8 and 9, it becomes clear that the expected building and renovation plans will not drastically change the building stock in the future. Despite this, the building category is one of the highest contributors to future demand and outflow of copper, as we saw in the subchapter before.
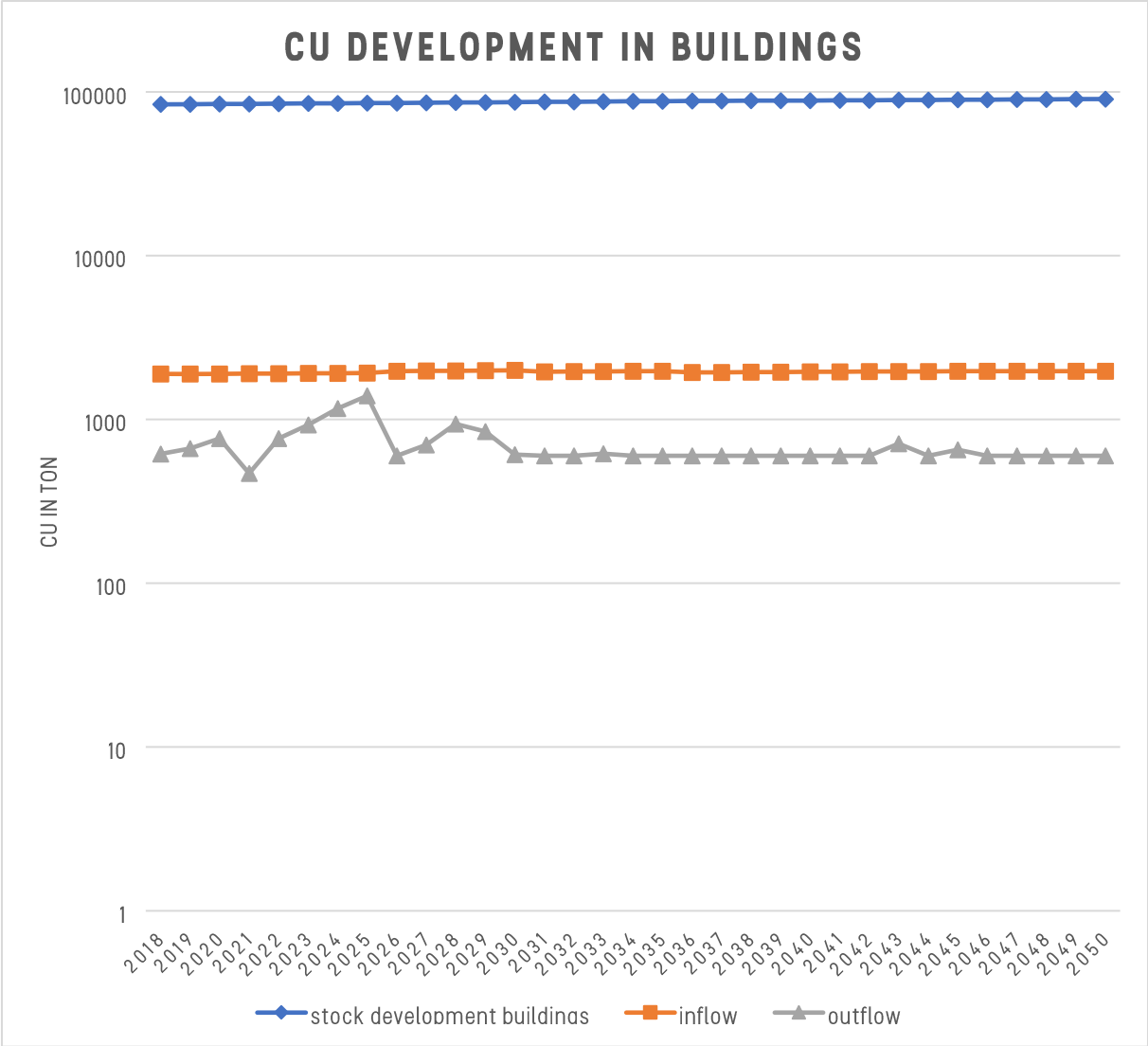
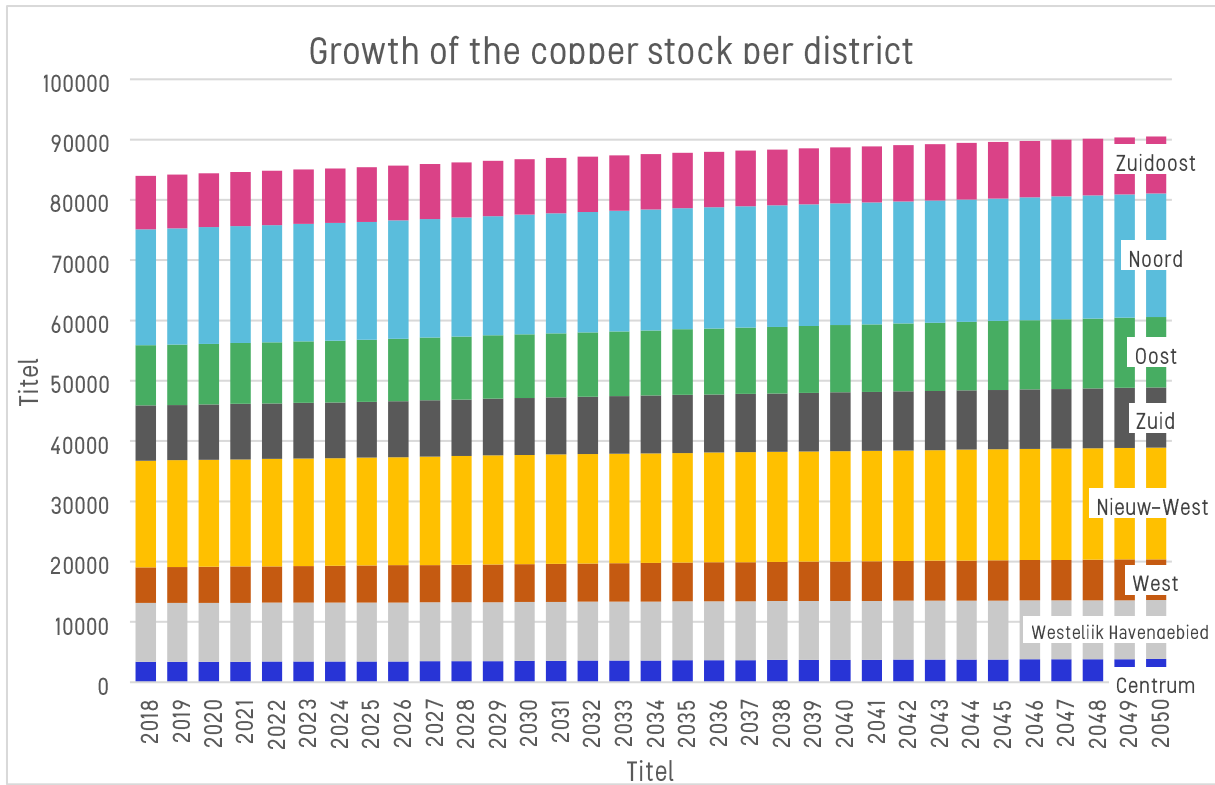*Figure 8 Stock and flow development of copper in buildings*

*Figure 9 Graph showing the development of annual copper stock in Buildings in tons per district*

4.2.2. Infrastructure

The current stock

The copper contents and lifetimes used for calculating the stock dynamics can be viewed in appendix 2.3.

The total stock of infrastructure in 2018 estimated to be approximately 32500 tons. Map 5 tells us that the highest densities are generally located in the centre. Some areas also have high densities. This distribution corresponds with the floor area density map in <u>appendix 1</u>.

The main contributor to the large stock of infrastructure, by far, is the power distribution grid.

Stock of copper 2018 (ton/hectare) in infrastructure
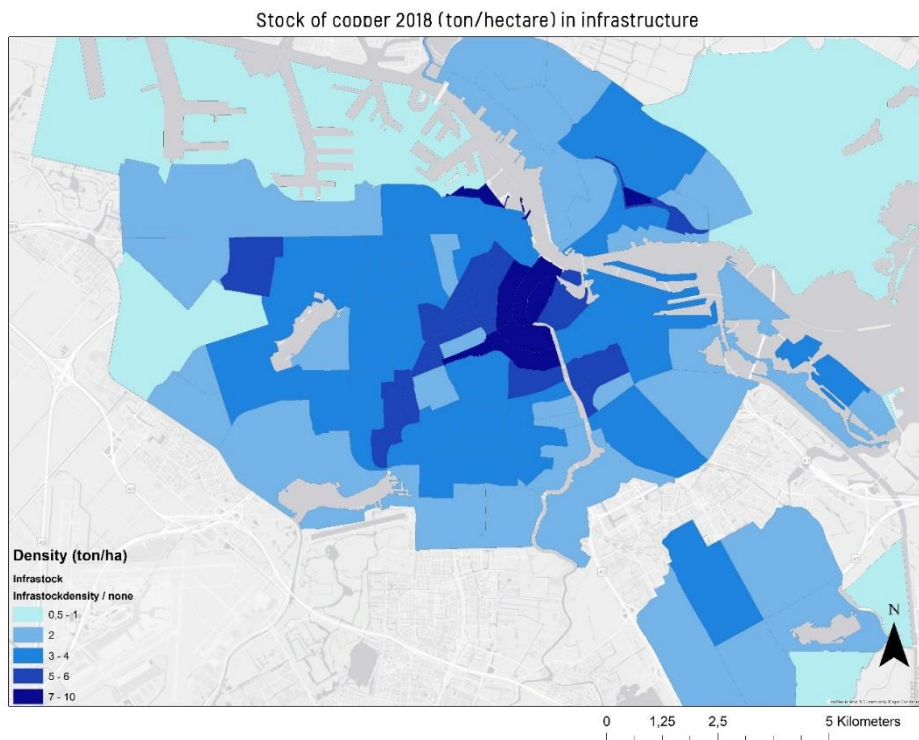
Map 5 density map of stock of copper (ton/ha) in infrastructure 2018

The potential mine

In figure 10 the total stock dynamics can be viewed. It is visualised in a logarithmic scale to be able to see the change of the inflow and outflow graphs.

The total stock is expected to grow to 55000 tons is 2050. The highest stock per hectare of copper in infrastructure can be found in the Houthavens. Furthermore, in the central areas of the city. The least dense areas are in the outer boundaries of Amsterdam. It is highly exceptional that an area has a higher inflow than outflow.

The average annual inflow for infrastructure is 2570 tons. In the future, the highest outflow per hectare is expected to be in Houthavens. This is mainly because of the expansion of the electricity grid in this dense area with many new building projects planned.

The average annual outflow is 640 tons. An important future source of secondary copper is the closing of the coalfired powerplant in 2034/35 at Westelijk Havengebied, which is visible the outflow

development in figure 10. Another peak of outflow is observed in 2045. This can be explained by the wind turbines which partly will reach the end of their life before 2050.

Largest stock	ton cu/ha	Largest inflow	ton cu/ha	Largest outflow	ton cu/ha
Houthavens	10.5	Houthavens	3.94	Houthavens	0.67
Burgwallen-Oude Zijde	8	Sloterdijk	0.47	Burgwallen-Oude Zijde	0.09
Grachtengordel-West	7.4	Spaarndammer-en Zeeheldenbuurt	0.40	Sloterdijk	0.09

Table 5 Hotspots with high copper densities in infrastructure
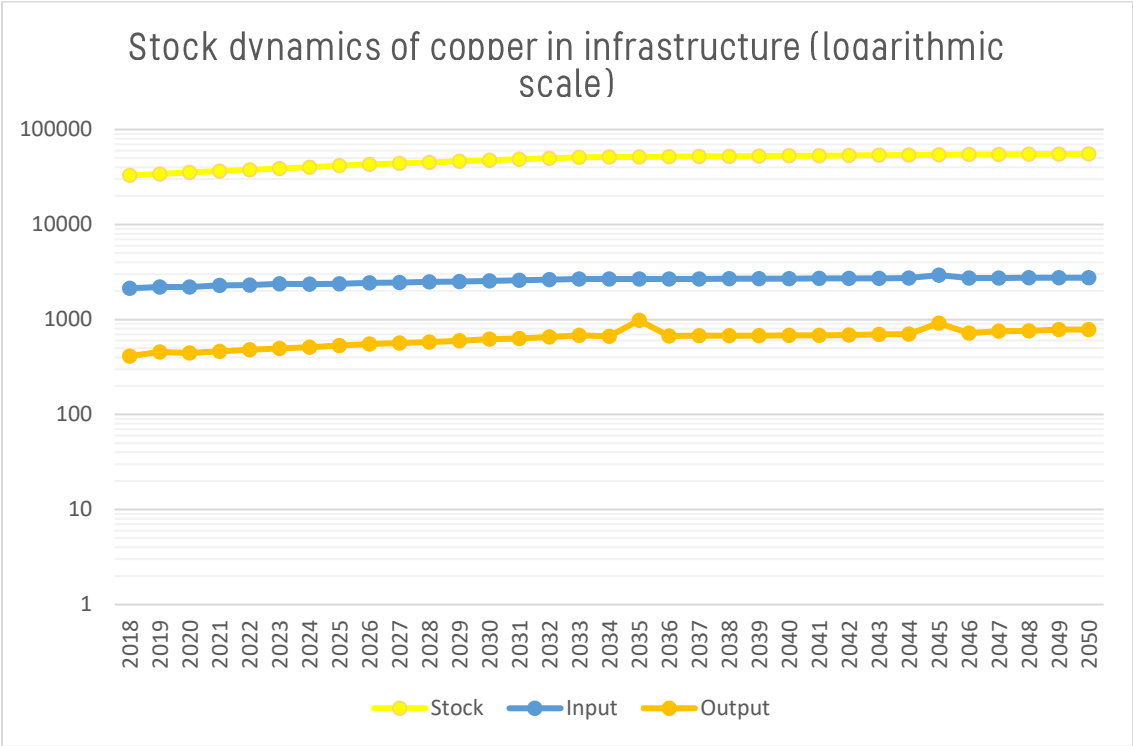
Figure 10 Stock dynamics, inflow and outflow development of infrastructure (logarithmic scale)

Figure 11 shows the stock development per district. In all districts a growth is visible, but the strongest growth of copper in infrastructure can be found in the western districts of Amsterdam. The least growth will occur in the centre.
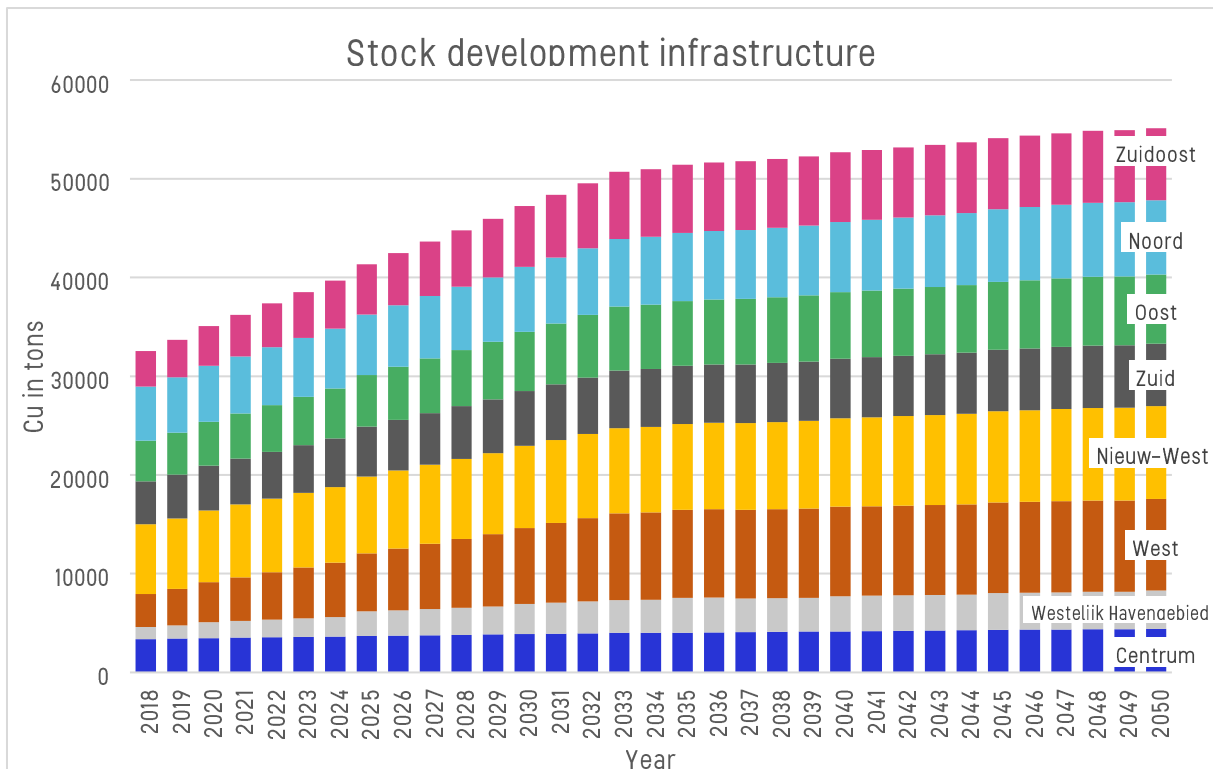
Figure 11 Stock development per district

Important products and variables

As demonstrated in figure 12, the highest contributing product to the amount of copper in infrastructure is the power distribution grid (contributes with about 30000 tons). This high amount of copper is the result of a high copper content in electricity distribution systems of 48 tons per MW (Zhang, 2011) and a high electricity distribution capacity in Amsterdam of 1294 MW (Lin, 2016). Because of intensive building plans and growing electrification of the city, the number of tons in the electricity grid is estimated to grow with 65% for the next 32 years to an amount of nearly 50000 tons. In these numbers the copper distribution within buildings is excluded, this is accounted for in the building category.

