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Effects of Additive Manufacturing on Urban Logistics and Mobility –

Examining the Potential to Substitute Physical Goods Transport with Data Transfer

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Abstract

Urban freight transport is a growing challenge for cities since home delivery demand is increasing, and delivery vans cause home delivery traffic by covering limited urban space while driving and parking during delivery activities. One of the main reasons for increased home delivery traffic is the growing e-commerce market. Especially in dense urban areas, delivery vehicles often have to park in the second row and thus disrupt the traffic flow or cause congestion. Furthermore, delivery vans can cause traffic and emissions (CO_2, particles, and noise), which might negatively affect the life quality of residents.

This dissertation examines if and how classical home delivery can be substituted using the concept of distributed additive manufacturing near the customer. Additive manufacturing or 3D printing of product orders in 3D printing shops near the customer or at home might prevent or reduce home delivery and freight transport by partly substituting physical goods transport with data transfer. For this reason, the solution approach of distributed additive manufacturing is examined. This dissertation contains three research studies.

The first research study estimates the 3D printability potential of products and consumer goods in e-commerce using potential analysis. In this context, a criteria catalog is developed to evaluate the printability of products. Furthermore, the market shares of printable products in e-commerce are estimated. The results of the first research study indicate that approximately 6% of orders in e-commerce could be substituted with distributed additive manufacturing assuming today's 3D printing technologies.

The second research study tries to evaluate the impacts of distributed additive manufacturing represented by so-called 3D printing shops using a quantitative simulation approach for the example of Munich. This approach simulates and compares home delivery tours of vans in different scenarios. The results suggest that the implementation of distributed additive manufacturing in 3D printing shops does not necessarily reduce the home delivery distances of vans. If substitution and adoption rates of distributed additive manufacturing are not high enough, home delivery distances and traffic of vans are likely to increase.

The third research study evaluates the potential impacts of distributed additive manufacturing on the system of urban mobility and urban logistics. For this purpose, a qualitative system model is developed to identify effects, interactions, cybernetic mechanisms, and potential rebound effects within this complex system. The results of the third research study suggest that the implementation of distributed additive manufacturing might trigger changes in shopping behavior. However, urban traffic is subject to stabilizing feedback loops and is thus difficult to reduce.

Furthermore, this dissertation provides recommendations for implementing distributed additive manufacturing in urban areas.

Zusammenfassung

Der urbane Güterverkehr stellt eine wachsende Herausforderung für Städte dar, da die Nachfrage nach Lieferungen zunimmt und Lieferfahrzeuge während der Fahrt und beim Parken begrenzten urbanen Raum besetzen und Verkehr verursachen. Einer der Hauptgründe für den zunehmenden Zustellverkehr ist der wachsende E-Commerce-Markt. Vor allem in dichten Stadtgebieten müssen Lieferfahrzeuge oft in zweiter Reihe parken und stören so den Verkehrsfluss oder verursachen Staus. Darüber hinaus können Lieferfahrzeuge Verkehr und Emissionen (CO_2, Partikel und Lärm) verursachen, was sich negativ auf die Lebensqualität der Anwohner auswirken kann.

In dieser Dissertation wird untersucht, ob und wie die klassische Hauszustellung durch das Konzept der verteilten additiven Fertigung in Kundennähe ersetzt werden kann. Die additive Fertigung bzw. der 3D-Druck von Produktbestellungen in 3D Printing Shops nahe des Kunden oder zu Hause könnte den Lieferverkehr und den Gütertransport verhindern oder reduzieren, indem der physische Warentransport teilweise durch Datentransfer ersetzt wird. Aus diesem Grund wird der Lösungsansatz der verteilten additiven Fertigung untersucht. Die vorliegende Dissertation umfasst drei Forschungsstudien.

In der ersten Forschungsstudie wird das Potenzial der 3D-Druckbarkeit von Produkten und Konsumgütern im E-Commerce mittels Potenzialanalyse abgeschätzt. In diesem Zusammenhang wird ein Kriterienkatalog zur Bewertung der Druckbarkeit von Produkten entwickelt. Darüber hinaus werden die Marktanteile von druckbaren Produkten im E-Commerce abgeschätzt. Die Ergebnisse der ersten Forschungsstudie zeigen, dass ca. 6% der Bestellungen im E-Commerce durch dezentrale additive Fertigung substituiert werden könnten, wenn man die heutigen 3D-Drucktechnologien voraussetzt.

Die zweite Forschungsstudie versucht die Auswirkungen der verteilten additiven Fertigung in 3D Printing Shops mit Hilfe eines quantitativen Simulationsansatzes am Beispiel von München zu bewerten. Dieser Ansatz simuliert und vergleicht Zustelltouren von Liefervans in verschiedenen Szenarien. Die Ergebnisse deuten darauf hin, dass die Implementierung von verteilter additiver Fertigung in 3D Printing Shops nicht zwangsläufig zu einer Verringerung der Lieferwege von Liefervans führt. Wenn die Substitutions- und Adoptionsraten der verteilten additiven Fertigung nicht hoch genug sind, werden die Lieferentfernungen und der Verkehr der Liefervans wahrscheinlich zunehmen.

Die dritte Forschungsstudie evaluiert die potenziellen Auswirkungen der dezentralen additiven Fertigung auf das System der urbanen Mobilität und der urbanen Logistik. Zu diesem Zweck wird ein qualitatives Systemmodell entwickelt, um Effekte, Interaktionen, kybernetische Mechanismen und mögliche Rebound-Effekte innerhalb dieses komplexen Systems zu identifizieren. Die Ergebnisse der dritten Forschungsstudie deuten darauf hin, dass die Einführung der verteilten additiven Fertigung Veränderungen im Einkaufsverhalten auslösen kann. Der städtische Verkehr unterliegt jedoch stabilisierenden Rückkopplungsschleifen und ist daher nur schwer zu reduzieren. Darüber hinaus gibt diese Dissertation Empfehlungen für die Implementierung der verteilten additiven Fertigung in der urbanen Logistik.