The product with the least significant impact is EV charging facilities (less than 1 ton in 2018). It is expected to grow to about 7 tons due to a high anticipated adoption of electric vehicles.

The contribution of copper by the other products is mostly between 100 and 1000 tons. The highest anticipated growth is expected for electricity production by wind and solar panels. For wind, ambitious goals are set for the coming 22 years: from a contribution of 85 MW in 2020 to 400 MW in 2040.

A decline of coal (this line also includes gas and biomass-based electricity production) is expected in 2034 for which the cause is the closing down of the coal fired power station at Hemweg in 2034.
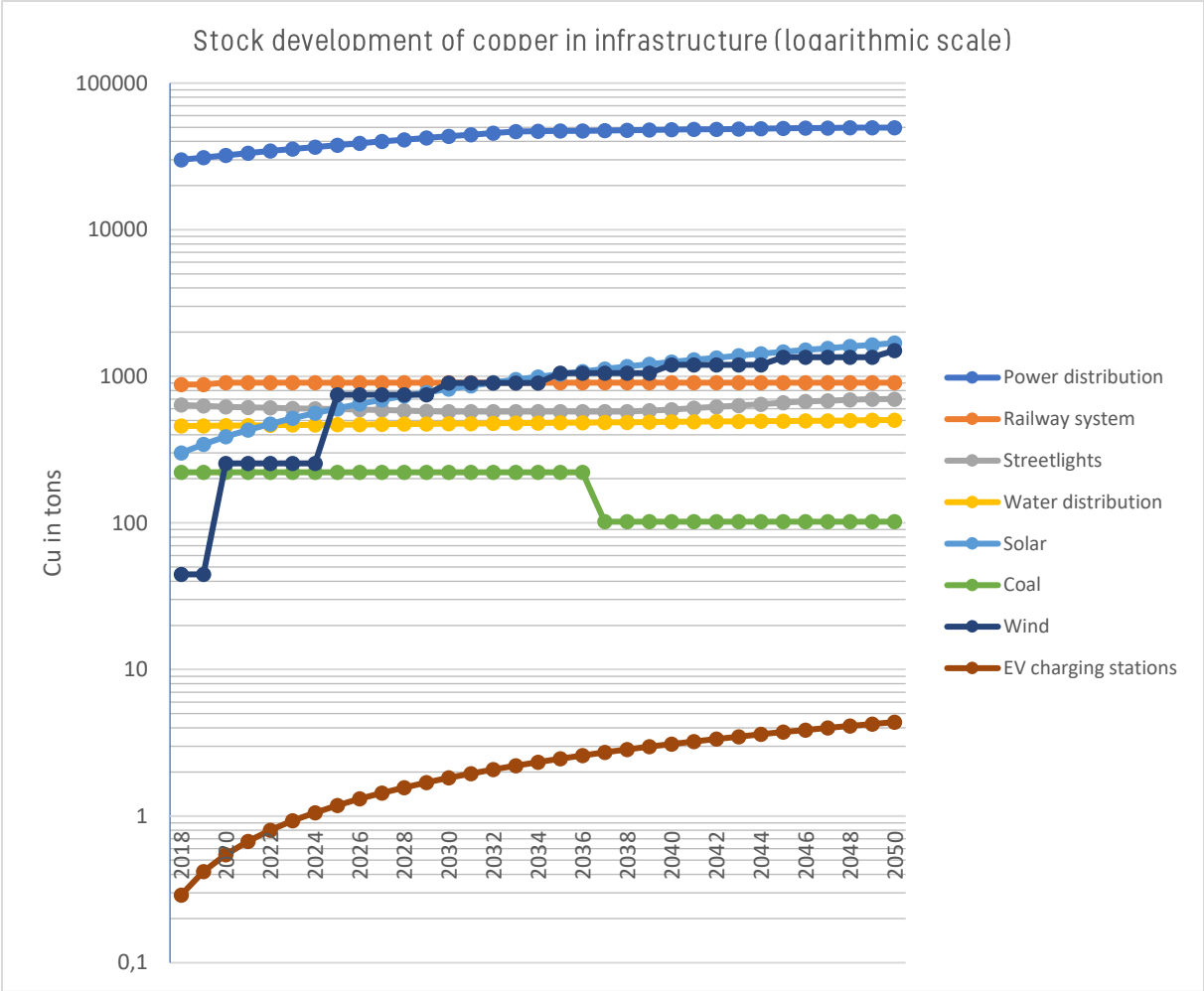
Figure 12 stock development of copper in the products of the infrastructure category

4.2.3. Transport

The current stock

The copper contents and lifetimes used for calculating the stock dynamics can be viewed in appendix 2.4. About 9000 tons of copper can be found in the transport mobiles in Amsterdam. The spatial distribution of the copper stock seems randomly spread over the central and semi central areas of Amsterdam (map 6). The highest amounts of copper per hectare can be found in the Schinkelbuurt, Rijnbuurt and the Van Lennep. The first two areas are areas where trams are stored when inactive (map 10 in Appendix 1). At the van Lennepbuurt there is a relatively high amount of boats, cars and ebikes for the size of the area.

Copper stock in 2018 (ton/hectare) in transport
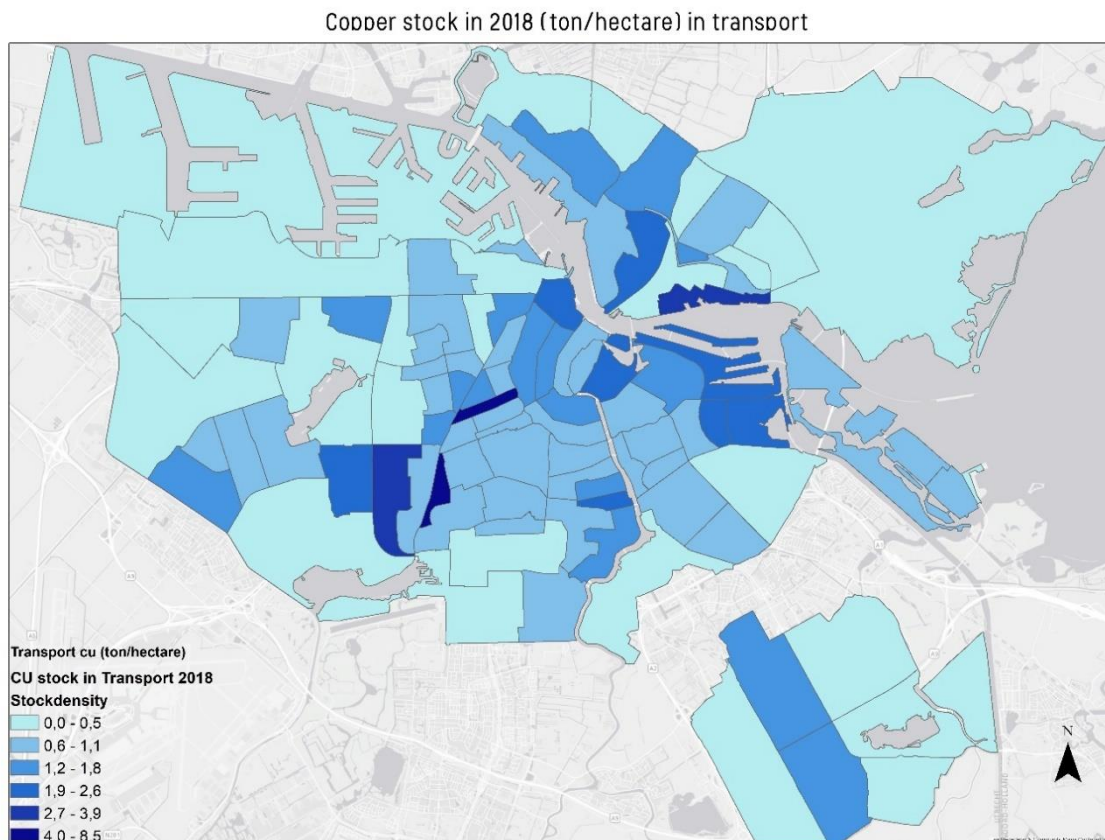
Map 6 density map of stock of copper (ton/ha) in transport in 2018

Largest stock	Stockdensity	Largest inflow	ton cu/ha	Largest outflow	ton cu/ha
Schinkelbuurt	4.2	Burgwallen oude zijde	0.75	Ijburg-Oost	0.47
Rijnbuurt	1.7	Schinkelbuurt	0.68	Schinkelbuurt	0.32
Van Lennepbuurt	1.5	Kinkerbuurt	0.46	Van Lennepbuurt	0.25

Table 6 Hotspots with high densities of copper stocks or flows in transport

The potential mine

The graph in figure 13 demonstrates the potential development of the stock, inflows and outflows of copper in transport on a logarithmic scale. In general, an increase is visible. Peaks are visible in inflow and outflow graphs at different years. Electrification ambitions of vehicles and end of life and consumption of public transportation mobiles are some important reasons for these peaks.

The stock will increase strongly in almost all districts, from 4585 in 2018 towards a total stock of about 11325 tons in 2050 (figure 13). This is an increase of 6700 tons in 32 years, making it a strong growing category (an increase of 150%).

An average annual inflow is expected of 436 tons per year. The inflow increases every year due to electrification of many of the vehicle types (figure 13). The inflow is expected to be the highest in the West Indische Buurt, the Schinkelbuurt and the Kinkerbuurt (table 7). The reason for the high inflow in Schinkelbuurt is mainly the replacement and addition of trams. The Kinkerbuurt has much space for boats and is a dense area with many cars and a small number of hectares: for this reason, the inflow is relatively high. On the fourth place is IJburg Oost, an area with a high expected growth rate: many (electric) cars, ebikes and boats will be consumed or moved to this area in the nearby future.

The outflow increases every year as can be seen in figure 13. An average annual outflow is expected of 287 tons. The largest outflows of copper are expected to occur in IJburg Oost, the Schinkelbuurt and the Van Lennepbuurt, which can be explained by the consequential high outflow of a high inflow and lifetimes shorter than 30 years.
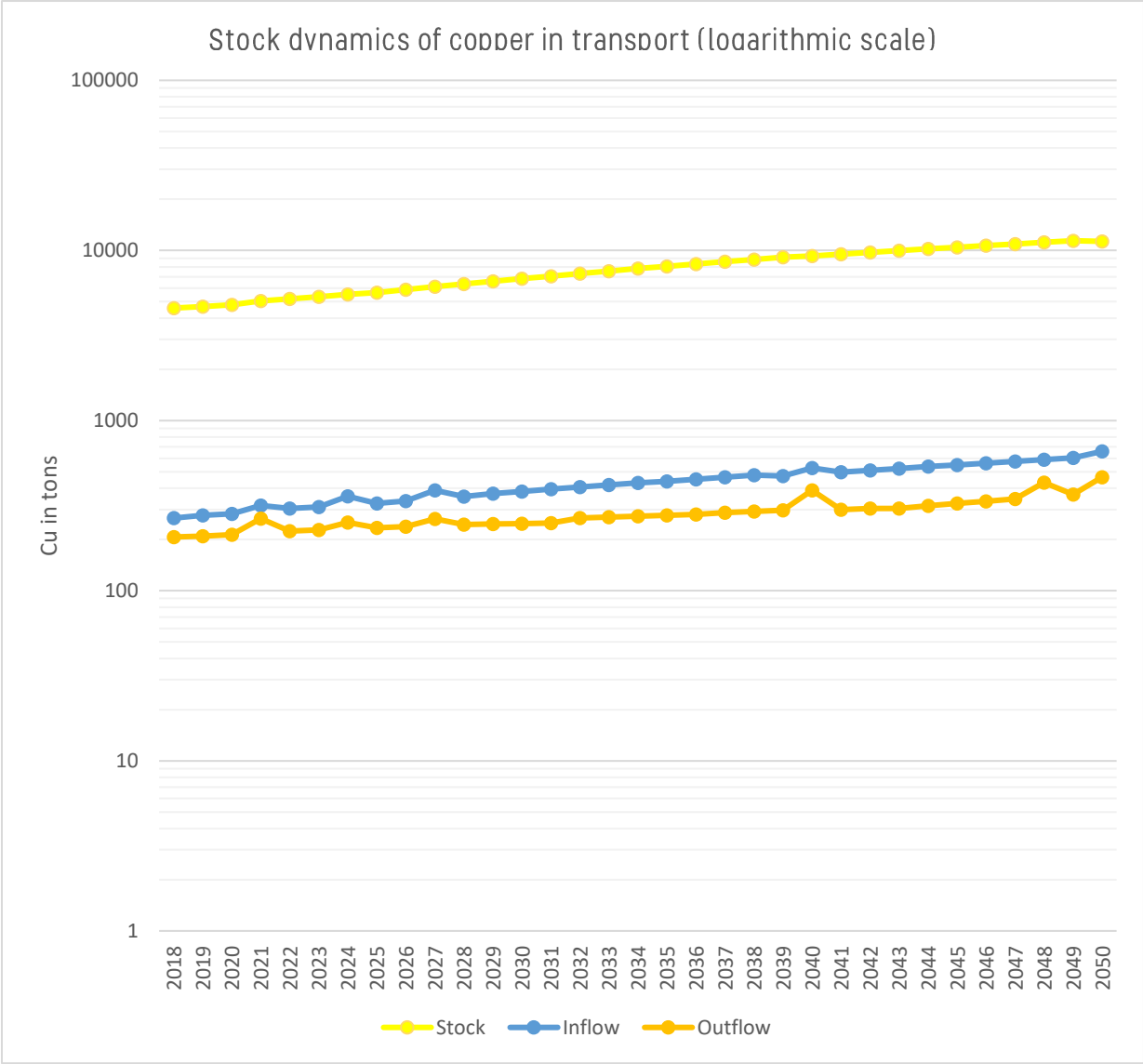
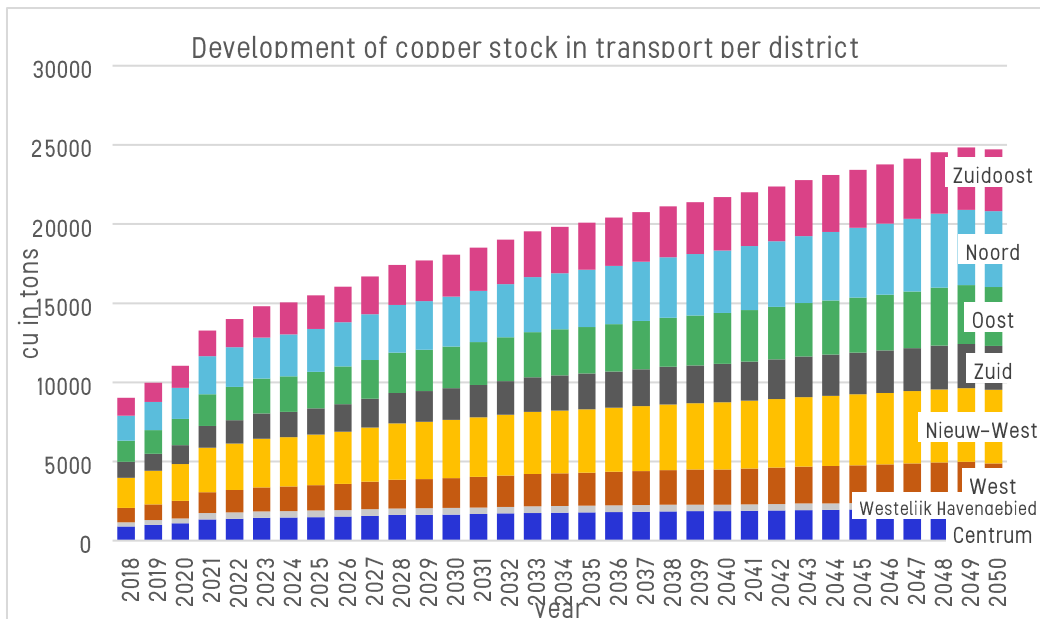*Figure 13 Graph of stock dynamics of copper in infrastructure (tons)*

Figure 14 Development of the copper stock in transport per district

Important products and variables

Figure 14 demonstrates that cars are the most important contribution to the copper stock in this category. There is a strong growth visible for cars: from 3650 tons in 2018 to 9280 tons in 2050. This can be explained the replacement of conventional cars by electric vehicles (EV's). The copper content of EV cars is about 5 times higher than the copper content in conventional cars.

Plans of the city to add new metros and replace old metros with new versions result in a strong increase in the stock of copper in metro (figure 14). Moreover, there is an increase visible for copper in boats, busses and trucks (figure 14). The electrification of vehicles is the main cause of the increase of the copper stock. Boats will electrify fast the next two years, as one of the goals considered in this model is to have all boats inside Amsterdam sail on electric motors by 2020. Ebikes do not significantly add up to the total amount of copper, there is a strong growing trend visible however, from a copper stock in ebikes in 2018 of 12 tons to a stock of about 30 tons in 2050.

For electric cars the development depends on the pace of adoption of electric vehicles. If the BAU scenario is applied the amount of copper will increase to 6000 tons of copper in 2050 in cars
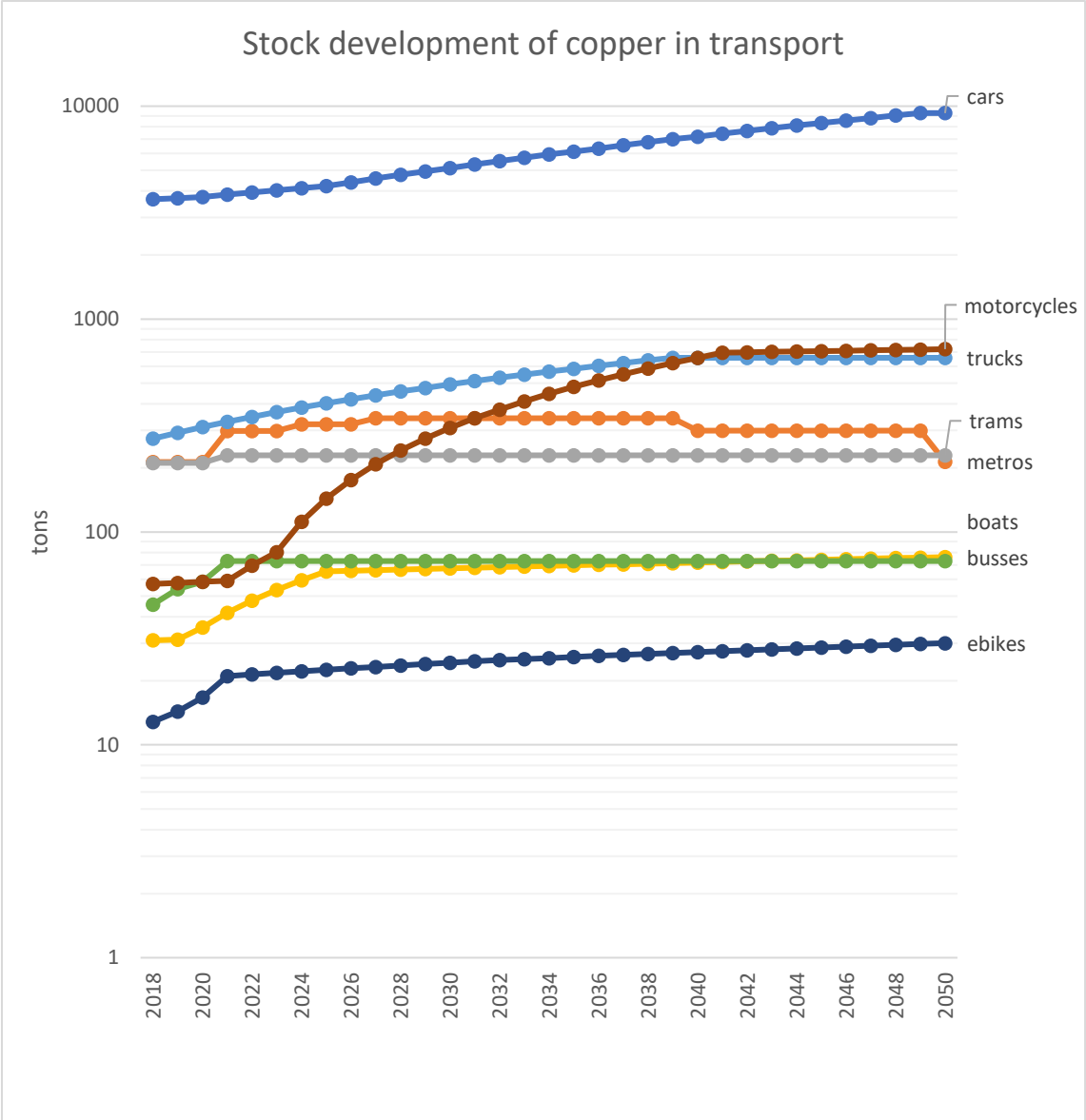
Figure 15 Graph of stock development of all elements in transport category
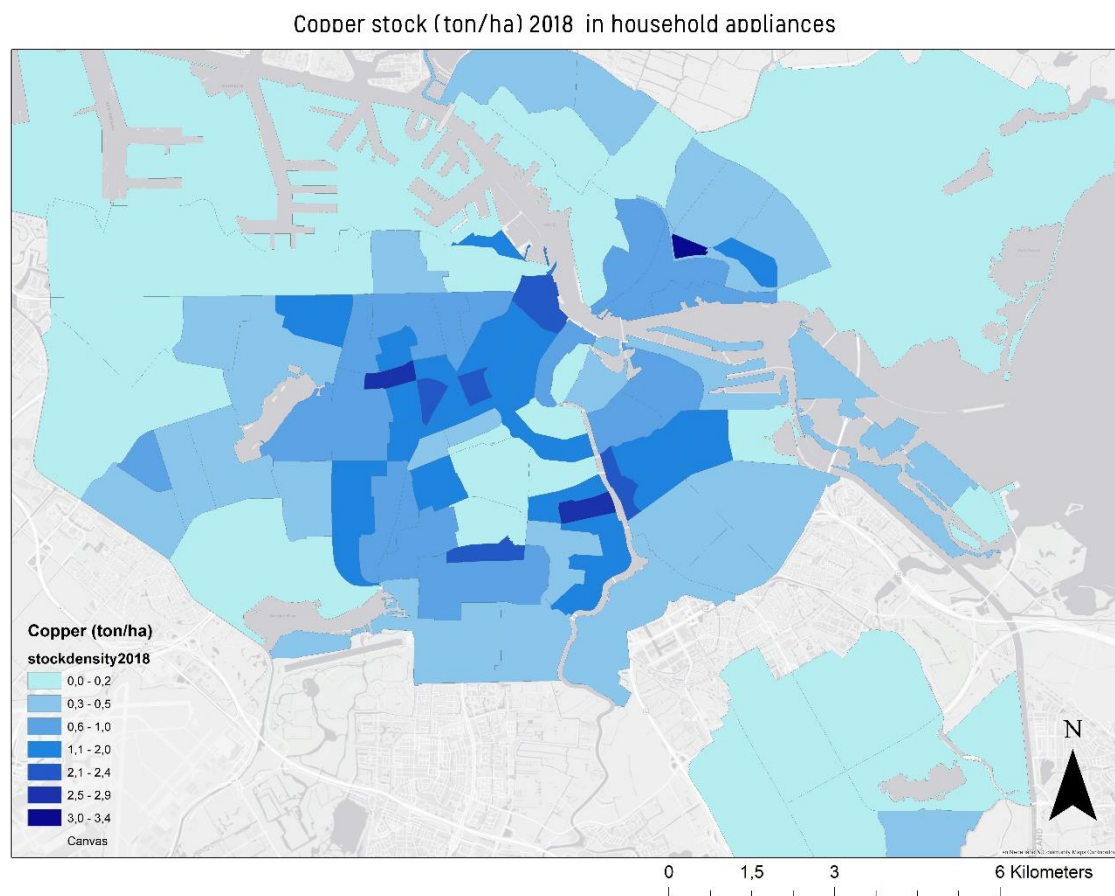
4.2.4. Household Appliances
The current stock
The copper contents and lifetimes used for calculating the stock dynamics can be viewed in appendix 2.5. The total stock of copper in household appliances in 2018 is estimated to be about 5000 tons. In this category, the main appliances containing copper are refrigerators (2 kg of copper per unit) and washing machines and microwaves (1 kg of copper per unit). The total stock per hectare is highest for the most densely populated areas.

Highest stock 2018	ton/ha	Highest inflow	ton/ha2	Highest outflow	ton/ha3
Tuindorp Buiksloot	1.8	IJburg Oost	1.1	Van Galenbuurt	0.51
Van Galenbuurt	7.1	Van Galenbuurt	0.6	Van Lennepbuurt	0.48
Zuid Pijp	5.8	Van Lennepbuurt	0.5	Overtoomse Sluis	0.47

Table 7 The geographic hotspots of copper in household appliances

Copper stock (ton/ha) 2018 in household appliances

Map 7 density map of stock of copper (ton/ha) in household appliances in 2018

The potential mine
In 2050 the stock of household appliances is projected to be grown to about 14000 tons. By combining the average amount of appliances per household with the projected population growth, and assuming that not all appliances that are returned after their end of life, an average inflow of copper per year is estimated per neighbourhood. The average lifespan of all involved appliances is 10 years, a much smaller delay than for example copper in infrastructure or buildings. Because the lifespan of

household appliances is short compared to the products in the other categories, the size of the outflow is relatively high, resulting in a high outflow.

Here as well, the areas that have a high household density and a high growth rate are the areas with the highest outflow densities. Thus, population density and population growth are the most important variables in this dynamic stock model of copper in household appliances.
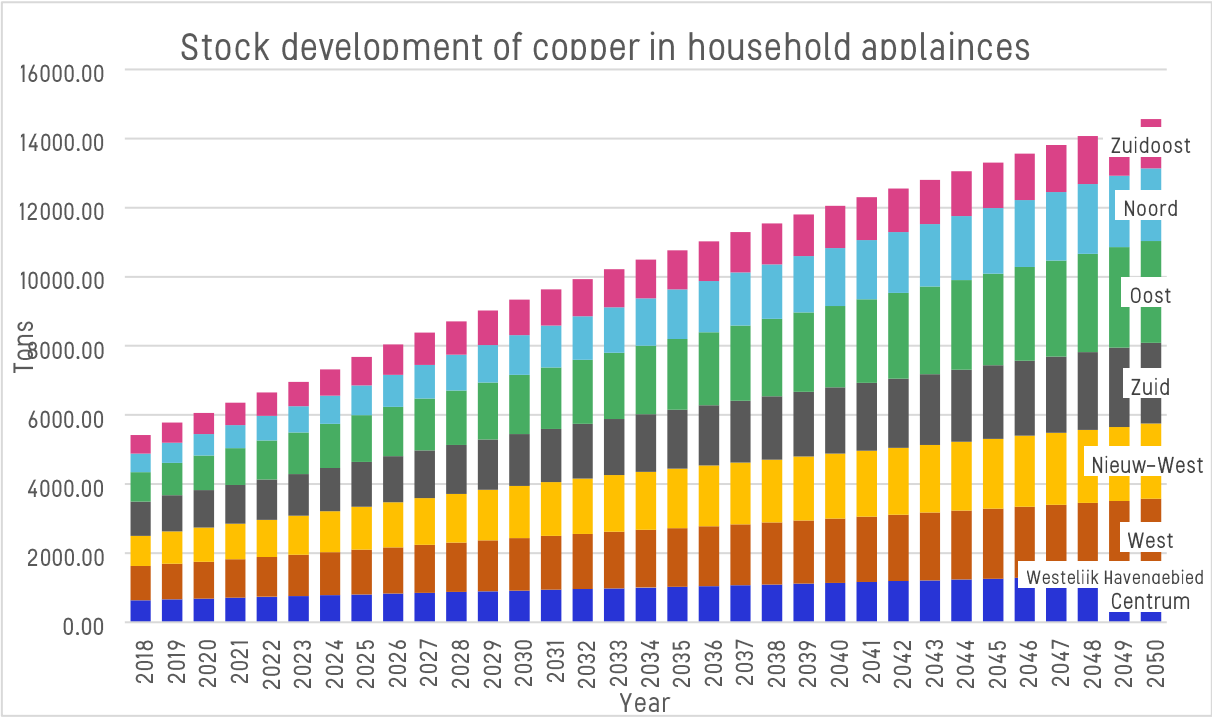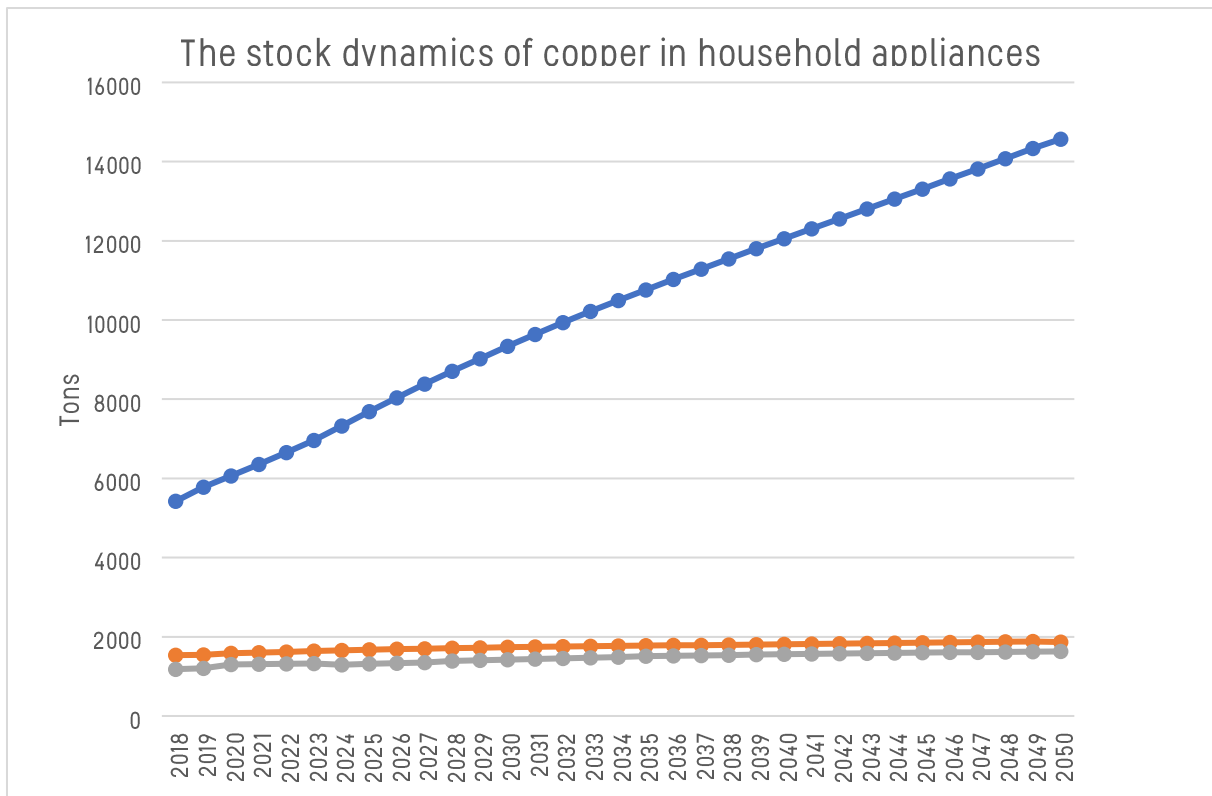

Figure 16 growth of stock of copper in household appliances

Figure 17 The stock dynamics of copper in household appliances

4.3 An energy transition scenario

Forms of electrification have been considered in the model, such as the increase of wind turbines, solar panels, electric vehicles et cetera. For some elements it is rather difficult to choose a pathway since there are many different pathways possible. This is the case for, amongst others, EV's, solar panels and heat pumps. These products all have a relatively high copper content. This part of the research has two aims: showing the impact on the copper demand if these products would be fully adopted. Secondly, exploring the combination of GIS and MFA for predicting the impact of policy measures on material stocks dynamics in the future. The scenario analysis is visualised in two ways. For cars a graph seemed to make more sense, since data about annual change was available and the distribution of cars depends on the distribution of households which can be visualised in the appendix. For solar panels and heat pumps a density map for the final stock seemed to make more sense: temporal change data is not available and hard to predict (when will people start installing panels on their roof?) and the distributions are dependent on interesting variables: roof surface potentials and gas connections.