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List of Abbreviations

3DP	3D Printing
AM	Additive Manufacturing
B2B	Business-to-Business
B2C	Business-to-Customer
BJT	Binder Jetting
BPMN	Business Process Model and Notation
BVL	Bundesvereinigung Logistik
CAD	Computer-Aided Design
CEP	Courier, Express and Parcel Service
CFLP	Capacitated Facility Location Problem
CPP	Chinese Postman Problem
CVRP	Capacitated Vehicle Routing Problem
CVRPTW	Capacitated Vehicle Routing Problem with Time Windows
DCPP	Directed Chinese Postman Problem
DED	Directed Energy Deposition
FLP	Facility Location Problem
ICT	Information and Communication Technology
MEX	Material Extrusion
MJT	Material Jetting
MOP	German Mobility Panel
OR	Operations Research
PBF	Powder Bed Fusion
REV3D	Erhöhung der Ressourceneffizienz durch Einsatz von verwendungsortsnahen 3D-Druck Technologien
RQ	Research Question
SDG	Sustainable Development Goals
SHL	Sheet Lamination
SNA	Social Network Analysis
TSP	Travelling Salesman Problem

TUM	Technical University of Munich
UCCP	Undirected Chinese Postman Problem
UFLP	Uncapacitated Facility Location Problem
VPP	Vat Photopolymerization
VRP	Vehicle Routing Problem
WLP	Warehouse Location Problem

Part I

Introduction, Theoretical Background and Top-Level Research Design

1. **Introduction**

1.1. Problem

With increasing urbanization, urban traffic poses a growing challenge for cities all around the world, especially in terms of congestion and decreased urban accessibility. According to the INRIX Global Traffic Scorecard, the time loss of an average car user in Munich due to congestion was 87 hours in 2021. This makes Munich the most congested city in Germany (Pishue 2021). Traffic, especially car traffic on streets, and congestion are major problems in cities because they cause costs, decrease people's accessibility, produce emissions and decrease life quality in cities. One decisive component of urban traffic is freight transport. Besides increasing passenger traffic, cities also face an increase in logistics and urban freight transport as well as urban freight traffic. One of the main reasons for this is the growing e-commerce market. According to Handelsverband Deutschland (2022), the German market volume of e-commerce has grown steadily in the last few years. In 2021, the market volume reached 86.7 billion euros, which represents a growth rate of 19% compared with the previous year.

Nowadays, vans or trucks are usually used to deliver e-commerce orders in cities (Kunze 2016, p. 291). These vehicles consume urban space while driving and stopping during their delivery activities (Muñuzuri et al. 2005, p. 15). Due to limited parking space in urban areas, these vehicles often have to park in the second lane, which may obstruct urban traffic and thus have negative effects on urban transport (Kunze 2016, p. 291). Thus, increased freight transport in cities directly influences passenger transport by increasing street traffic and reducing people's accessibility on streets.

The resulting emissions (CO_2, particles, and noise) from delivery vehicles are another problem, especially when they use combustion engines (Kunze 2016, p. 291). These emissions have negative effects on the global (due to climate change) and the local scale (due to the reduction of quality of life).

Besides traffic and environmental concerns, the logistics sector also faces challenges regarding business and coordination. The transportation of goods poses costs for the shipper, which can be subdivided into transport costs, warehousing costs, inventory carrying costs, costs for (logistics) administration, (transport) packaging costs, and indirect costs of logistics (Engblom et al. 2012, p.29). In addition, delivery delays may cause further costs (Andersson et al. 2017, p. 60). These mentioned costs pose an economic challenge in urban logistics. Besides costs, logistics companies face another challenge in coordinating different stakeholders involved in long supply chains (Tamagawa et al. 2010, p. 6003).

The problems associated with increased traffic are challenging for cities and urban areas. There are many approaches in the literature to solving these problems. Most of them focus on passenger traffic. Some approaches to solving the mentioned problems and to increase urban accessibility are to use connected and autonomous cars (Talebpour & Mahmassani 2016), increase shared mobility (Shaheen & Cohen 2013), or reduce the dependency on cars by improving land use for better proximity and accessibility (Banister 2008).

In addition to passenger transport, urban traffic consists of freight transport. It is therefore essential to efficiently design urban freight transport and urban logistics so that street traffic for delivery is minimized. The scientific literature identifies some approaches to achieving such efficiency. A classical approach to reducing freight traffic is the optimization of transport planning using operations research models (e.g., Crainic & Laporte 1997). In addition, there are emerging technologies and concepts which aim at optimizing and reducing urban freight traffic, especially on the last mile. Two examples are the use of the physical internet and the crowd for city crowd logistics (e.g., Crainic & Montreuil 2015) and autonomous transport systems/drones for deliveries (e.g., Flämig 2016). The technologies for freight transport often raise the potential for synergies or technological combinations, like using autonomous transport systems in conjunction with the physical internet.

1.2. Solution Approach

This dissertation examines a slightly different approach compared with the existing literature. Most papers focus on a classical optimization of passenger and freight transport. In contrast, the goal of this dissertation is to examine if and how freight transport can be partly substituted and avoided. To understand what such a substitution of traffic may look like, we have to consider the third type of traffic, which complements classical passenger and freight transport, data traffic. Kunze & Frommer (2021) describe how data can complement and substitute classical passenger and freight traffic.

The substitution of freight transport with data transfer may be counterintuitive. However, the use of data is highly influential in logistics. Due to globalization, production and manufacturing nowadays are spread all over the world. This fact implies long delivery distances to customers and intensive freight transport. To substitute physical freight transport with data transfer, the concept of production near the point of use, often denoted as decentralized or distributed manufacturing, can be applied (Lowe 2019, Matt et al. 2015). In this concept, manufacturing data stored in a digital twin of a particular product is sent to a local production facility instead of sending the produced physical product to the customer. There, it can be manufactured locally near the customer. This way, physical freight transport can be partly substituted, and delivery distances can be reduced.

Specific requirements have to be fulfilled to enable distributed manufacturing near the customer. Distributed manufacturing facilities typically supply smaller catchment areas and thus fewer customers compared to global centralized manufacturing facilities. Distributing manufacturing facilities still must be lucrative despite smaller catchment areas, fewer customers, and smaller production capacities. Production has to be versatile and automated and should cover as many product requests of customers as possible to ensure economic success.

A technology, which can be used to fulfill the mentioned requirements of distributed manufacturing, is additive manufacturing (AM). AM is also referred to as 3D printing (3DP). Therefore, both terms will be used synonymously in the further course of the dissertation. The production principle of additive manufacturing consists of applying certain printing materials layer by layer until the desired shape is manufactured. This principle differs from conventional subtractive manufacturing, where desired shapes are manufactured by removing material from a solid block through cutting, boring, drilling, or other processes. The 3D Printing process is highly automated. For most 3D Printing technologies, human labor is only required in pre- and post-processing. Additive manufacturing is usually based on a so-called digital twin, which not only contains data on the shape of a part but also stores data on the production process with a focus on specific printing parameters. This digital twin serves as input for 3D printers and thus enables automated production. The digital twin can easily be transferred via the internet and is therefore crucial for substituting physical goods transport with data transfer and production near the point of use. Furthermore, additive manufacturing meets the versatility requirement because 3D printers are not limited to one particular product or shape. In contrast to most conventional manufacturing technologies or machines, one printer can produce a wide range of different shapes and products already today, which is a huge advantage for local production near the customer. In the future, technological developments in AM may enable the production of even more products. On the urban scale, distributed manufacturing can be performed in so-called 3D printing shops throughout the city. The concept of such shops is explained in subsection 2.3.5 and enables shorter delivery distances to or pick-up of ordered parcels by customers.