4.3.1. Fast adoption of EV scenario

In this figure in appendix 2, the difference is visible between the speed of adoption of EV's between a business as usual scenario (BAU) and an energy transition scenario (ET). These numbers are based on national scenario projections done by Ecofys (2016). The numbers were converted to cars per capita per neighbourhood in Amsterdam and then summed per year, resulting in this graph. In the previous subchapter, for predicting stock behaviour of cars, the BAU scenario was incorporated in the model. Here, the ET scenario is modelled to get an idea of the effect on the copper stock dynamics in the future if electric vehicles would become the new normal for private transport. The additional copper needed when EV's would be adopted sooner is about 2168 tons (or 68 tons per year), on average 6% more than the inflow in a BAU scenario.
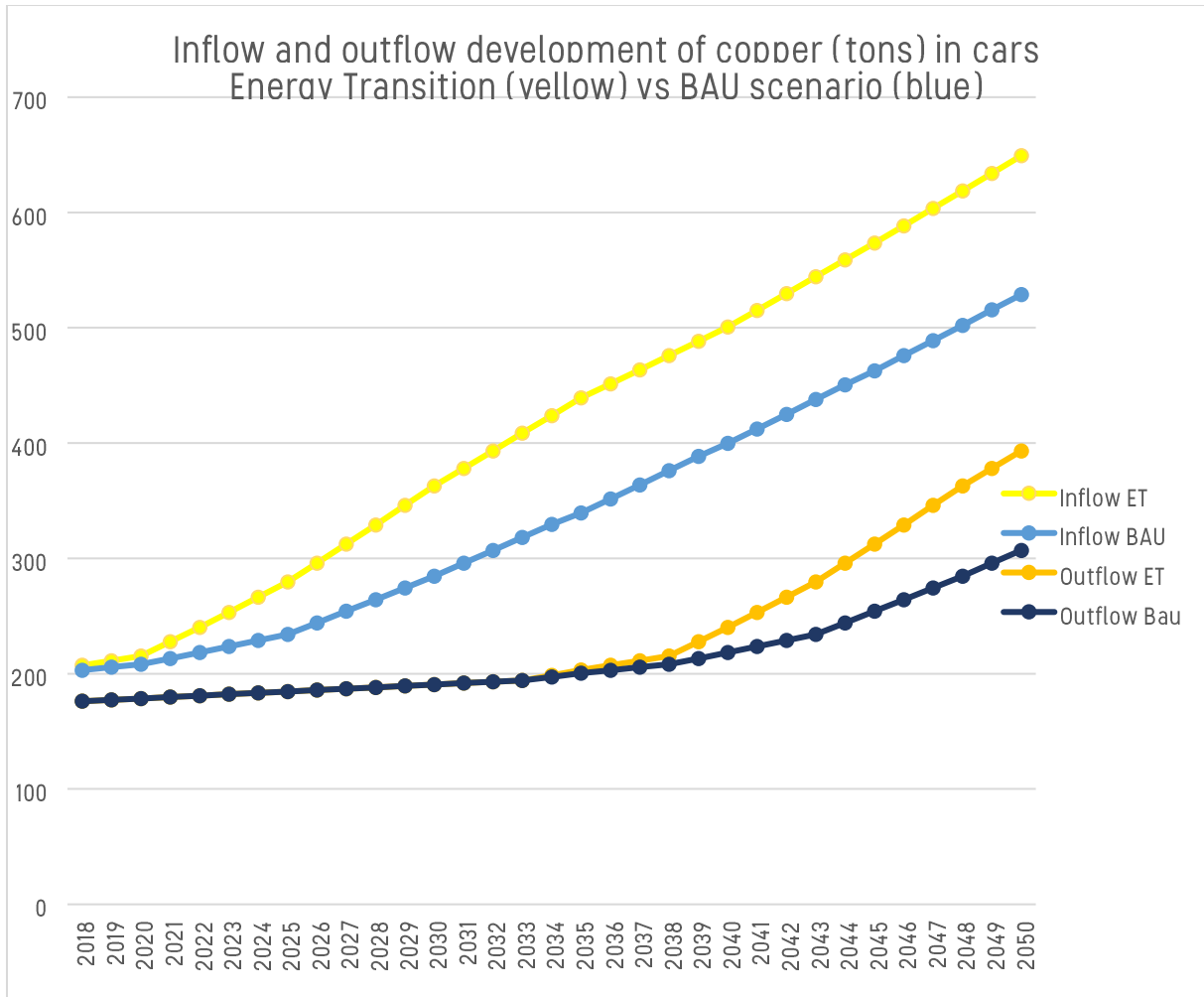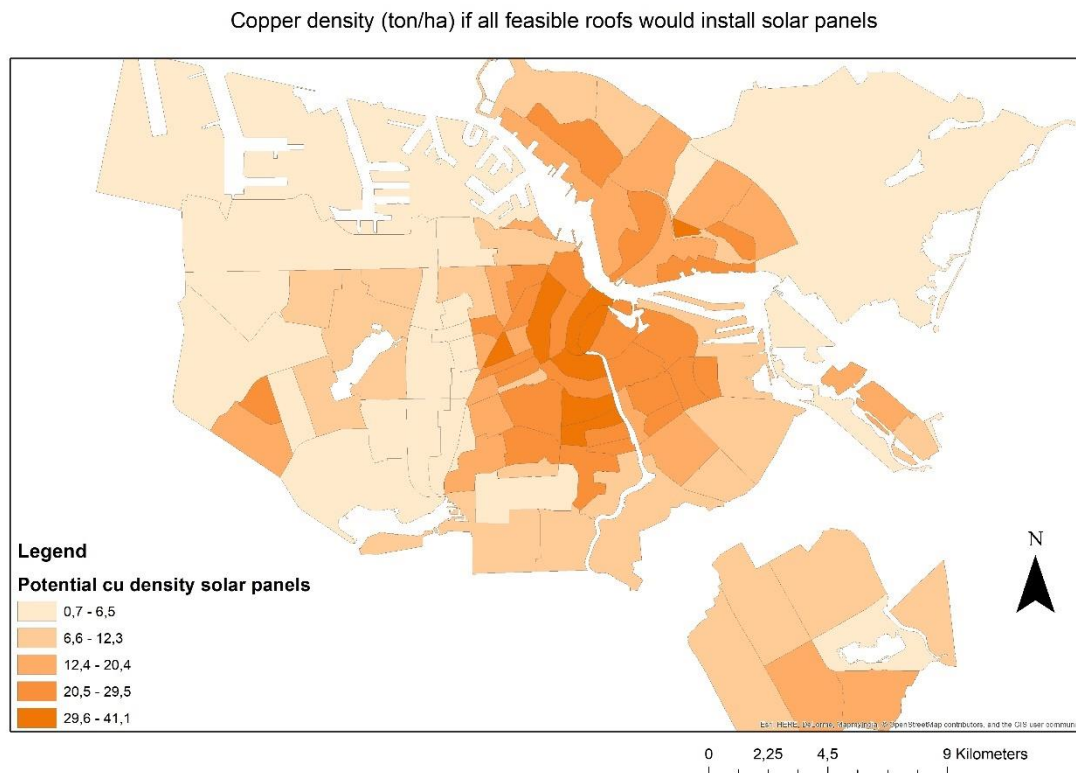
Figure 18 Graph of inflow and outflow of copper difference in an ET and BAU scenario for cars

4.3.2. Completely solar

In the previous chapter, it was assumed that the 50% of the feasible roof surface would have solar panels in 2050. In this scenario a 100% installation of panels on feasible roof surfaces is assumed. The energy atlas of Amsterdam contains information on the suitability of each roof for solar panels, and the potential energy it could deliver. If this potential would be used, from an energy perspective, a strong decrease of dependency on fossil fuels would occur. However, from a material perspective, a very strong increase of copper inflow could be expected as well, since the amount of copper in one m2 of solar panel is 0,14 kg. Mainly the centre and the North of Amsterdam would have a high inflow between 30 and 40 tons of copper. The average annual inflow of copper would become about 49 tons of copper per year. The impact on the copper demand would be at least 20 tons per year higher than during BAU scenario. The lifetime of a solar panel of 25 years results in a strong increase of the outflow starting in 2025.

Copper density (ton/ha) if all feasible roofs would install solar panels

Legend

Potential cu density solar panels

- 0,7 - 6,5
- 6,6 - 12,3
- 12,4 - 20,4
- 20,5 - 29,5
- 29,6 - 41,1

0   2,25   4,5   9 Kilometers

Map 8 The copper density (kg/hectare) if all feasible roof surface would be used for solar energy

4.3.3. From gas to heat pump

About 90% of all heat in residential buildings in Amsterdam comes from gas (Nuon, 2017). If the city of Amsterdam wants to achieve its goal of becoming a gas-free city in 2050, a big transition is necessary towards other technologies for heat production. There are multiple alternatives to provide households with heat of which one popular option is the electrical heat pump. According to Graedel (2003) a heat pump contains 22 kg of copper. While gas pipelines in Amsterdam do not contain copper, this would mean a large increase of copper use in the future. How much and where is visualised in GIS (map 9). The map demonstrates the copper demand per neighbourhood if each residential building would install a heat pump. In total, an amount of 9000 tons of copper would be required. Several new neighbourhoods are already on schedule and are not connected to the gas grid at all. These are the neighbourhoods across the IJ-oevers, Zeeburger Eiland and new areas in Nieuw West and Zuidoost. When excluding these areas, the map with floor area per hectare in appendix 1 is quite reflective for the future demand of copper for heat pumps.

Copper demand (ton/ha) if all residential buildings were to switch from gas to heat pumps

Cu density per hectare
TonCuDens
- 0,00 - 0,36
- 0,37 - 0,92
- 0,93 - 1,42
- 1,43 - 2,22
- 2,23 - 3,18

0   3   6   12 Kilometers

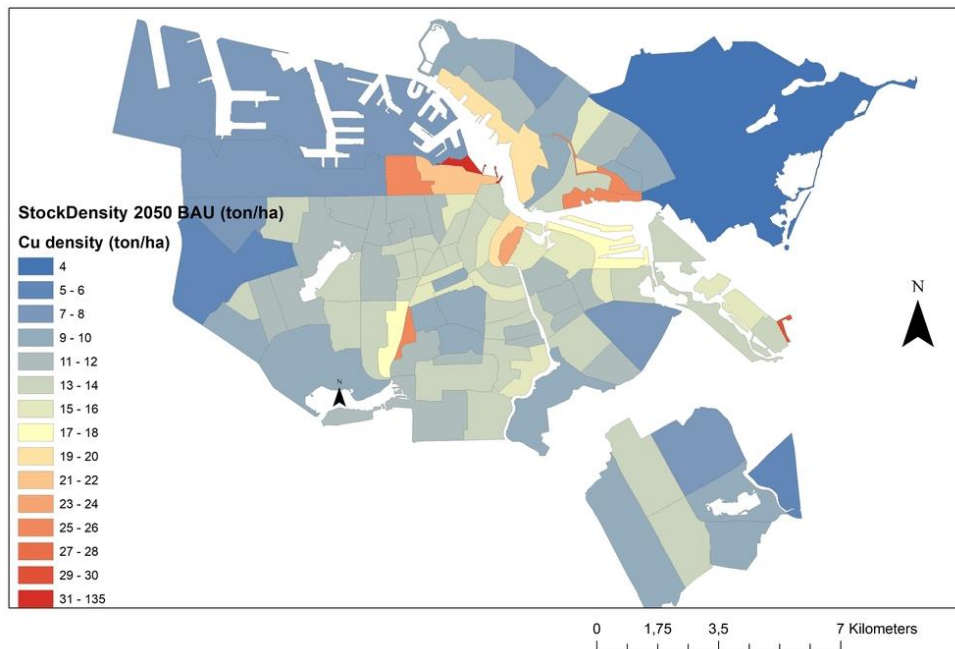*Map 9 Copper demand (ton/ha) if all residential buildings were to switch from gas to heat pumps*

4.3.4. The overall difference between BAU and ET

When all three energy transition scenarios would happen, the total stock of copper in 2050 would be higher than in a BAU scenario: 179000 tons (ET) against 166500 tons (BAU). This is a difference of about 12500 tons. To put this in perspective: this is about the same amount of copper currently present in the total stock in household appliances and transportation in Amsterdam. The additional copper per product to the stock in 2050 is described in table 8. Especially heat pumps would add a lot of copper, the same amount of copper in all our transport now, to the stock in 2050. To see the difference between the stock of 2050 in the BAU scenario and ET scenario, double click on map 10 and wait. The middle area around the centre, where population growth will speed up and development plans are ambitious (appendix 1), mainly light up. This shows the importance of these variables for the stock behaviour of copper.

Product	Additional copper in 2050
Cars	2168,3
Solar	1386,0
Heat pumps	9000,0

Table 8 additional copper to the copper stock of 2050 if ET scenario would happen

Total stock density of copper (tons/ha) in 2050. BAU scenario

StockDensity 2050 BAU (ton/ha)

Cu density (ton/ha)
- 4
- 5 - 6
- 7 - 8
- 9 - 10
- 11 - 12
- 13 - 14
- 15 - 16
- 17 - 18
- 19 - 20
- 21 - 22
- 23 - 24
- 25 - 26
- 27 - 28
- 29 - 30
- 31 - 135

0   1,75   3,5   7 Kilometers

Total stock density of copper (tons/ha) in 2050. ET scenario

StockDensity 2050 ET (ton/ha)

Cu density (ton/ha)
- 4
- 5 - 6
- 7 - 8
- 9 - 10
- 11 - 12
- 13 - 14
- 15 - 16
- 17 - 18
- 19 - 20
- 21 - 22
- 23 - 24
- 25 - 26
- 27 - 28
- 29 - 30
- 31 - 136

0   1,75   3,5   7 Kilometers
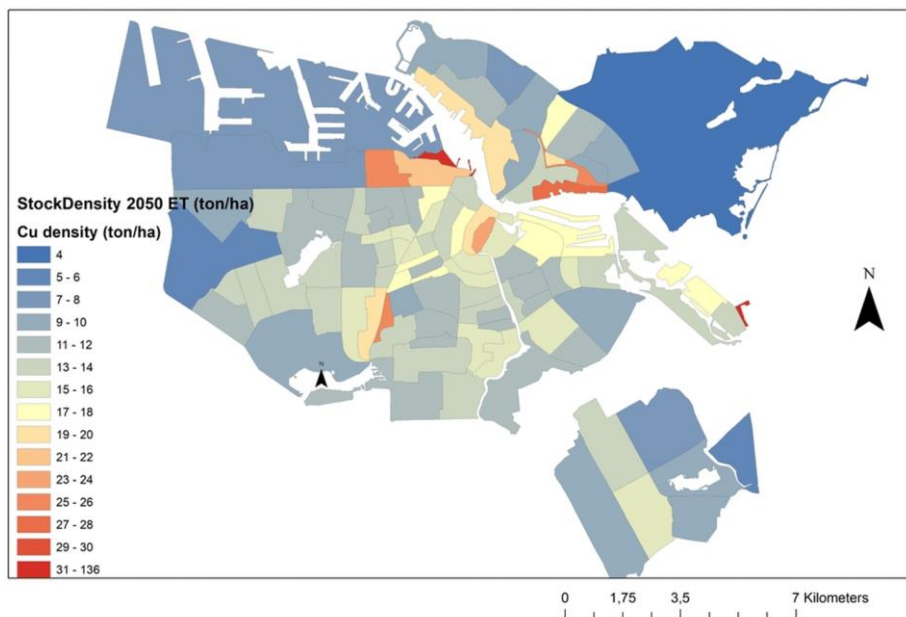
Map 10 DOUBLE CLICK FOR ANIMATION. Difference between stock 2050 in BAU and Energy Transition Scenario

4.4. Uncertainty

In an MFA, often data is sourced from many different sources such as individual measurements, expert interviews, online statistics and prospects. Consequently, it is difficult to quantify the uncertainty of the input data and the parameters. To deal with this issue, exemplary studies were sourced. As a starting point, the meta-analysis of Kirchherr's et al., (2016) was taken to see what kind of uncertainty analyses are fit for a prospective dynamic stock model. According to Kirchherr et al., (2016), half of the studies did not consider an uncertainty analysis, about a third applied a sensitivity analysis and a small group uses uncertainty intervals. A sensitivity analysis is useful for assessing the

relevance of uncertainties of the used parameters (Müller et al., 2014). The relevance is visible in the reaction of the models output to an increase or decrease of the selected parameter.

Parameters that can be changed in this thesis are: developing plans, population growth, copper contents, product lifetimes, uptake rates of new products, and proxy maps (see chapter 3 and appendix 2 for details about parameters). Since this research applies a prospective model, all parameters that concern future change are uncertain. The scenario analysis already shows the impact on the output if the future uptake/replacement rate of products change. Parameters that were often selected in other studies are average lifetimes, lifetime distributions, material intensity, scrap recovery rate, population size, stock saturation level and duration time (Kirchherr et al., 2016). The metal concentration levels in commodities was often found to have a high impact on the stock calculations. Thus, here, a sensitivity analyses will be applied to see the relevance of uncertainty of one of the copper contents of a product.

4.4.1 Sensitivity analysis

When we look at the copper content of floor area of buildings, this significantly differs in literature. What would happen to the output of the model if this variable would change here? The PUMA framework is designed for estimating copper contents in residential buildings and is based upon the height and surface area of buildings. All residential buildings are categorized according to these characteristics. Then, a possible copper range is linked to a building. This simple method is simplified in this research to an overall average of 0,3 kg/m2 floor area and expanded to all building types.

As demonstrated in the previous results, buildings contain a large part of the copper stock in this research. Therefore, the sensitivity analysis will be applied to this category. In the sensitivity analysis the average copper content per floor area will be changed to 0,6 kg/m2. Higher, because in other MFA studies of copper, copper content estimations were often higher than 0,3 kg/m2.

The steps of the model in flowchart 2 in chapter 3 are done again, but now with a material density of 0,6 kg/m2. The results of the category are summed with the other categories' stocks of 2018. The result of the increased copper content on the amount of copper in kilograms per capita is shown in table 8. When the copper content per floor area is doubled the copper content per capita changes with two thirds. This demonstrates that the impact of the assumed copper content, based on a simplification of the PUMA method, has a very significant impact on the outcome of the model.

The sensitivity shows the relevance of the copper density parameter. The more this parameter corresponds with reality, the more realistic and useful the output of the model. Currently it is highly uncertain that the used parameter corresponds with reality for two reasons. Firstly, the result of the validation check of the PUMA method, executed by the company Metabolic (explained before in chapter 2) showed that the estimated copper contents did not always correspond with reality. Secondly, the PUMA method was simplified to an average of 0,3 kg/m2, thereby the impact of floor area, age and height of the buildings on the amount of copper were neglected in the calculation.

Copper content	0,3 kg/m2	0,6 kg/m2	Change (%)
Cu kg/cap stock 2018	148	247	67

Table 9 Results of sensitivity analysis: total copper per capita if copper density parameter in buildings is doubled

4.4.2. Comparison

As a reality check, a comparison was done with other MFA studies of copper. Cities and countries differ in many ways; wealth, size, densities, building styles. Consequently, comparison of in-use stocks is problematic, unless the stocks are expressed in amount of copper per capita (Beers & Graedel, 2007). MFA studies of copper were collected and translated to copper per capita. As demonstrated in table 9, the resulting copper stock of this research (150 kg/cap) is closest to the copper stock per capita in Japan, New haven and Stockholm. In this research, industrial and commercial appliances are neglected however, which was not the case for Japan and Stockholm. Also, this

research has demonstrated that sources of data for input of and MFA model are dispersed and can be uncertain. Thus, comparing on a detailed level would only be interesting if all studies would have chosen the same categories and applied the same methods. To conclude, this small comparison study is only useful for determining whether the results of this study are within a realistic range: which is the case. It is in the same order of magnitude as the other results.

Categories	Area & year	kg/cap	Source
All categories	Sydney (2007)	605	(van Beers & Graedel, 2007)
All categories	Amsterdam (2016)	240	(LIN, 2016)
Buildings, infrastructures and mobiles	Switzerland (2000)	220	(Bader et al., 2011)
All categories	Cape Town (2020)	187	(van Beers & Graedel, 2003)
Buildings	Vienna (2008)	178	(Kral, Lin, Kellner, Ma, & Brunner, 2014)
All categories	Stockholm (2000)	170	(Bergbäck et al., 2000)
Excluding industrial and commercial appliances	**Amsterdam (2018)**	**150**	**this research**
All categories	Japan (2005)	146	(Daigo, Hashimoto, Matsuno, & Adachi, 2009)
All + scrap yards	New Haven, USA (2005)	144	(Drakonakis, Rostkowski, Rauch, Graedel, & Gordon, 2007)
All categories	Shanghai (2012)	51	(Liu, Xu, Zhang, & Zhang, 2014)
All categories	World (2013)	49	(Liu et al., 2014)
All categories	Taipei (2009)	28	(Kral et al., 2014)

Table 10 Comparison with other MFA studies of copper (kg/cap)

5.Discussion & Conclusion

This final chapter is used for elaborating on the most important assumptions that influenced the outcomes of the model. Here, also ideas and suggestions for additions and follow-up research are discussed. Secondly, the answers to the subquestions and the main question are provided. The main question is answered by discussing the scientific value of the method. The benefits of the method, but also the impracticalities are elaborated. Lastly the main question is answered by involving a discussion on the potential societal value. How could the outcomes or a research as this be of use for implementors of circularity and urban mining measures?

5.1. General assumptions and recommendations for a follow-up research

The most important assumption that was adopted before starting the model, is the assumption that a future where a paradigm exists in which strategies for local sourcing can be applied is likely to happen. This paradigm incorporates the strategy of modular and light construction. A way of building where no demolishment is necessary, just deconstruction, enabling direct reuse of the material in its surroundings. In such a scenario, where urban mining would be viable, this model would be of great use support mining plans for actors that are involved in construction and design of the city.

For deciding how the stocks are formed and how they will behave, inflow based, or historic numbers were found. Many times, however, assumptions had to be made, to keep the model simple. Some assumptions were formed before the model, and some were formed during the modelling. Before the calculations were done, a perspective was chosen from which new assumptions could be chosen. It was assumed that the main force behind future development of inflow were local policy goals. If the City of Amsterdam had set targets for the product that was modelled, these were used as final stock number. This was clearly done for inflow calculation of generation of electricity by wind and solar panels, electric vehicles, boats and bikes and buildings. For some products however (such as all household appliances) there were no clear ambitions formulated by the government. Then the growth assumptions were made safely, by assuming that ratio's or growth rates would continue as they did in the past.

Assumptions that are most likely to have influenced the outcome of the model are: 1. the copper content of the products we currently use will not change significantly, 2. the way change will occur is mainly determined by the policy and ambitions formulated by the current local government of the city of Amsterdam, 3. buildings contain the same amount of copper based on their size, 4. we will not shift towards a sharing economy for the next 32 years, 5. The city will continue to grow. Additionally, plenty of copper products were not considered (public, industrial and commercial goods), thus, there is a high possibility the mine is larger than the current estimation.

When compared to other material flow analyses, the chosen economic and demographic variables for the inflow (population growth, historic or projected demand-rates), the approach in this research is comparable for determining the inflow. Outflow of a substance however, is defined by leaching and delay (Elshkaki et al., 2016). In this research, only delay was incorporated in the model. It would be interesting in a follow-up research to incorporate leaching into the model and to see what happens to the outflow and how this can be spatially visualised. For modelling the outflow an average life span was applied. Many material flow analyses however used lifetime distribution functions. For a follow-up research a lifetime distribution function could be applied to see more detailed dynamics of the spatial and temporal behaviour of the stock.

Many follow-ups or additions to this research are possible. For example, the monetary value of secondary copper supplied per neighbourhood could be interesting to trigger attention to the gold mine

of copper we can find in the city. The environmental impact of the copper inflows and outflows in Amsterdam could be modelled by involving a research to the processing and transportation of copper flows. The data could be used to design an urban mining logistics plan for improving the business case of secondary copper by reducing storage time and transportation distance, and so on. On a personal note, as an industrial ecologist, it is sometimes harder to stick to one specific focus than to involve the many different aspects related to the interdisciplinary topics we study. During the process, especially during the writing of the research proposal, the scope of the research varied drastically. After plenty of conversations with the supervisors, and after deciding to ignore all the other aspects an MFA method can add to a research, and by using the Geographical Approach and the flowcharts in chapter 3 consistently, the final scope of the thesis became just about narrow enough to round up the research before the summer holidays. I would recommend the next young researcher to really choose a clearly narrowed down scope and stick to it to save a lot of time.

5.2. Answer to the subquestions

1. What is the current stock of copper within the built environment of Amsterdam?

In total the stock of copper in 2018 in this research is estimated to be approximately 130000 tons. This is about 150 kilos of copper per capita. The spatial MFA has demonstrated that the distribution of copper is mainly concentrated in the centre areas of the city, and less in the industrial and outer areas.

Of the total stock, buildings contain the highest amount of copper (about 84000 tons), then infrastructure (32000 tons), transport (9000 tons) and household appliances (5400 tons).

For buildings the highest amount of stock is around the centre, with high densities of buildings. The highest increase of the stock will occur around the centre. For infrastructure, the largest stocks of copper are found in the centre and in the port area. The highest increase of stock is expected for the newest districts in the outer circle. The copper stock in transport is scattered lightly but is mainly found in the densest areas with the highest amount of floor area per hectare, and the areas in which remises for trams and metros are located. And lastly the distribution of household appliances: the largest stock is found in the densest areas, of which mainly the areas are in the centre.

2. What socio-economic variables are important in future development of stock dynamics per copper category?

In this research, population growth, projected consumption rates, building plans, electrification goals set by the local government were used as variables of change. It can be stated that these variables will strongly increase the demand of copper. The total demand is estimated to be almost 6000 tons of copper per year. When analysed geographically, several maps with variables correspond with the density maps in the results chapter. The most important map seems to be the density of floor area (appendix 1): the higher the amount of floor area in a neighbourhood, the higher the stocks and outflows in this neighbourhood. Another important map that corresponds with the many of the results is the population growth map. In this map the population growth until 2050 is visualised per neighbourhood. These insights can make the process of data collection for urban mining easier: a floor area density map and a projected population growth map can quickly help estimate the areas with the highest copper densities.

3. How much copper can be mined annually from Amsterdam until 2050?

Until 2050, about 4000 tons could be mined from the city on an annual basis, as part of different products and elements. The contributions per category to the outflows of copper are different than their contribution to the stock of copper. Household applications are the smallest stock but cause the highest outflow (37% of the total flow). They are followed by copper from demolishment and

renovation of buildings (36%), copper in transportation (20%) (mainly in cars), and lastly infrastructure, where the outflow will mainly come from the electricity distribution grid and electricity production elements such as wind turbines and solar panels. Because household appliances have a short lifespan and thus cause large a large outflow, they are one of the most important categories to be taken in to account when exploring steps for urban mining.

Spatially, the overall stock is shifting to the middle circle, away from the centre. The stock is shifting towards areas with many known developing plans, where floor area densities are high and where prospected population growth is high. The centre seems to become saturated, with less space left for growth. The outer areas, such as Waterland or Westelijk Havengebied, still have very much space for growth. It could be expected, if the trend (visible in the moving map) continuous, that the future mine will eventually also become dense in these areas.

The stock of copper will increase with 31% between 2018 and 2050 in the business as usual scenario. In an energy transition scenario, the stock will increase more, with 41%. This indicates that the energy transition potentially causes a significantly higher demand for copper.

4. How can spatial and temporal information concerning stock dynamics of copper best be visualized and implemented in a circular action plan for Amsterdam?

The maps show which neighbourhoods are hotspots of copper stocks in 2018 and outflows for 2018-2050. Two animation maps help to see the change of the stocks in a fast way. Bar graphs show the development of the stock through time. When there are many products in a category, a line graph was used to show the development of the copper in the products. Thinking about visualisation of the mine is important for communicating the plans to actors that could play an important role in the implementation of urban mining. With animated maps of the future hotpot areas for urban mining, one can see in a split second which areas are important to take in to account in urban mining plans.

5.3. Answer to the main question

How can spatial-temporal stock modelling of copper in Amsterdam contribute to reaching circular economy ambitions?

The scientific value
The model developed and presented is a bottom-up prospective spatial dynamic stock model. It can be used for estimating the amount of copper within a geographic area, revealing its hotspots, and projecting its future inflows and outflows. It extends more generally applied MFA models by adding a temporal and spatial dimension. This methodology can lead to detailed spatial visualisation of the distribution of the current stock and future stock behaviour. It can give insights on the potential of the urban mine, and the potential demand of a material in a city.
For doing so, several socio-economic factors or explanatory variables are needed to predict future flows of copper containing products and thus of the substance copper. It is important that there is a strong basis of future projections to work with. In this case, future building plans, future population growth, policy plans and ambitions, and future consumer behaviour scenarios were very useful. Additionally, this methodology can show the potential material impact of policy plans. In this case, the energy transition ambitions were used as inputs for the model. The different impacts on the copper demand between the business as usual scenario and the energy transition scenario were significant. The combination of GIS and excel for modelling works but is labour and data intensive. It is recommended to see whether the modelling could become less labour intensive when GIS is combined with python, a readable language in ArcGIS.

The goal of an MFA is to track materials or substances within a system to reveal their behaviour and their potential impact. The analysis is done in steps, including an inventory of the current stock. GIS

partly contributed to this part of the research. Spatial data of length and amounts of rails for example, enables a quick and precise estimation of the copper stock in the railway system per area. Another part of the analysis where GIS was supplementary, was for prospecting the future behaviour of the substance. An example is the calculation of the potential roof surface within the city. Spatial data of roof characteristics was available for each roof in Amsterdam. With this data, no more than a simple calculation in GIS was needed for measuring the number of solar panels each neighbourhood could potentially install. Thus, GIS has been valuable in this MFA due to its addition of big databases, the results are even more informative: we now also know where the materials are located, and that an MFA can be spatially visualised.

For copper in products or entities that are linked to parts of the system defined by historic actions of actors in the city itself, lack of data often seemed an issue. An extremely important source of copper for example was the location and extent of the power distribution grid. An attempt was made to retrieve accurate data from the local energy provider Alliander, but they did not reply with useful data. There was a handful of options to try and estimate the (hibernating) grid below Amsterdam (in this case the road grid of Amsterdam was used as basis), but besides some other studies that attempted to estimate the hibernating stock and some public data of grids in other cities, the uncertainty of this estimation is high. The same is the case for the water distribution system, Waternet did send data about the size and amounts of copper, they however did not know the exact locations of the waterpipes. Knowing the quantities but not the location limits the possibilities for making a concrete plan for urban mining.

The potential societal value
A spatial temporal MFA research (of any material) can be useful for refining and rethinking the circular ambitions formulated by the government, to become fully circular in 2050. Firstly, because the quantitative results give an idea of the vastness of the outflow, the urban mining potential, of a material within a city in the future. This research has led to the insight that Amsterdam cannot by 100% circular at a local scale: its demand for copper is higher than its outflow. Additionally, a research such as this has demonstrated that policy measures that aim for sustainability, such as replacement of the gas grid by heat pumps or stimulating solar panels, have a significant impact on the material demand in the future. This indicates that governments will have to rethink the way they picture their country or city to become sustainable and take in to account, for example, for which materials, and on which scales they should aim for becoming circular.

For each category in this research, there are important actors for which the results of this study could be useful. The two largest stocks are shortly discussed.

For actors in buildings - it is not really clear who they are, one would think of companies that collect and process secondary materials (AEB in Amsterdam) - detailed knowledge of the spatial distribution of the mine and its potential behaviour could be of good use for improving logistics. When buildings are demolished or deconstructed, materials will be replaced and stored before they will be processed further. The longer the construction materials are stored or transported, the higher the (environmental/economic) costs. When a scrap collector knows how much and where potential copper flows will show up he can already create a plan to decrease the costs caused by storage and transport. Or, in a paradigm where buildings are not demolished but deconstructed and all elements can be reused right away, the materials do not even have to be stored or transported long: with the knowledge provided by this model, they can be reused as fast and nearby as possible, saving many costs.

A large copper stock is found in the power distribution grid. According to Wallsten, (2012), hibernating grids under cities are large. By involving hibernating stocks in the spatial visualisation and combining this with locations of renovation cycles, a plan could be made for mining large quantities of copper from the ground. Additionally, estimation beforehand by applying this method, helps to plan how much equipment will be necessary to get the grid out of the ground. Another important product in

this category are the forms of renewable energy. When material scarcity would be incorporated in sustainability criteria or ambitions, then it could be problematic to entirely focus on wind turbines, solar panels and heat pumps. This research can help to decide on whether limitations are necessary for implementation of renewable energy sources. Research to generate renewable energy with other, less scarce, materials (wooden wind turbines or example) could be triggered on time, before material scarcity become problematic.

If this type of analysis would be applied to all cities and villages, then, for every area the potential urban mine of the material could be revealed. This could benefit circular ambitions, as now actors know what and where they can expect outflows and inflows of all materials. They can improve their logistic and recycling scheme by anticipating to future in and outflows. The values and opportunities to reuse materials that are embedded in the city's metabolism could become common knowledge and incorporated in efficiently designed loops. If all data were to be collected, on a global scale, society could anticipate to material scarcity and start exploring alternative solutions on time.