For the above reasons, 3D Printing is a technology enabling distributed manufacturing near the point of use and customer, which may contribute to solving the problem of urban freight traffic. Khajavi et al. (2014), and Lowe (2019) also describe this potential and examine the use of additive manufacturing in decentralized, distributed manufacturing systems. Evaluating the effects of distributed additive manufacturing on urban logistics and urban mobility is the main objective of this dissertation. The research questions in section 1.4 make the objectives more specific.

1.3. Motivation

> **"Quidquid agis, prudenter agas et respice finem." - Herodot**
>
> **"Whatever you do, do it wisely and consider the end." - Herodot**

This quote represents the primary motivation of this dissertation. The literature review in section 2.2 and subsection 2.3.4 indicates that the emerging technology of additive manufacturing has great potential for production and logistics. However, our history shows that the implementation of new technological concepts not only brings technological progress, advantages, and positive effects to our lives. Instead, new technologies also often lead to negative rebound effects and new problems that were not considered at the time of their development and implementation. The invention of the car brought mobility to the majority of people. Today, the long-term disadvantages of cars are present. Cities and people face car traffic, congestion, crashes, and emissions. Another technology whose effects have not been fully considered at the time of development is nuclear power. On the one hand, nuclear power covered significant energy demand, raised the standard of living, and enabled the development of new technologies. On the other hand, the storage and disposal of radioactive waste is a problem that is not solved until today. Furthermore, nuclear power enabled the development of nuclear bombs, which pose a global threat.

The implementation of distributed AM in urban logistics has to be planned "wisely" and should consider "the end" to reap the benefits and minimize long-term negative effects. In particular, the long-term effects on human behavior, urban traffic, mobility, and logistics must be considered and examined. This dissertation intends to support the planning and implementation of distributed AM in urban logistics by estimating changes in home delivery fulfillment traffic of vans due to distributed AM in urban areas. Furthermore, long-term effects on the system of urban mobility and urban logistics are examined. After analyzing the results, this dissertation provides recommendations for implementing distributed AM in urban areas. Thus, urban planners and operators of 3D printing shops are supported to act "wisely and consider the end".

1.4. Research Questions

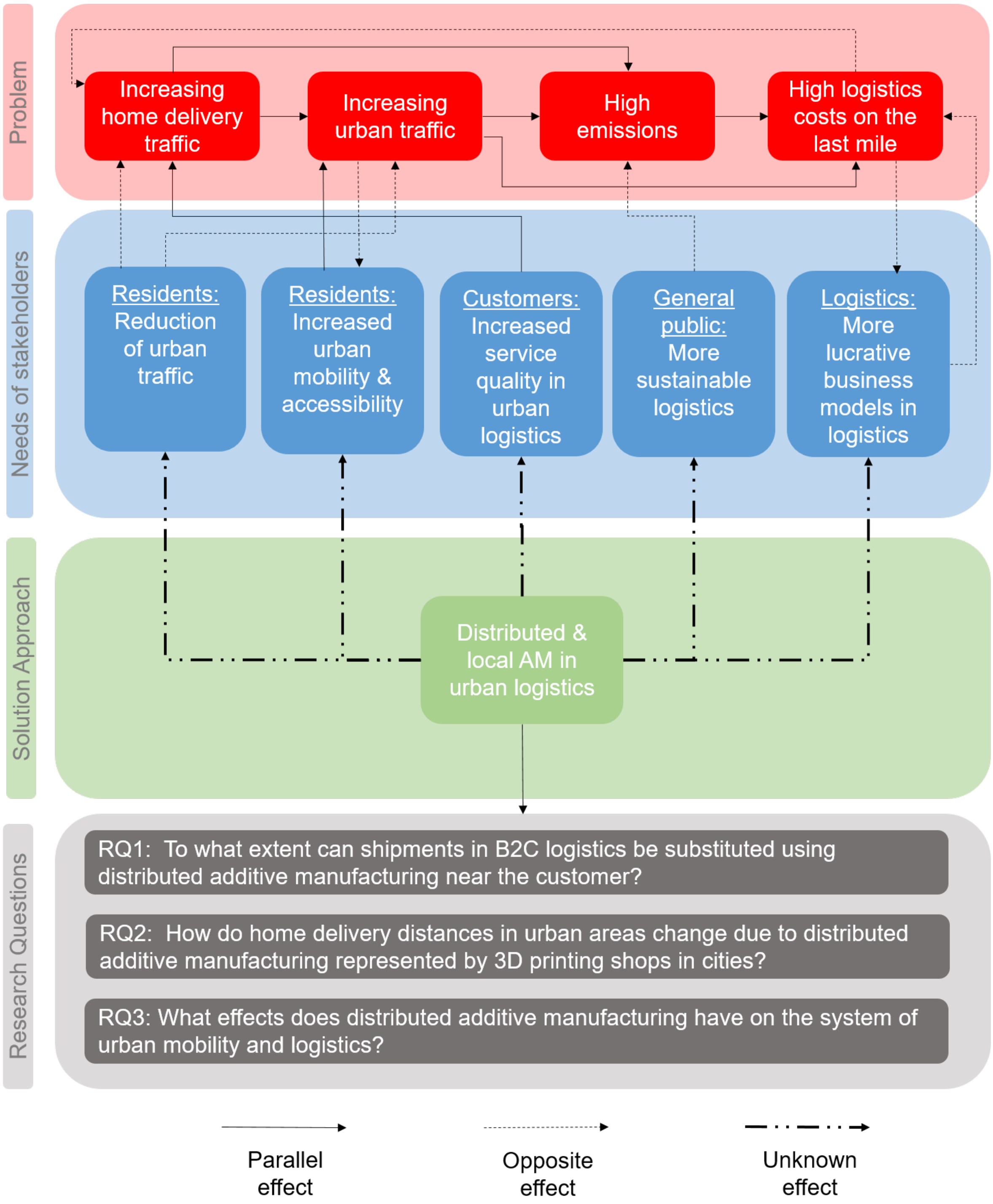
As mentioned above, this dissertation examines if and how physical freight transport can partly be substituted with data transfer and distributed AM near the customer. The focus is on the substitution of freight transport and traffic in urban areas. The city of Munich is used as a concrete example for the investigations. Three main research questions are examined:

- RQ (Research Question)1: To what extent can shipments in B2C (Business-to-Consumer) logistics be substituted using distributed additive manufacturing near the customer?
- RQ2: How do home delivery distances in urban areas change due to distributed additive manufacturing represented by 3DP shops in cities?
- RQ3: What effects does distributed additive manufacturing have on the system of urban mobility and logistics?

The research questions are derived from the problems, needs of stakeholders, and the solution approach of distributed AM in urban logistics. Figure 1 depicts the derivation of the research questions using a heuristic effect system to present the interrelations between problems, demands, and the examined solution approach. It is not clear how the solution approach of distributed AM in urban logistics affects the presented demand of stakeholders in an urban system. Answering the derived research question in this dissertation should support the evaluation of these effects.

To answer the first research question, it is important to examine which products can be manufactured locally near the customer using today's AM technologies. For this purpose, the types of products that can be 3D printed and the share of these products in home delivery logistics are investigated. Furthermore, the extent to which classical home delivery shipments in B2C e-commerce can be substituted with distributed and local AM is estimated. A criteria catalog is developed and applied to estimate the technological printability of products in e-commerce. Subsequently, market-based potential analysis is applied to estimate the substitution potential.

The purpose of the second research question is to examine how home delivery distances of delivery vans may change in urban areas due to distributed AM in local 3D printing shops. The city of Munich serves as an example for this investigation. Geospatial data, as well as depot data of CEP



RQ1: To what extent can shipments in B2C logistics be substituted using distributed additive manufacturing near the customer?

RQ2: How do home delivery distances in urban areas change due to distributed additive manufacturing represented by 3D printing shops in cities?

RQ3: What effects does distributed additive manufacturing have on the system of urban mobility and logistics?

Figure 1 Derivation of the research questions using a heuristic effect system

companies in Munich, are used. The classical parcel delivery bases or depots of CEP services are supplemented with the concept of the so-called 3D printing shop representing distributed AM. In reality, this concept has not yet been implemented on a large scale, but DHL, a major CEP service provider in Germany, has already investigated the concept in their research (DHL Customer Solutions & Innovation 2016). Home delivery distances in different scenarios are simulated, optimized, and compared using vehicle routing. Thus, differences in home delivery distances are identified. Evaluating differences in home delivery traffic and distance is crucial to estimate potential freight traffic reduction. As distributed manufacturing near the customer is very likely to occur in our future cities, it is important to figure out how home delivery transport is affected and how respective concepts and production facilities must be designed to ensure sustainable urban logistics with less freight traffic on streets.

The third research question does not only focus on the delivery traffic of CEP services. Since delivery traffic poses only one component of urban traffic, it is important to examine the possible effects of distributed AM on the whole system of urban mobility and logistics. This system is complex, with many interrelations between various variables. The introduction of distributed AM in urban logistics might have unknown effects on mobility behavior and traffic. Thus, undesirable rebound effects may occur. Therefore, a systems thinking approach by Vester (2019) is applied to investigate this complex system and better understand the cybernetic mechanisms and possible effects of distributed additive manufacturing. Detailed information on the research design is presented in chapter 3.

1.5. Structure

This dissertation consists of three parts. The first part contains the introduction, the theoretical background, and the top-level research design. As a first step of chapter 1, the problem is presented. Then, the solution approach of distributed AM in urban logistics is explained, and the personal motivation in this dissertation is described. The research questions and the structure conclude the first chapter. Chapter 2 presents the theoretical background. This chapter is used to define relevant terms for the dissertation and to review existing concepts and literature that are connected to this dissertation. In this context, the technology of additive manufacturing and the potential to substitute physical transport are examined. In addition, literature using system analysis of urban mobility and logistics is reviewed. Chapter 3 presents the top-level research design of this dissertation containing three research studies. The chapter describes the work plan of the Ph.D. project and explains how the three research studies are connected.

The second part of this dissertation contains the research studies. The methodological approach, results, and critical discussion are presented for each research study. The first research study estimates the printability potential of products in e-commerce. The second research study applies a simulation approach to evaluate the potential impacts of distributed AM on home delivery fulfillment traffic in Munich. Last, the third research study examines the impacts of distributed AM on the system of urban mobility and logistics with a focus on interrelations and interactions between different variables in the system.

The third part concludes the dissertation. The results are summarized and connected in chapter 7. Subsequently, a concluding critical discussion of the methodological approaches and the results is provided. Furthermore, recommendations for the practical implementation of distributed AM in urban areas are presented. Last, the need for further research is derived from the results and limitations of this dissertation. Figure 2 presents a graphical representation of the thesis structure.