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7. Appendix

Appendix 1 – Case study figures
1. Spatial Amsterdam
Map 1. Neighbourhoods and districts

Neighbourhoods and districts of Amsterdam
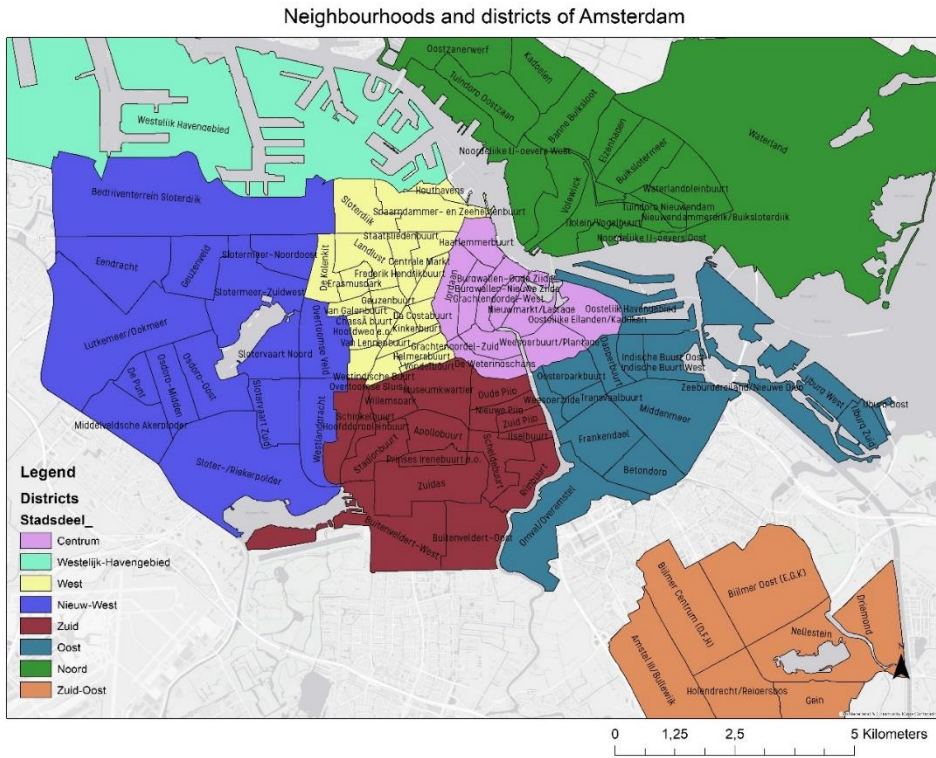
2. Demographics

Map 2. Demographics

Projected population growth (%) 2010-2050
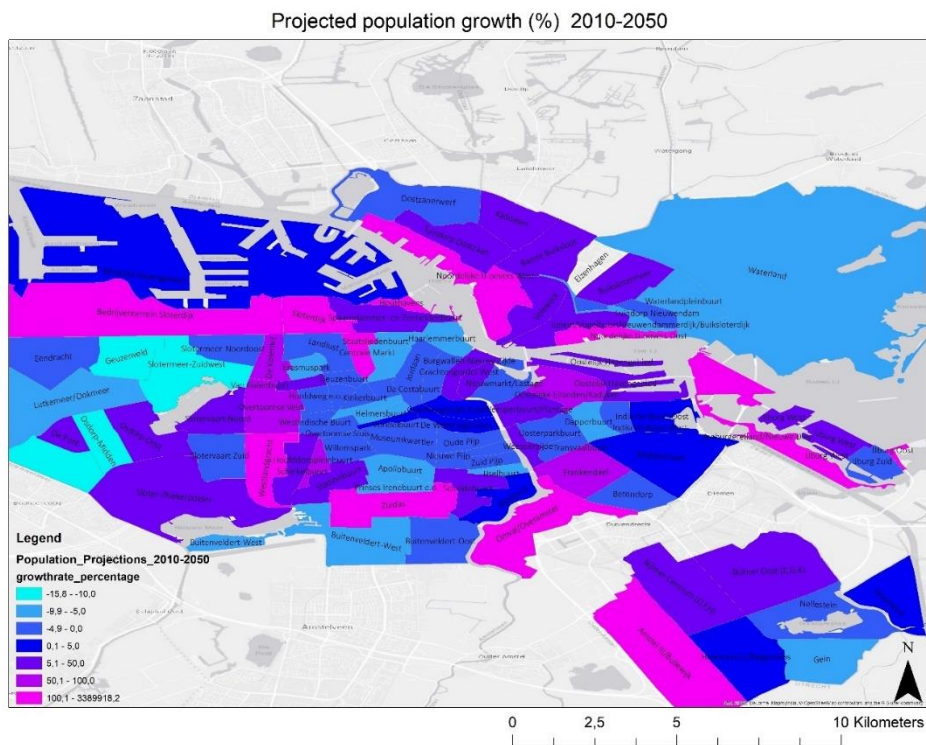
3. Spatial characteristics & public Data

3.1. Buildings

Map 3. Floor area density per neighbourhood

floor area (m2) per hectare

Map 4. Age of buildings

Average age of buildings in neighbourhood

Legend
Average Age Buildings
JAARMIN
1676 - 1704
1705 - 1800
1801 - 1900
1901 - 1920
1921 - 1930
1931 - 1940
1941 - 1953
1954 - 1970
1971 - 1980
1981 - 1990
1991 - 2000
2001 - 2009
futurespace

N

0   1,75   3,5   7 Kilometers

Map 5. Spatial plans

Areas of orientation for spatial change (buildings and infra) untill 2050

Legend
Neighbourhood
Decided areas
Strategic orientation

N

0   1,25   2,5   5 Kilometers

3.2.   Infrastructure

Map 7. Grid for water & electricity distribution

Roadgrid of Amsterdam

Map 7. Electricity production

Spatial data related to energy and water infrastructure Amsterdam 2018
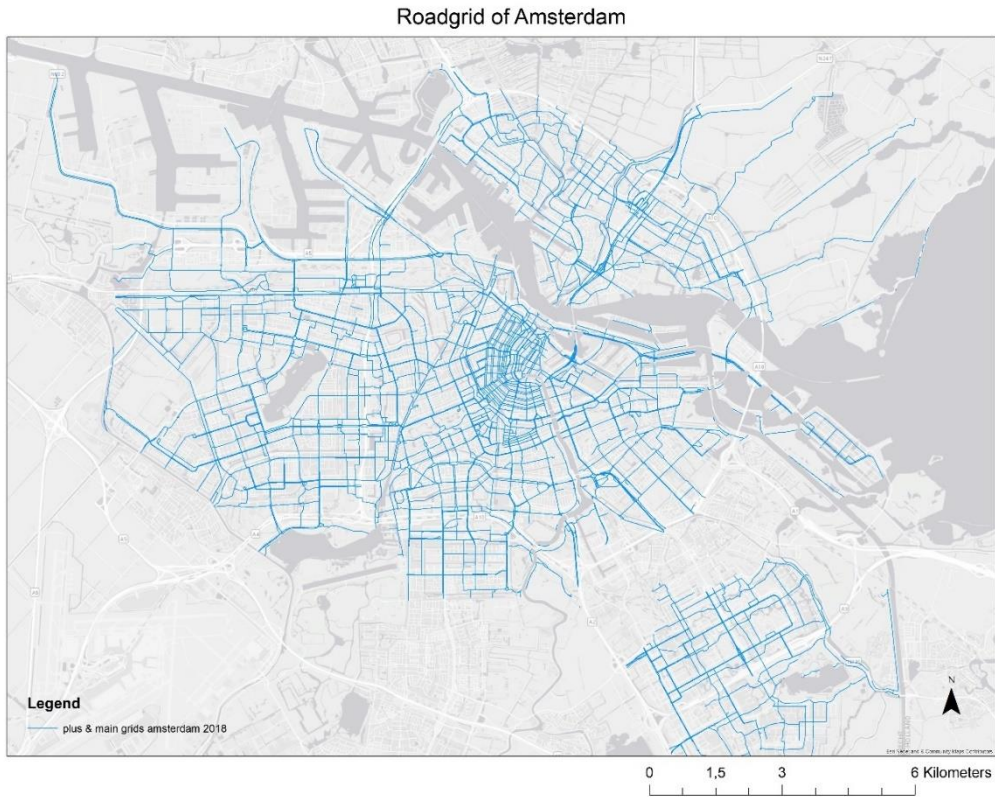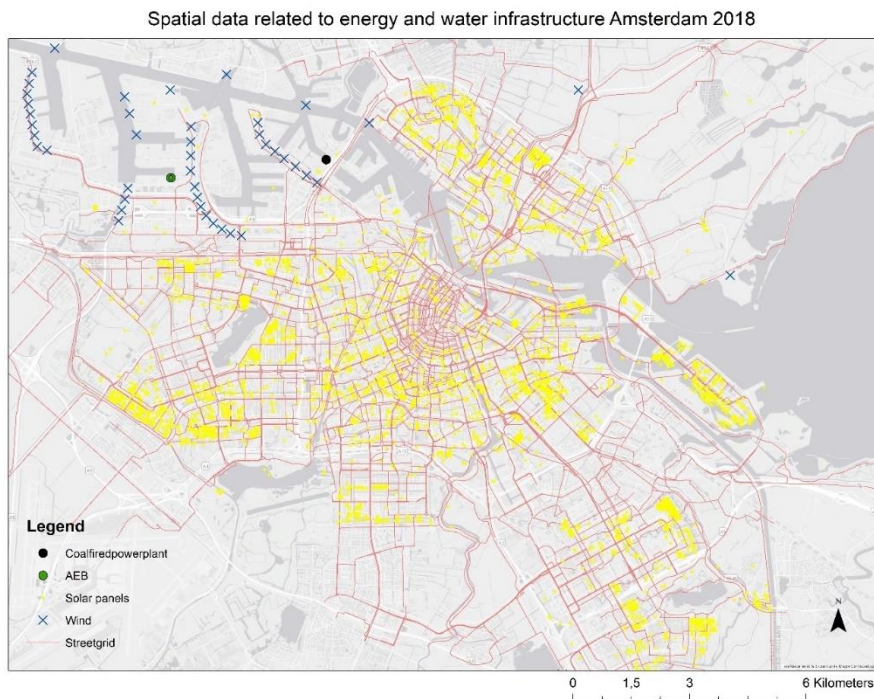
Map 8. railway system
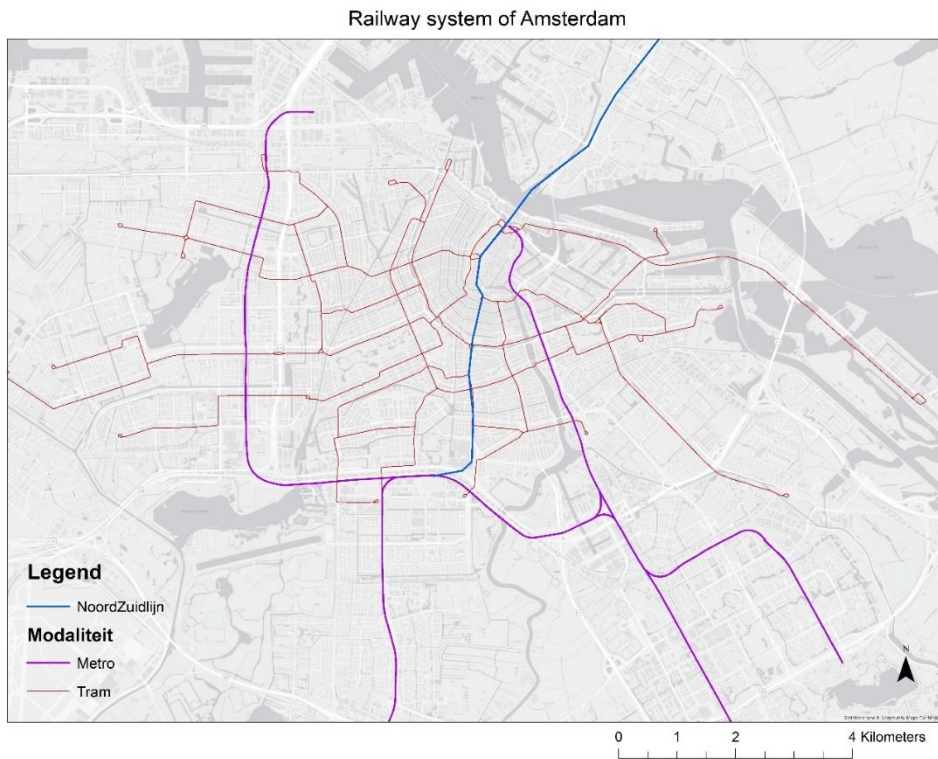
Map 9. EV charging stations
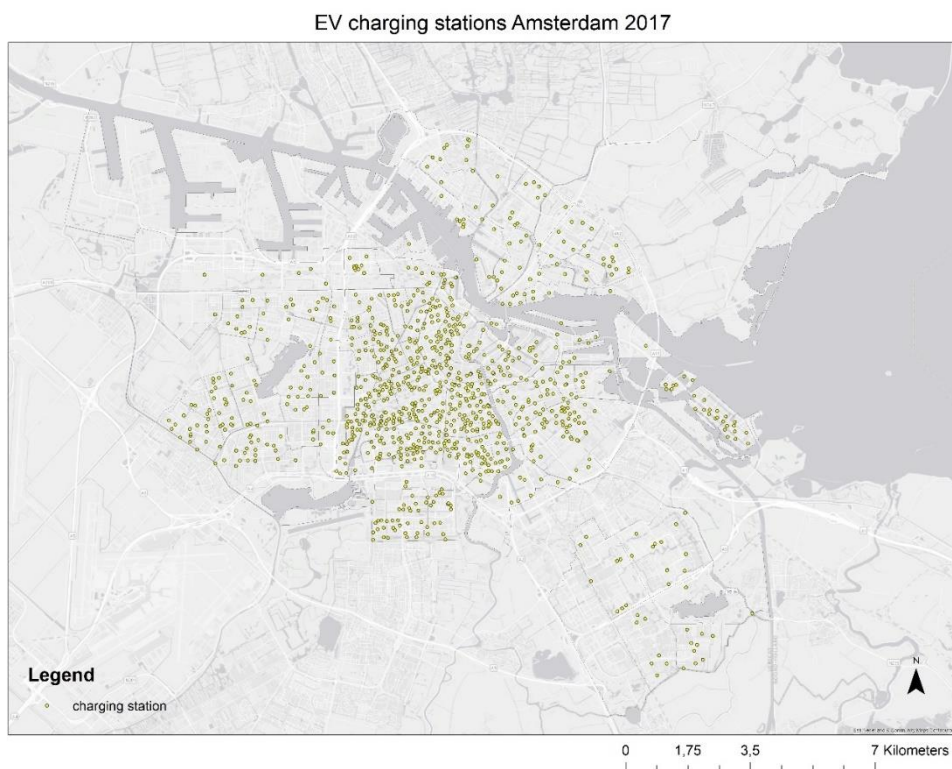
3.3. Transportation

Map 10. Locations of storage of public transport

Areas with depots for public/large tansportation
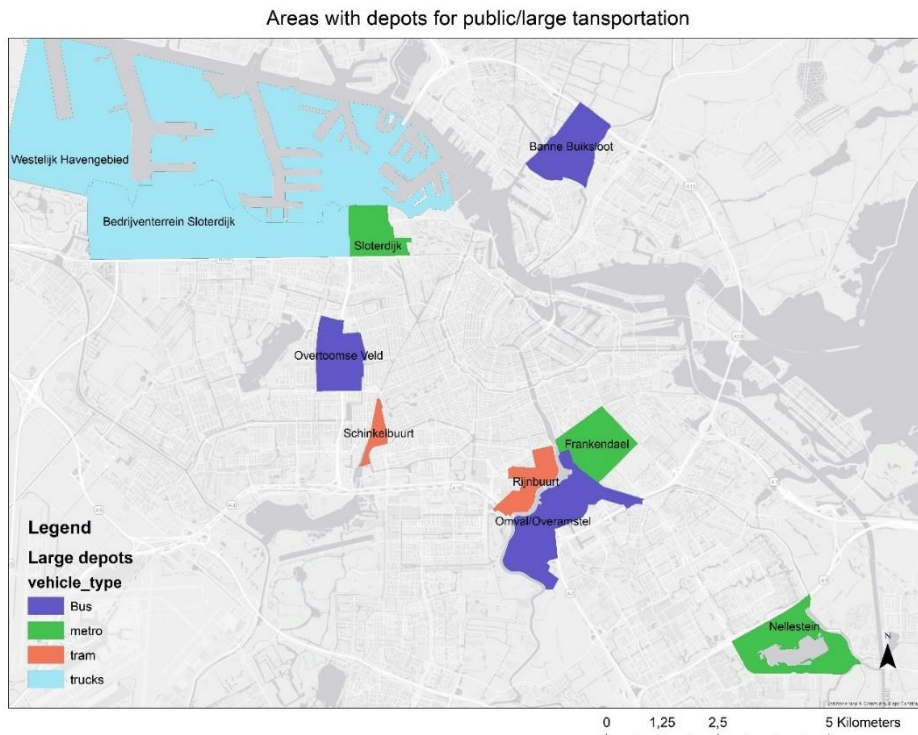
Appendix 2 – Detailed processes and assumptions

This appendix is structured as follows: for each category the steps, the trends and then a table and/or list with assumptions are listed for each product. Sometimes a product is more sensitive to trends or needed more research than others.

2.1. Buildings

Steps for mapping the current stock

1. WMS and WFS data with addresses, floor area and postal code areas retrieved from: https://api.data.amsterdam.nl/api/
2. Converted with QGIS to tables for excel and ArcGIS
3. Demographic and economic data per neighbourhood retrieved from https://maps.amsterdam.nl/open_geodata/
4. Json file conversion to shapefile 'stock layer'for ArcGIS > copied attribute tables to excel
5. Applied 0,3 kg to floor area per address
6. Inserted excel table in ArcGIS and summed tons per neighbourhood with Spatial Join tool

Steps for mapping future stock dynamics

1. Development plans retrieved from: http://afnemers.ruimtelijkeplannen.nl/afnemers2012/services?REQUEST=GetFeature&service

2. Converted WFS to QGIS and converted to esri layer 'strategic areas' for ArcGIS
1. Laid strategic areas layer over 'stock layer' in ArcGIS and joined tables for excel
2. Added 7200 units (floor area of 80 m2) per year in neighbourhoods in strategic areas in excel until 2023
3. Added 5000 units (floor area of 80 m2) per year in neighbourhoods in strategic areas in excel for each year in 2023-2050
4. Applied renovation to a max of 2% of the building stock with a lifetime of 25 years in excel, assumed input = output.
5. Applied historic inflow and outflow tabs in excel to stock tab in excel resulting in three tables showing inflow, outflow and stock change per year per neighbourhood between 2018-2050

Tables/figures/descriptions with assumptions and projections per product

Buildings	Amount	Unit	Source
Average cu per m2 according to PUMA	0,3	kg/m2	Huele et al., 2015
Average cu per residential appartment	0,02	ton/unit	Huele et al., 2015
CU-Service buildings	0,5	kg/m3	Kleemann et al., 2016
Renovation/newly built ratio	2		Meijer (2009)
Renovation cycles (used)	**25**	**years**	**Hoog, 2018**
Inflow after 2023	5000	appartments/year	Hoog, 2018

1. For estimating the current stock it was assumed that every m2 contains 0,3 kg of copper. This was multiplied with the amount of floor area per address.
2. For estimating future inflow until 2023 it was assumed that 7200 apartments are annually added to the housing stock in the strategic development areas.
3. For estimating inflow 2023 it was assumed that 5000 units are added to the building stock in the strategic development areas.
4. For estimating future inflow and outflow, a renovation rate of 2% per year was assumed, applied to the building stock that had a lifetime of 25 years in the year of consideration. Additionally it was assumed that half of the copper entities in the selected building stock for renovation are replaced during renovation.

The PUMA method uses the following baseline metal content assumptions for copper:

- <55m2: no significant presence, or no different facilities than 55-75m2
- 55-75m2: 1 kitchen, 1 bathroom, 1 separate toilet
- 75-150m2: additional amount of copper in wiring, tubing and tabs and double amount as compared to 55-75m2
- 150-300m2: second bathroom and/or toilet, amount of copper in wiring, tubing and tabs and triple amount as compared to 55-75m2.

Due to lack of data, time and knowledge for buildings in the Netherlands, the average amount of copper found when the PUMA method was applied to the building stock (an average of 0,3 kg copper/m2 of floor area) was used for estimating copper contents in all types of non-residential buildings. For comparison there are some methods found in literature used earlier to estimate copper composition in buildings in other countries. Kleemann et al (2016) used a similar method which he applied to 6 different types of buildings, which resulted in the cu averages showed in the table below. From this table there can be concluded (when the cu content in all three hospital buildings is averaged) that the overall average of cu per m2 is about 0,34 kg cu/m2. Service buildings here, on average contain 2,88 times more cu then residential, industrial buildings contain 0,03 times the amount of cu in residential and commercial contain 0,57 times the amount in residential buildings. The average of 0.3 kg/m2 floor area is also compared with estimations done by Rauch (2007) and Drakonakis (2006), whos estimations do not differ strongly when averaging out the lower amounts in industrial buildings and the higher amounts in commercial or other functional buildings.

Kleemannn method (2016)						
Building type	m2	m3	completion	cu kg/m3	cu kg/m2	Compared to residential
Residential	18000	60000	1970	0,11	0,36666667	1,00
Hospital	6033,33	26733,33	1944,33	0,18	0,76	2,07
Inudstrial production	3900	21000	1900	0,0019	0,01023077	0,03
Commercial residential	1100	3700	1859	0,062	0,20854545	0,57

Cu content of buildings by Kleemann (2016)

2.2. Infrastructure

Steps and rules for producing maps

Power generation:

For each form of generation (coal, biomass, solar, wind etc) an address or coordinates were found to which the cu stock was allocated in GIS

Power distribution:

A total amount of copper was calculated and divided by the roadgrid of Amsterdam. This lead to an average amount of copper per meter of road. This way an estimation was done of the grid density per neighbourhood.

Water distribution:

The same way as for power distribution.

Streetscape:

For both traffic lights and street lights an average amount and distance was linked to the roadgrid of Amsterdam.

EV points:

A map was provided on maps.amsterdam.nl with EV points. The growth was linked to the growth of EV's per neighbourhood and assumed that for every 10 EV's a charging point was installed.

Tables/figures/descriptions with assumptions and projections per product

Stock Power generation

Solar energy production	Amount	Unit	Source
Cu content panels	0,114	kg/m2	Latunussa et al., 2016
Weight of solar panels	10	kg/m2	Zonnepanelen.net 2018
Wind turbines			
Lifetime	25	years	USGS, 2011
Cu content	3	tons/MW	USGS, 2011
Coal			
Cu content	650	Ton	Lin, 2016

Inflow development wind:

Goals in windvisie (2012)
2020: 85 MW by wind
2025: 250 MW
2040: 400 MW

After 2040, growth of 10 MW/year

Inflow development Coal:

After 2034 the coalfired powerplant at the Hemweg will close down (Lin, 2016)

Inflow development solar:

It was assumed that ever roof with a high feasibility for solar panels would be covered with panels by 2050 with an annual growth rate of

Stock Power distribution

Electricity distribution			
Cu content	48000	kg/MW	Zhang, 2011
Lifespan	40	years	Wang and Graedel, 2009
Cu in cables	2,2	kg/m	Bateman
	2017	2018	
Growth of amount of connections to grid	460400	465000	Alliander, 2018
Growth of connections to gas grid	379600	379000	Alliander, 2018
Renovation	during renovation cycles of buildings and infrastructure		Alliander, 2018
Cu stock AMS electricity distribution 2015	60000	tons	Lin, 2016
Cu stock in 2030	100000	tons	Lin, 2016
Cu stock in 2050	104000	tons	Lin, 2016

Inflow development:

Part of the grid is already counted for by estimating an average amount of cables per building in the building chapter. The part of the grid that is not part of buildings has to be estimated, as there is no spatial data available about how and where the cables are located in Amsterdam. It is assumed that under every road there is a cable. As basis for the estimation, a map with all roads of Amsterdam is used.

Stock Water distribution

Water distribution	Amount	Unit	Source
stock water distribution pipes	410	ton	Lin, 2016
length copper main pipes	208.410	m	Waternet, 2018
Lifetime pipelines	100	Years	Waternet, 2018 Assumed (for using roadmap as basis since no spatial data
watepipe/road	0,181		pipelines)
copper in water pipes	2,2	kg	Waternet, 2018

Inflow development:

Installation of new waterpipes occurs along with development plans. The percentage of the pipes that is installed more than 68 years ago is assumed to be replaced during the next 32 years (since the lifespan is 100).

Stock Railwav

Railway	Amount	Unit	Source	
total rail length	482,425341		OiS, 2018	
total cu stock	879,540276			
Length of opstelspoor	1	km		

cu content	1,79	ton/km	GVB, 2016		
lifespan	35	years	GVB, 2016		
So next ten years:	2018	2020	growth	added	
Sloterdeijk	4	12	200%		8
Frankendael	11	15	36%		4
Nellestijn	4	6	50%		2
Assumption: every year the 6% of railway gets renovated				Lin, 2016	

Inflow development:

It has been 35 years so the depotrails will be renovated soon. Consequences: Isolatorweg: 12 new rails, Amstel: 15 new rails and Gaasperplas 6 (Municipality of Amsterdam, 2018).

EV charging points

EV points	amount	unit	source
Cu content	1,58	kg/unit	Johansen, 2013
Cu content	0,000158	ton/unit	
Lifespan	30	years	Engholm et al., 2013
Points per EV car	10	units	Nuon, 2018

2.3. Transport
Steps and rules for producing maps

Two different methods were applied for transport, depending on whether the form of transport was owned privately or publicly. For private vehicles an average number per household was found. This was multiplied by the amount of households per neighbourhood. Then trends were translated in to growthnumbers per household to project the input. For boats a possible degree of saturation of the canals was taken into account by incorporating the maximum hectares of the canals in to the calculation.

For public cars, precise numbers were provided in the city's database. When renovation or consumption plans were known, (often found in news letters or on their website), this was used as basis for inflow development. When this was not known, average lifetime of the vehicles and historic stock numbers were combined to calculate future outflows, and inflows.

Tables/figures/descriptions with assumptions and projections per product

Cars

Cars			
# EV's 2020	40000,00	vehicles	City of Amsterdam (2009)

# EV's 2040	200000,00	vehicles	City of Amsterdam (2009)
cu content motor vehicle	14,00	kg/vehicle	Beers & Greadel, 2007
cu content conventional car	15,00	kg/vehicle	Riotinto, 2013
cu content hybrid car	35,00	kg/vehicle	Riotinto, 2013
cu content electric car	60,00	kg/unit	riotinto, 2013
lifespan	18	years	WBCSD, 2004
Cars/citizen	0,33761044	units	OiS, 2017
Conventional cars/citizen in 2017	0,32511389	units	OiS, 2017
Evs/citizen in 2017	0,01249655	units	OiS, 2017

Stock calculation & visualisation: average car/capita * popnbrhd

Inflow development:

Scenario 1: Business as usual

Type auto	2015	2020	2025	2030	2035
PHEV	78.100	81.600	215.100	450.500	711.400
BEV Zakelijk	8.000	44.900	146.500	487.700	581.100
BEV Woon-werk	0	3.400	120.700	497.200	933.700
BEV Prive	0	800	35.400	179.000	630.000
BEV Carsharing	300	800	4.200	23.400	65.800
BEV Autonoom	0	0	0	0	3.500
BEV Bestelauto's	1.500	1.400	14.900	95.200	233.900
Totaal	87.900	132.900	536.800	1.733.000	3.159.400

Jaar	Thuis-laadpunten	Publieke laadpunten	Werk laadpunten	Autodeel laadpunten	Autonoom rijden laadpunten	Corridor snellaadpunten
2016	60.000	17.000	12.600	300	0	Een goed dekkend netwerk van corridorladers is leidend
2020	78.300	45.500	50.900	800	0	
2025	274.000	178.000	208.000	4.000	0	
2030	721.000	579.000	570.000	23.000	0	910
2035	967.000	961.000	741.000	66.000	170	1.050

Table 11. BAU scenario Future scenarios of EV (Ecofys. 2016)

Scenario 2: Versnelde energietransitie

Type auto	2015	2020	2025	2030	2035
PHEV	78.100	122.800	267.600	488.900	659.700
BEV Zakelijk	8.000	106.000	574.600	804.700	822.700
BEV Woon-werk	0	66.900	536.300	1.134.100	1.696.600
BEV Prive	0	16.900	215.500	853.300	1.673.700
BEV Carsharing	300	800	4.200	23.400	65.800
BEV Autonoom	0	0	0	0	3.500
BEV Bestelauto's	1.500	13.700	120.700	344.400	562.700
Totaal	87.900	327.100	1.718.900	3.648.800	5.484.700

Jaar	Thuis-laadpunten	Publieke laadpunten	Werk laadpunten	Autodeel laadpunten	Autonoom rijden laadpunten	Corridor snellaadpunten
2016	60.000	17.000	12.600	300	0	Een goed dekkend netwerk van corridorladers is leidend
2020	187.600	145.800	157.200	800	0	
2025	845.000	717.000	698.000	4.000	0	
2030	1.477.000	1.342.000	997.000	23.000	0	2.200
2035	1.698.000	1.798.000	1.036.000	66.000	170	2.080

Table 12. Fast Energy Transition scenario. Future scenarios of EV. Ecofys (2015)

Result of two scenario's of Ecofys for EVE development in NL:

Forecast amount of EV's NL 2015-2035 (Ecofvs)
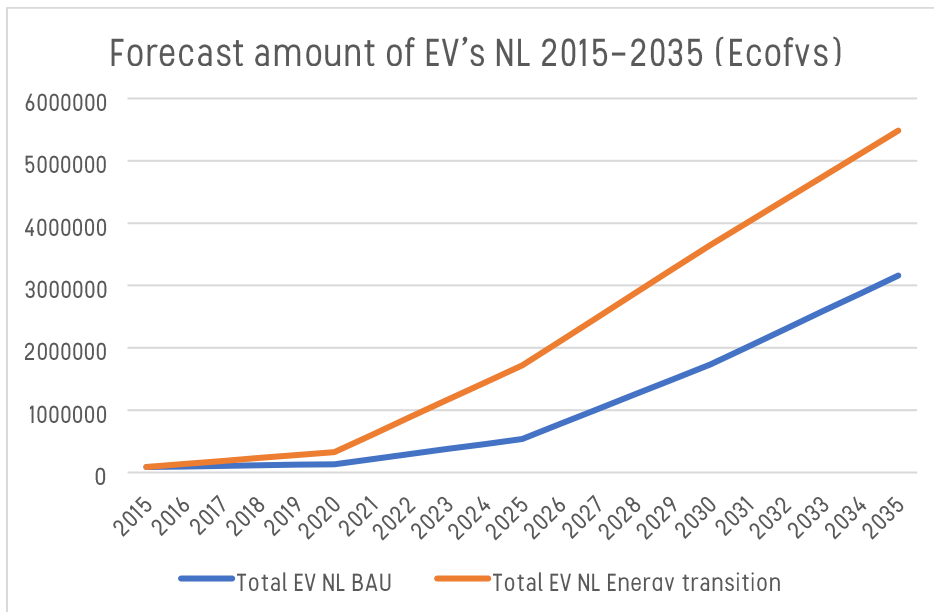
Graph of development of EV and conventional cars BAU and Energy Transition Scenario:

Development of Electric vechicles/Conventional vehicles in Enerav Transition Scenario (vellow) and BAU scenario (blue) in Amsterdam
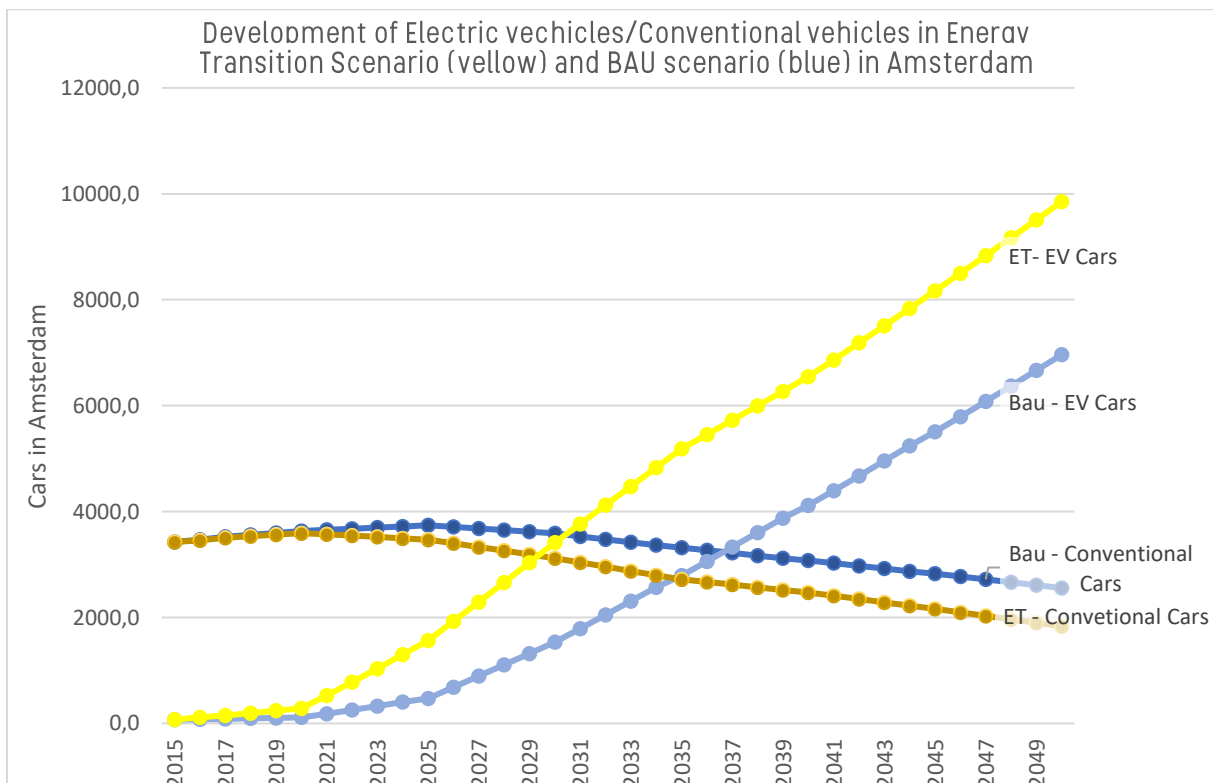
Stock Public transport (metro's. trams and busses)

Public Transport			

Cu in metro's	3,00	%	Siemens, 2006
Metrotype Metropolis, amount: 28	190,00	ton	GVB (2018)
Metrotypes CAF & S, amount: 62	48,00	ton	GVB (2018)
automotive equipment, railway equipment, ship building, aviation	20-40	years	Beers & Greadel, 2007
Cu in Railway transport	23,00	kg/m	Beers & Greadel, 2007
Average weight of metro's	92,18	ton	
Amount of trams AMS	211,00	units	GVB, 2016
Average weight of tram	35	ton	GVB, 2016
Copper in trams	1,00	ton	
Cu content in electric bus	219,00	kg/unit	Cherry et al., (2009)
Cu content in hybrid bus	212,00	kg/unit	Kärnä, 2012
Cu content in diesel bus	109,00	kg/unit	Kärnä, 2012
Lifespan bus	18,00	years	WBCSD, 2004
Annual growth EB's	2,00	units/year	
EB's goals	100% electric by 2025		Municipality of Amsterdam
Amount of busses in 2015	280,00		CBS, 2015

Development input metro's

Stock calculation & visualisation: sum of all metro's/m2 of opstelterreinen

Amount: 90

Isolatorweg: 4 opstelsporen, Amstel: 11 and Gaasperplas 4 (Municipality Amsterdam, 2014). Diemen as well but no part of Amsterdam.