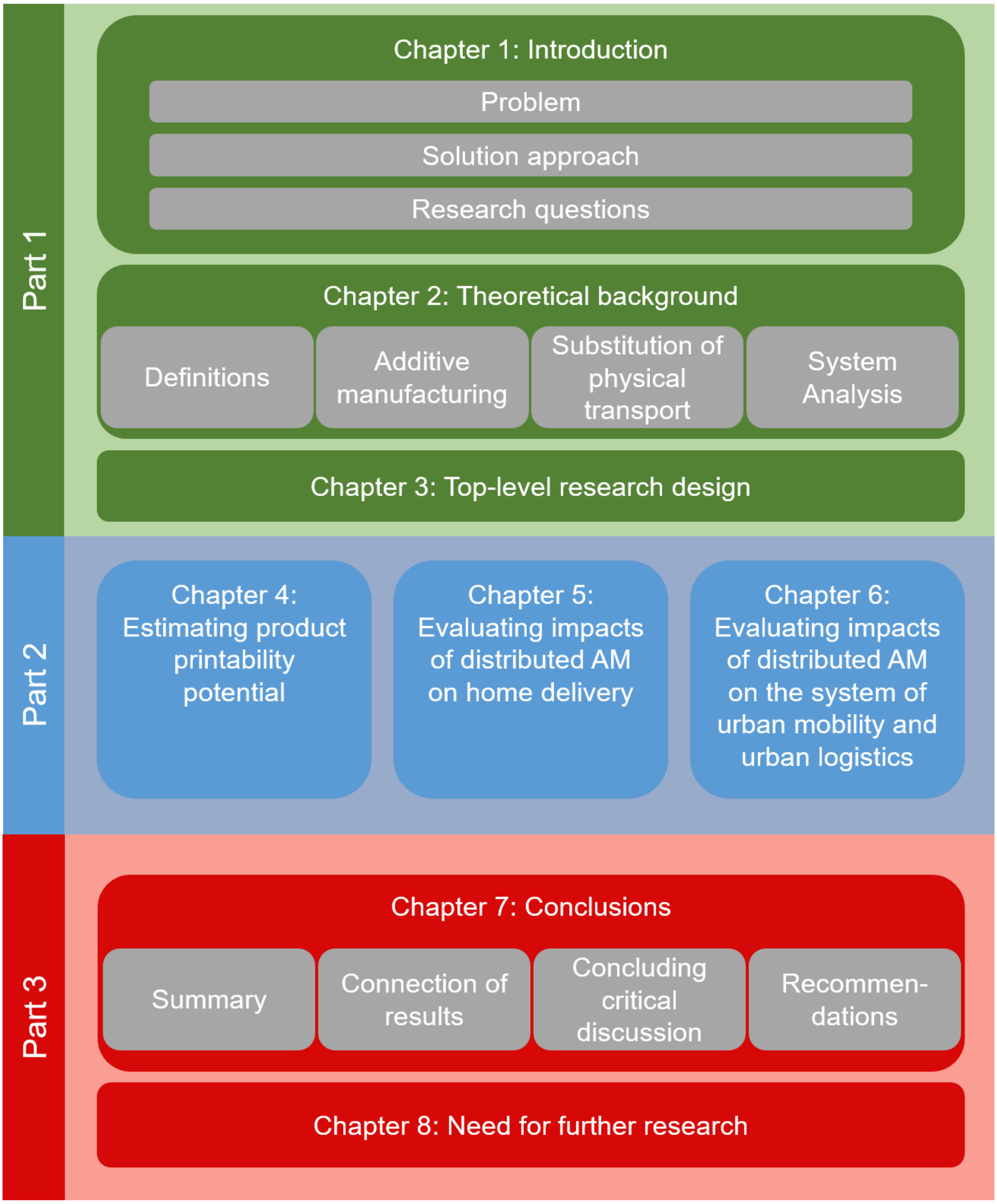


Figure 2 Thesis structure

2. **Theoretical Background**

In this chapter, the dissertation objective is placed into a scientific context. Fundamental concepts and the existing literature in the research fields, which are relevant to the following investigations, are presented. After defining relevant terms, the current status of additive manufacturing is reviewed from a technological and scientific perspective. As it will turn out, additive manufacturing or 3D Printing may drive the substitution of physical transport and the establishment of distributed manufacturing. The existing literature on these two areas is reviewed. Subsequently, the recent scientific literature using systems modeling in the fields of sustainable urban transport and mobility is analyzed.

2.1. Definitions of Relevant Terms

This dissertation examines the impacts of using distributed AM in urban logistics on the urban mobility system. This system is complex and contains many aspects closely related to transport and traffic. Due to this complexity, it is important to clearly define and differentiate the relevant terms. This is the only way to understand the variables and interrelations within the system, which is presented in section 6.2. The terms traffic, transport, mobility, and logistics are not defined uniformly in the existing literature. The following term definitions are used in the further course of this dissertation.

2.1.1. Traffic

Gertz (2021, p. 6) defines traffic as the sum of changes in location of passengers, freight, information or energy in a defined area and within a defined period. According to Gertz (2021, p. 6), traffic is usually not a purpose in itself but a derived activity. Rarely does traffic have an intrinsic component, such as driving for fun. In contrast to transport, traffic is a stock size and describes the number of location changes. In the defined context, traffic demand can be defined as the number of required vehicles. In colloquial speech and other languages such as German, the terms traffic and transport are often used synonymously. For this reason, the terms are defined and differentiated in this dissertation.

2.1.2. Transport

In contrast to traffic, transport describes the act of moving passengers, freight, information, or energy from one location to another. Transport can be subdivided according to the transported object into passenger transport, freight transport, information transport, and energy transport. In the defined context, means of transport represent vehicles for transporting passengers or freight as well as walking (Gertz 2021, p. 9). Means of transport have to be differentiated from modes of transport. According to Gertz (2021, p. 9), modes of transport can be defined as the medium in which transport takes place. Classical modes of transport are air, rail, road, and water. Furthermore, transport can be subdivided according to accessibility into individual transport and public transport. Other interesting terms in the context of transport are multimodality and intermodality. According to Gertz (2021, p. 11), multimodality is defined as the use of different modes of transport during a defined period. Intermodality represents the use of different modes of transport for one way (Gertz 2021, p. 11).

2.1.3. Accessibility

Accessibility is an aspect that is closely related to mobility, transport and traffic. In the scientific literature there are different definitions of accessibility. Geurs & van Wee (2004, p.128) define accessibility as "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)". Bach (1981) criticizes the lack of a definition of accessibility. Furthermore, Bach (1981, p. 957) proposes to distinguish accessibility from a point from accessibility to a point. In addition, Bach (1981, p. 957) presents two ways of interpreting accessibility. First, accessibility can be considered as accessibility between two points. Second, it can be considered as accessibility from one point to all other points in an examined area. Bhat et al. (2000) and Knox (1978) argue that accessibility of people should be more relevant than accessibility of locations. Gertz (2021, p. 21) defines three dimensions of accessibility. The first dimension is referred to as location-based accessibility, which is determined by spatial structure and land-use. The second dimension is referred to as personal accessibility, which is determined by individual aspects such as budget, knowledge, available time, physical capabilities or age. The third dimension is referred to as infrastructural accessibility, which is determined by transport offer and transport infrastructure.

2.1.4. Mobility

The term mobility is used in confusing ways. It covers a wide field and is used in many disciplines. According to Gertz (2021, p. 7), mobility can be subdivided into social mobility, intellectual mobility and spatial mobility. One component of spatial mobility is transport mobility, which is defined by Gertz (2021, p. 7) as the ability to move and change locations. This definition is used for the term mobility in the further course of this dissertation. Mobility behavior is defined as the individual change in location of a person, including spatial, temporal, modal and purpose-specific characteristics (Gertz 2021, p. 7). In contrast to traffic and transport, mobility includes the intention and purpose of an individual location change. According to this definition, mobility can cause traffic. Furthermore, accessibility is one component affecting mobility. Due to these interrelations, this dissertation defines mobility is a generic term highly interrelated with traffic, transport and accessibility.

2.1.5. Logistics

Logistics is another term which is not uniquely defined in the literature. The term is often confused with freight transport and therefore requires a definition for the further course of this dissertation. Göpfert (2013, p. 22) defines logistics as a management concept for the development, design, control and realization of effective and efficient flows of objects (goods, information, money and finance) in company-wide and cross-company value-added systems. According to the German BVL (Bundesvereinigung Logistik), logistics represents the holistic planning, management, coordination, implementation and control of all internal and cross-company flows of information and goods[1]. In the further course of this dissertation, the definition from BVL is used as a basis and further expanded. Thus, logistics is more than just the transport of freight. Similar to mobility, logistics is defined to include the intention and purpose of transporting goods and information. One intention of transporting goods is the supply of customers with ordered products. Thus, purchasing behavior is a main component of the intention and purpose in logistics. Furthermore, purchasing behavior influences the way how and where products or goods are transported. Online shopping most often induces home delivery. In contrast, shopping in local stores induces transport of products and customers to these stores. Both aspects are part of logistics.

2.2. Additive Manufacturing

One main objective of the dissertation at hand is to investigate the potential impacts of additive manufacturing on urban logistics. It is therefore essential to explain the fundamental concepts of AM, which is also popularly called 3D printing according to Gibson et al. (2021), and to review existing scientific literature in this field. AM is of particular interest as the characteristics of the technology may enable distributed production near the point of use. This section contributes to a better understanding of the concept of additive manufacturing from both a technological and scientific perspective.

2.2.1. Additive Manufacturing Principles

Additive manufacturing follows certain production principles that differ from the principles of conventional or subtractive manufacturing. While subtractive manufacturing technologies like CNC machining or laser cutting produce parts and shapes by removing material from blocks or bars, additive manufacturing applies materials layer by layer to produce desired shapes and products. Figure 3 depicts this difference in production methods. The illustration based on Levesque et al. (2020) indicates that AM produces less waste material compared to subtractive manufacturing because the starting material does not have to be removed from an existing block. This aspect can be considered as an advantage of AM over subtractive manufacturing technologies. Gibson et al. (2021, p. 3) confirm that the main production principle of AM consists of adding material in layers. These layers are thin cross-sections derived from a CAD (Computer-Aided Design) file of the whole part. The method of applying the layers varies depending on the technology. These different AM technologies are described later in subsection 2.2.3. The principles of additive manufacturing are further defined in ISO/ASTM DIS 52900 (International Organization for Standardization 2018). This standard defines additive manufacturing as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" (International Organization for Standardization 2018, p. 1). Another definition of additive manufacturing comes from Gebhardt et al. (2016). The authors define the AM principle as an automated process for producing three-dimensional physical objects from CAD data. This process is based on a layering principle and does not require

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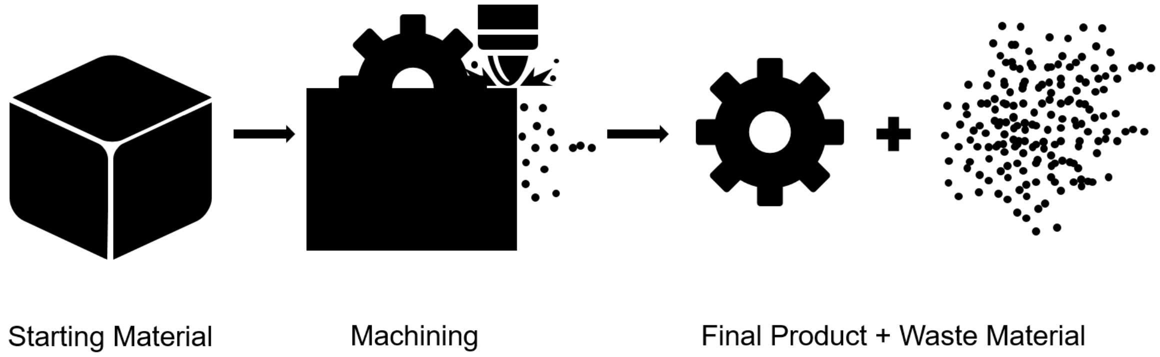
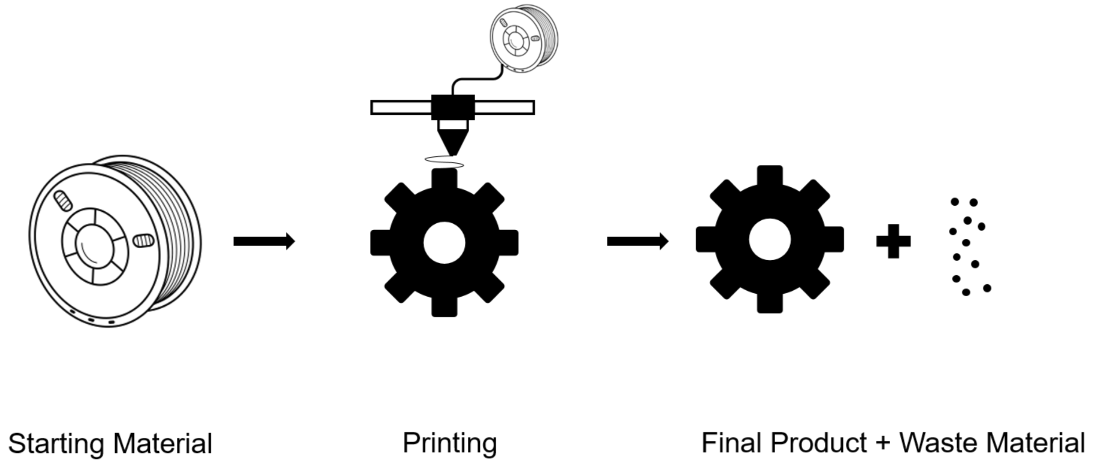
[1] `https://www.bvl.de/service/zahlen-daten-fakten/logistikdefinitionen`



(a) Subtractive Manufacturing



(b) Additive Manufacturing

Figure 3 Production principles of additive and subtractive manufacturing (own illustration based on Levesque et al. (2020))

any component-dependent tools (Gebhardt et al. 2016, p. 2). Selected synonyms for AM are 3D printing, rapid prototyping or generative manufacturing (Gebhardt et al. 2016, p. 2). According to Gebhardt et al. (2016, p. 2), the latter two names are obsolete. Thus, only the terms additive manufacturing and 3D printing are used in this dissertation.

The additive manufacturing principle requires some preparation to enable layer-by-layer production. For this purpose, the additive manufacturing process is essential. This process is described in subsection 2.2.2.

2.2.2. Additive Manufacturing Process

The additive manufacturing process is defined and standardized in VDI 3405 (Verein Deutscher Ingenieure 2014). According to this guideline, AM is based on flexible and direct fabrication from three-dimensional CAD data. Furthermore, the guideline divides the AM process into three stages that are depicted in Figure 4.

According to Verein Deutscher Ingenieure (2014), the pre-process contains all the necessary operations taking place before the parts can be produced in the additive manufacturing system.

Figure 4 Additive manufacturing process according to Verein Deutscher Ingenieure (2014)

Relevant steps in the pre-process are data processing, preparing auxiliary structures, nesting parts in the build room and generating the layer data (Verein Deutscher Ingenieure 2014, p. 6). The generation of layer data is often referred to as slicing. Slicing is usually conducted in specific slicing software that is in most cases provided by the manufacturer of the used AM machine. This kind of software supports the user in almost every step of the pre-process. Besides slicing the CAD model into many layers, slicing programs enable nesting, various machine settings like printing temperature, as well as an automated generation of support structures. As a result of the slicing process, a specific file that can be used as an input for the used AM machine or 3D printer is generated.