1977: first metro's +30

1997: second metro's +30

2016: Metro's north south line +30

2021: 30 new CAF M7 metro's replacing old S2 metro's and increasing stock +30 -15

2024: 15 new CAf M7 metro's replacing S3 and increasing stock +15 - 8

2027: 15 new CAF M7 metro's replacing M4 and increasing stock +15 -7

2050: stock = 150

CAF M7 = 60 meter long (OVmagazine 2018) (instead of 112 like older ones)

2050: 150 Metro's (LIN, 2016) Increase because night economy, densification of urban functions, increase of use of PT and more connection Amsterdam and metropole area.

Future stock: It has been 35 years so the optselterreinen will be renovated soon. Consequences: Isolatorweg: 12 opstelsporen, Amstel: 15 and Gaasperplas 6.

Development of input Trams

Stock calculation & visualisation: sum of all trams/m2 opstellterreinen

Data: 200 trams, 213 km rails(Amsterdam.org)

Remise Havenstraat, Havenstraat 18 1075 PR (8 tramlines)

Remise Lekstraat, Kromme Mijdrechtstraat 25, 1079 KN (6 trams)

In 2019: 63 new 15g-trams will replace old trams (OVmagazine 2018)

Development of input busses

Stock calculation & visualisation: sum of all busses/m2 opstellterreinen

Amount: 203

Locations: Garage West, Jan Tooropstraat 647, 1061 AE

Garage Zuid, Joan Muysjenweg 29, 1114 AN Amsterdam Duivendrecht

Garage Noord, Metaalbewerkerweg 23, 1032 KW

Stock Boats:

boats			
Cu content Canal Cruise	250	kg	NSRP, 2013
Cu content Leisure boats <12m	37	kg	NSRP, 2013
cu content 24 m ferry	300	kg	port of amsterdam, 2013
Boats/hectare of canal in Adam	7,70249453	Units/hectare	
Assumed amount of cu in conventional boat	3	%	Hess et al., 2001
Assumed amount of cu in electric boat	12	%	Conventional car = 15 kg and EV = 60, so EV is 4 times more cu
Annual output of wrecked boats	700	units	Amsterdamfm.nl, 2014
Annual consumption in NL of new boats	1200	units	http://www.waterrecreatieadvies.nl/nl/crowdfunding/aantal-nieuwe-boten.html
Annual consumption in Amsterdam of new boats	60,2337882	units	http://www.waterrecreatieadvies.nl/nl/crowdfunding/aantal-nieuwe-boten.html
Boats in center	3300	Units	Municipality Amsterdam, 2015
Estimated total boats	15000	Units	Municipality Amsterdam, 2015

Stock calculation and visualisation: sum of all boats / m2 of sailing water within ring

Stock ebikes

ebikes			
Cu in motorcycles	2,77	kg/unit	Lin, 2016
Cu in electric motorcycles	15,98	kg/unit	Lin, 2016
E-bike share NL	6,14%	%	cbs, 2017
Bikes in Amsterdam	900000	units	OiS, Amsterdam

E-bikes in Amsterdam	55260	units	
E-bike /capita	0,06468333	unit/cap	
lifetime e-bike	6	years	
copper content e-bike	1,62	kg	Sho Lin, 2016
forecasted growth rate ebikes	4%	%	bike-eu.com/sales-trends
annual forecasted growth rate ebikes	0,5	%	

2.4. Appliances

Steps and rules for producing maps

Since the historic inflow is not known, for the coming 10 years (the average lifetime of HA) an average national disposal rate is used for modelling the outflow. Afterwards, the average lifetime of the products that entered since 2018 is applied for modelling the outflow.

Outflow is based on the estimation that on average every household disposes 10 tot 12 kg of electronics per year and that the total weight of appliances per household is 309 kg. This means that 3,9% of the electronic appliances is disposed of yearly. Additionaly, the outflow is based on annual growth rates in Amsterdam. After 10 years, the outflow becomes the inflow of ten years ago. This led to the interruption in the graph.

Tables/figures with projections

Assumptions

Abbreviations:

HAPP = Household appliance per person. HAPH = household appliance per household. Hh = household. This information

Object	Average lifetime (av)	min lifetime (a)	max lifetime(b)	HAPP	HAPH	Total kg of product per household	Product weight	kg Cu per household	Source
Inkjet printers	8	1	13	0.37	0.67	0.1206	5.6	0.18	Lin, 2016 and Baz et al., 2016
Cellphones	3	0.1	6	1.06	1.93	0.006369	0.11	0.0033	Lin, 2016 and Baz et al., 2016
Laptop computer	5	1	10	0.91	1.66	0.0498	2.9	0.03	Lin, 2016 and Baz et al., 2016
Desktop PC	8	1	13	0.27	0.5	0.07	15	0.14	Lin, 2016 and Baz et al., 2016
Television	15	1	20	0.54	0.98	2.0286	17.14	2.07	Lin, 2016 and Baz et al., 2016
Dishwasher	10	1	15	0.26	0.47	0.47	*40*	*1*	Ardente, F,, & Talens

									Peiró, L, (2015), and Baz et al.. 2016
Dryer	10	1	15	0.32	0.59	0.74753	55	1.267	Rauch, J., Eckelman, M., & Gordon, R. (2007) and Baz et al.. 2016
Washing machine	12	1	18	0.53	0.96	0.96	39	1	Lin. 2016 and Baz et al.. 2016
Vaccuum cleaner	10	1	15	0.55	1	1.846	8	1.846	Rauch, J., Eckelman, M., & Gordon, R. (2007)
Electric oven	10	1	15	0.34	0.62	0.46934	23	0.757	Rauch, J., Eckelman, M., & Gordon, R. (2007)
Microwave oven	10	1	15	0.46	0.84	0.8064	15	0.96	Lin. 2016 and Baz et al.. 2016
Refrigerator/freezer	13	1	18	0.55	1	2.07	61	2.07	Lin. 2016 and Baz et al.. 2016
Other						2.109	50	2.109	Lin. 2016 and Baz et al.. 2016
Average/total	10	1	14			11.75	326.15	13.43	

Inflow development:

On average dutch municipalites collect 5,1 kilo electronic waste per capita (NVMP, 2012).

On average a citizen spent 230 euros on household appliances in 2016 (Panteia & Inretail, 2016).

Or according to KSO2016, this 346 euros/capita (incl BTW)

On average a household spends 1100 euros on electronics (CBS, 2017)

On average an electronic appliance costs: 370 (Uneto VNI, 2016)

Thus on average a citizen buys 0,9 devices per year and a household 2,97 units

On average the inflow per household weighs 80,8 kg/hh/year

Appendix 3 – Interviews and e-mails

Vermeulen, Rick

aan mij

Beste Sabine,

Het klopt dat de bouwplannen afnemen. Daar zal ongetwijfeld de komende tijd wat aan worden toegevoegd maar hoeveel en waar is echt afhankelijk van economie, ontwikkeling woningmarkt en bestuurlijke ambities. Dat weten wij ook nog niet. Wat je zou kunnen doen is uitgaan van de gemiddelde bouwproductie van de afgelopen collegeperiode (uit mijn hoofd 6400) of het langjarig gemiddelde (uit mijn hoofd rond de 3500) en dat tempo doortrekken met locaties uit de strategische ruimte.

Prima om daar over mee te denken maar de aannames daarover zijn voor jouw rekening. Ik zit de rest van de dag in een workshop maar die is rond 17.00 klaar dus ik zou je daarna even kunnen bellen.

Groeten,

Rick

Van: Sabine De Haes [mailto:sfdehaes@gmail.com]
Verzonden: dinsdag 3 april 2018 10:38
Aan: Vermeulen, Rick; Hoog, Maurits de
Onderwerp: Re: 2025 en verder

Beste Rick,

Bedankt voor je reactie! Het gaat er om dat ik tot 2050 een goed onderbouwd en enigszins realistisch model heb met in- en outputs van koper uit bouw en infrastructuur in Amsterdam per jaar. Een gemiddeld scenario (met een college tussen convervatief en progressief in denk ik dan?) is dus het meest wenselijk. Nu is het model alleen gebaseerd op de openbaar beschikbare plannen mbt sloop/nieuwbouw/renovatie projecten. Deze nemen sterk af naar mate de tijd vordert en gaan niet verder dan 2035 waardoor de resultaten nogal krom uitvallen (hoe verder in de toekomst hoe minder koper er vrij komt). Renovatiecycli op basis van bouwjaar ga ik nog meenemen om dit te compenseren maar extra informatie over mogelijke bouwplannen is zeer welkom om de onderbouwing van het model te versterken. Een (bel)afspraak is ook prima, het liefst zo snel mogelijk. Wanneer komt jou uit? Ik kan alleen de komende vrijdagen niet.

Vriendelijke groet,

Sabine de Haes

Op 3 april 2018 om 10:11 schreef Vermeulen, Rick <R.Vermeulen@amsterdam.nl>:

Beste Sabine,

Dat klinkt als een studie waar mijn circulaire collega's erg blij van worden. In de maps.amsterdam pagina met woningbouwplannen zit in de legenda ook de eenheid "strategische ruimte" die kun je aanvinken voor een beeld van waar in de toekomst mogelijk nieuwe projecten opgestart zouden kunnen worden. Deze datasets zijn als geodata beschikbaar via de homepage van maps en dan "MapsData" in het horizontale menuutje bovenaan (bijvoorbeeld: https://maps.amsterdam.nl/open_geodata/?LANG=nl).

Belangrijk is het onderscheid lopende projecten (werken we al aan) en strategische ruimte (mogelijk als project op te starten). De mate waarin we de komende jaren uit de strategische ruimte putten is sterk afhankelijk van de richting die een nieuw college kiest, zowel kwantitatief (hoe meer woningbouwambitie hoe meer locaties nodig) als kwalitatief (wil een nieuw college actiever verdichten in bestaande woonwijken, vooral bedrijventerreinen transformeren, het laatste deel van IJburg ontwikkelen of zelfs bouwen in het groen?). Ik vind het lastig daar zonder verdere achtergrond bij je vraag wat over op te schrijven. Als het je helpt kunnen we wel een (bel)afspraak maken waarbij jij dan verder toelicht waar je naar zoekt en ik probeer mee te denken over passende scenarios die daarbij zouden kunnen horen.

Vriendelijke groet,

Rick

Dr. Rick Vermeulen

Ruimte voor de Stad: Opdrachtgever Gebiedsuitwerkingen – Verkenning verdichting - Mobiliteitsstrategie

https://www.amsterdam.nl/gemeente/volg-beleid/koers-2025-amsterdam/

Planoloog

Gemeente Amsterdam, Ruimte en Duurzaamheid

Team Nieuwe Opgaven

T 06 1299 3095

r.vermeulen@amsterdam.nl

Aanwezig: ma t/m do

Weesperplein 8, 1018 XA Amsterdam

Van: Hoog, Maurits de
Verzonden: vrijdag 30 maart 2018 20:43
Aan: Vermeulen, Rick
CC: Sabine De Haes (sfdehaes@gmail.com)
Onderwerp: 2025 en verder

Ha Rick,

Ik sprak vanochtend Sabine de Haes, die aan het afstuderen is op een 'mining'-studie over koper dat in de komende jaren/decennia bij renovatie/sloop-nieuwbouw/transformatie in Amsterdam beschikbaar kan komen.

Zij had op maps de kaart gevonden van jan smit met de lopende bouwprojecten. Voor haar prognose van de periode tot 2025 en verder zou zij graag een paar scenario's opstellen.

-       Kun jij jouw verwachtingen in een paar smaken over de productie op langere termijn met haar delen?

-       Is er kaartmateriaal van de volgende tranche gebiedsontwikkelingsprojecten – de strategische ruimte – in een pdf of misschien zelfs GIS-format?

Haar mailadres zit in de cc. Alvast bedankt voor de antwoorden.

Groet, Maurits

Maurits de Hoog

Stedebouwkundige Ruimte en Duurzaamheid gemeente Amsterdam

Projectleider Gebiedsuitwerking Groot-Amsterdamse-Bos en Principebesluit Sixhaven

M 06 23976848

E m.de.hoog@amsterdam.nl

https://www.amsterdam.nl/projecten/sixhaven/

Smit, Jan **<J.Smit@amsterdam.nl>**

aan mij, Klaas, Maurits

Hoi Sabine,

De woningbouwprojecten zijn onder te verdelen in vier projecttypen:

Vervanging: bouwen op een locatie waar voorheen ook woningen stonden, plek had voorheen ook woonbestemming (NIEUWBOUW).

Inbreiding: woningbouw binnen de bestaande stad, op plekken die voorheen tot de openbare ruimte behoorden (NIEUWBOUW).

Uitbreiding: idem inbreiding, maar dan buiten de bestaande stad, bv. Nieuw Sloten, De Aker, IJburg (NIEUWBOUW).

Functieverandering: bouwen op een locatie die voorheen een andere bestemming had (industrie, haven, school e.d.) Ook wordt onder functieverandering verstaan het realiseren van woningen in gebouwen die voorheen geen woonbestemming hadden (NIEUWBOUW of TRANSFORMATIE). Als bij categorie functieverandering de bestaande bebouwing wordt gesloopt is er sprake van NIEUWBOUW; wordt het bestaande gebouw verbouwd naar woningen spreken we van (gebouw-) TRANSFORMATIE

Ik hoop dat dit een en ander iets verduidelijkt.

met vriendelijke groet,

Jan Smit

Beheerder Basisbestand Woningbouwlocaties

Grond en Ontwikkeling

Gemeente Amsterdam

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Weesperplein 8, Amsterdam, 6e verdieping

Postbus 1104, 1000 BC Amsterdam

Werkdagen: ma, di, do en vr

Van: Haan, Klaas Bindert de
Verzonden: zaterdag 31 maart 2018 09:46
Aan: Hoog, Maurits de
CC: Sabine De Haes (sfdehaes@gmail.com); Smit, Jan
Onderwerp: Re: afvalstromen

Dag Maurits en Sabine,

Deze vraag speel ik hierbij door naar Jan Smit, de inhoudelijk contactpersoon van de kaart/dataset.

Groet van Klaas-Bindert

Verstuurd vanaf mijn iPhone

Op 30 mrt. 2018 om 20:59 heeft Hoog, Maurits de <M.de.Hoog@amsterdam.nl> het volgende geschreven:

Hallo Klaas-Bindert,

Ik sprak vanochtend Sabine de Haes, die aan het afstuderen is op een 'mining'-studie over koper dat in de komende jaren/decennia bij renovatie/sloop-nieuwbouw/transformatie in Amsterdam beschikbaar kan komen. Zij borduurt door op de PUMA-studie van metabolic en AMS.

Voor haar prognoses maakt zij gebruik van de kaarten op maps, onder andere die van jan smit over de woningproductie. Daar worden categorieen projecten onderscheiden, zoals vervanging, functiewijziging, transformatie.

-      Is er ergens omschreven wat precies onder deze begrippen verstaan wordt?

Sabine's mailadres zit in de cc. Alvast bedankt voor de antwoorden!

Groet, Maurits

Maurits de Hoog

Stedebouwkundige Ruimte en Duurzaamheid gemeente Amsterdam

Projectleider Gebiedsuitwerking Groot-Amsterdamse-Bos en Principebesluit Sixhaven

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