The in-process "describes the manufacturing operations which are performed by the additive manufacturing system" (Verein Deutscher Ingenieure 2014, p. 6). Besides the layer-by-layer production, in-processing also includes the loading and unloading of AM machines (Verein Deutscher Ingenieure 2014, p. 6).

According to Verein Deutscher Ingenieure (2014, p. 6), post-processing contains all operations that have to be carried out after a manufactured part is removed from the manufacturing system. Examples of post-processing steps are the removal of powder residues or support structures (Verein Deutscher Ingenieure 2014, p. 6). Post-processing plays an increasingly important role in the AM process and is constantly evolving. Today, thermal and chemical post-processing are most often used. These types of post-processes enable the use of more materials and increase product quality. The AM process presented in Figure 4 is widely adopted in practice and the scientific literature (for instance by Dilberoglu et al. 2021, p. 624 and Kumar 2022, p. 42). However, this process definition has a weakness because the creation of the digital three-dimensional CAD model is not clearly presented and differentiated. Therefore, the AM process depicted in Figure 4 was extended as one result of the research project REV3D (Erhöhung der Ressourceneffizienz durch Einsatz von verwendungsortsnahen 3D-Druck Technologien).

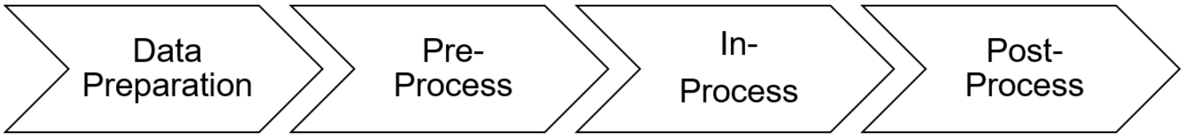


Figure 5 Additive manufacturing process according to Kunze et al. (2023)

The extended process is presented in Figure 5 and contains an additional data preparation step that has to be performed before the pre-process (Kunze et al. 2023). The goal of the data preparation step is to generate the three-dimensional CAD file of the desired part. There are typically two methods for generating these models. Reverse engineering is the first option which is usually performed using 3D scanners to digitize existing physical parts. If the desired part or product does not already exist, the digital model has to be generated using CAD construction in CAD software. So-called polygonization can be considered as the final substep of data preparation. Polygonization creates a volume-based facet model consisting of a network of triangles. This format is usually saved as an STL file and can be used as input for the pre-process (Kunze et al. 2023).

Data preparation is an important step in the AM process. The additive manufacturing principle which is presented in subsection 2.2.1 enables the production of complex shapes. This benefit can and should be used in practice to optimize topology, reduce material use and create highly individualized products. According to Thompson et al. (2016), additive manufacturing provides many benefits for product design. Some examples of these benefits are freedom of design, topology optimization for material reduction and customization (Thompson et al. 2016, pp. 5-9). To realize these benefits, the additive production principle should already be considered in the data preparation, and especially in construction. In this way, components can be optimized so that they require fewer resources while retaining sufficient load-bearing capacity. Furthermore, completely new designs can be realized if the additive manufacturing principles are exploited.

2.2.3. Additive Manufacturing Technologies

Section 2.2.1 presented the additive manufacturing principle which is characterized by applying materials layer-by-layer. There are many different technologies in AM sharing these production principles. Nevertheless, the different AM technologies differ in the way these layers are applied. Section 2.2.3 is intended to provide an overview of relevant AM technologies as well as their functionalities, capabilities and characteristics. This dissertation aims to evaluate the printability of certain product types using AM. Therefore, it is important to have an understanding of existing AM technologies. The terminology of these technologies is standardized in DIN EN ISO/ASTM 52900 (Deutsches Institut für Normung 2022). Kunze et al. (2023) propose a structured technology categorization which is depicted in Figure 6. The illustration indicates that AM technologies can be clustered by the medium in which the printing takes place. The first cluster contains technologies printing in the air or in other gas environments. In this medium the printing material is usually applied on a building platform. The printing process of 3DP (3D Printing) technologies in the second cluster is executed in a solid medium. In most cases this medium consists of a powder bed which is filled with printing material. The third technology cluster uses liquid printing materials. Thus, the printing process is executed in a vat filled with this liquid medium. Figure 6 contains the most relevant AM technologies and specific variations of them. In the following, some of these relevant technologies are described to provide a better understanding of the capabilities of AM and 3DP.

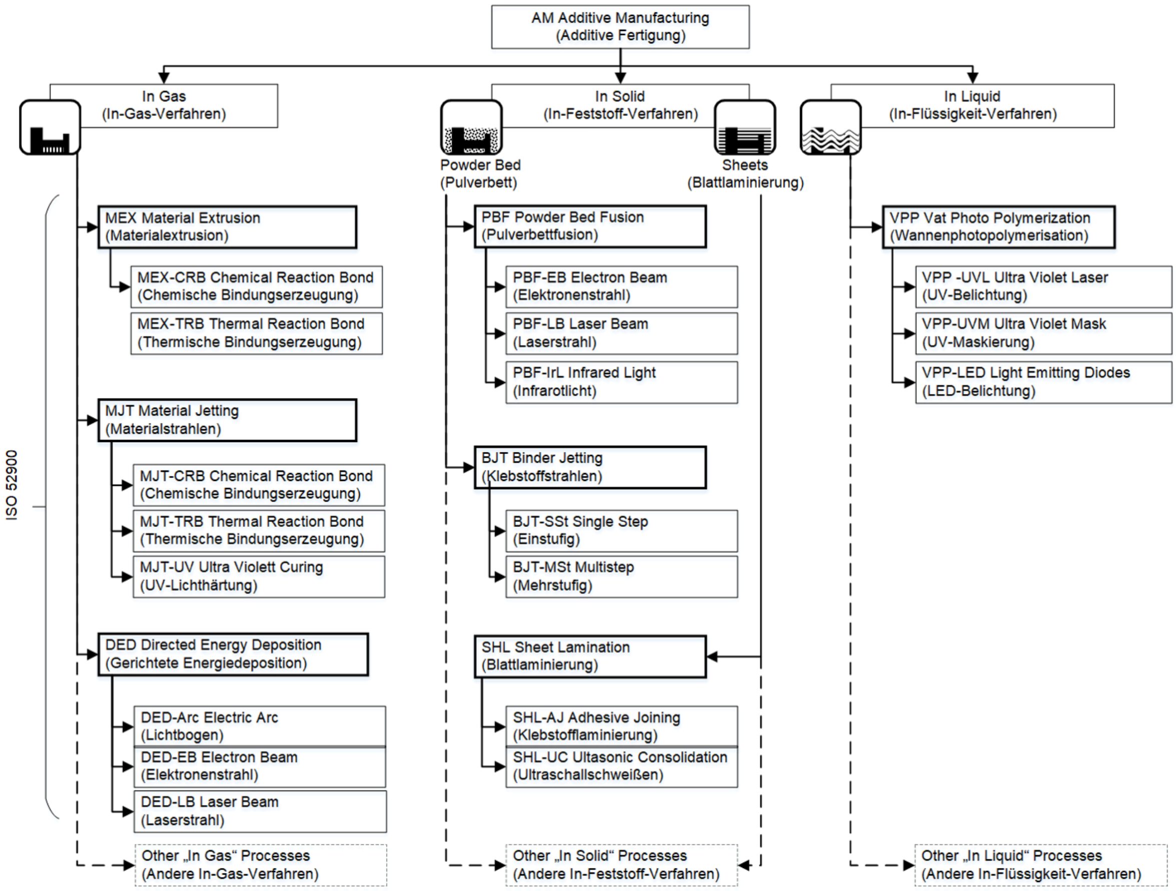


Figure 6 Technology overview of AM according to Kunze et al. (2023)

Material Extrusion (MEX)

MEX (Material Extrusion) is one of the most common AM technologies applied in private use as well as in industry. This technology uses printing materials in filament form. The filament is fed into a heated extruder where the material is fused. A nozzle moving on the x- and y-axis extrudes the fused material on the build platform. In most cases, the build platform is capable of moving on the z-axis. Thus, one layer can be applied after another (Kunze et al. 2023). Most MEX 3D printers have the opportunity to print a second material through a second extruder. Thus, support structures consisting of specific support materials can be printed to support overhangs of the printed part during the manufacturing process when the material is not yet cured. Thus, the production of complex and hollow structures is enabled. The support material has to be removed in the post-process (Kunze et al. 2023). Due to relatively low costs compared with other AM technologies, MEX is often used by private individuals to manufacture certain products at home. Most often plastics or polymeric materials are used for MEX. Nevertheless, recent technological developments in the MEX technology have enabled the production of metals. In order to print metals using MEX, a thermal post-process is required. MEX is very suitable for the rapid and cheap production of simple parts. Products or parts with high requirements for dimensional accuracy and surface quality are less suitable for production by MEX.

Material Jetting (MJT)

The German institute for standardization describes MJT (Material Jetting) as an additive manufacturing technology which selectively deposits droplets of the starting material (Deutsches Institut für Normung 2022). In detail, a liquid printing material is jetted in small droplets through one or more nozzles layer by layer onto a build platform. After applying the liquid printing material in layers, it is necessary to immediately cure the applied material. This curing process can be carried out in different ways. Most common is curing using irradiation with UV light or triggering chemical reactions of the printing material (Kunze et al. 2023). Recent technological developments in MJT enable multi-material printing as well as the printing of different colors within one print. These aspects are major advantages of the technology. Nevertheless, there are also some disadvantages of MJT. Two main weaknesses of MJT are the dependence on support structures as well as limited building volumes.

Directed Energy Deposition (DED)

DED (Directed Energy Deposition) is an AM technology which uses thermal energy to fuse materials by melting and welding them as they are applied (Deutsches Institut für Normung 2022). DED technologies can be differentiated by the energy effect at the welding point. Some DED machines use a laser for welding, while others use kinetic energy and hyper-sonic speed to apply the material (Kunze et al. 2023). One main advantage of the technology is the ability to produce metal parts in a short time at relatively low costs. On the other hand, poor surface quality is a major disadvantage of DED.

Powder Bed Fusion (PBF)

PBF (Powder Bed Fusion) is an AM technology which uses thermal energy to selectively melt or sinter powder materials in a powder bed (Deutsches Institut für Normung 2022). The build platform, which serves as the base for the building chamber, is successively covered with thin layers of the powder material during the printing process. After a layer is applied, the areas that should be part of the component are selectively melted or sintered, using a laser beam in most cases. Thus, the powder material merges into one or many solid parts. PBF is capable of printing polymers, ceramics and metals. Thus, there are many applications for the technology and a lot of products with different characteristics can be manufactured. One main advantage of PBF of polymers is the independence of support structures, as the unprocessed material in the powder bed serves as a support. This unprocessed material can be reprocessed and recycled in the post-process. While PBF provides high dimensional accuracy, printed products tend to have rough surfaces stemming from the merged powder. Furthermore, PBF has relatively high costs and long processing times.

Binder Jetting (BJT)

Similar to PBF, BJT (Binder Jetting) is an AM technology using liquid adhesive or binders to selectively merge powder materials in a powder bed (Deutsches Institut für Normung 2022). The production principles as well as advantages and disadvantages are quite similar to PBF. The main difference compared to PBF is the way of merging the material. Instead of thermal energy, BJT uses binders for production. Residues of these binders can be removed in the post-process.

Sheet Lamination (SHL)

SHL (Sheet Lamination) poses an AM process which merges sheets, arches or plates to form three-dimensional objects (Deutsches Institut für Normung 2022). In the process, materials in the form of sheets are applied in layers and subsequently merged using lamination (Kunze et al. 2023). To obtain desired shapes of products, the block of layers is cut out. SHL can produce colored objects by using a colored glue. Besides sheets of papers, SHL is also capable of processing metal plates (Deutsches Institut für Normung 2022).

Vat Photopolymerization (VPP)

VPP (Vat Photopolymerization) is described as an AM technology which uses light-activated photopolymerization to selectively cure liquid materials in a vat (Deutsches Institut für Normung 2022). In the printing process, a build platform dips into the vat containing the printing material. As soon as the platform is immersed in the liquid, UV light is used to selectively irradiate the areas on the platform that should be part of the desired component. Thus, the liquid photopolymer is cured. The process of dipping and irradiation is repeated so that the individual layers are printed on top of each other. Due to the curing by light, VPP offers high dimensional accuracy. Thus, the technology is capable of printing detailed products with high complexity.

2.3. Substitution of Physical Transport

This dissertation examines how physical transport can be substituted by data transport. In the existing literature, this question is only partially addressed. Traffic and transport can be structured on different levels. Scientific literature often differentiates between passenger and freight transport (Kunze & Frommer 2021, p. 4). With the rise of ICT (Information and Communication Technology), data can be considered as another type of transport (Kunze & Frommer 2021, p. 2). Pirath (1934, p. 164) already described the transport of data and messages at an early time and mentioned the low transport times compared with other types of transport. According to Kunze & Frommer (2021, p. 2), data transport has the potential to partly substitute physical transport. Thus, the different types of transport interact (Figure 7).

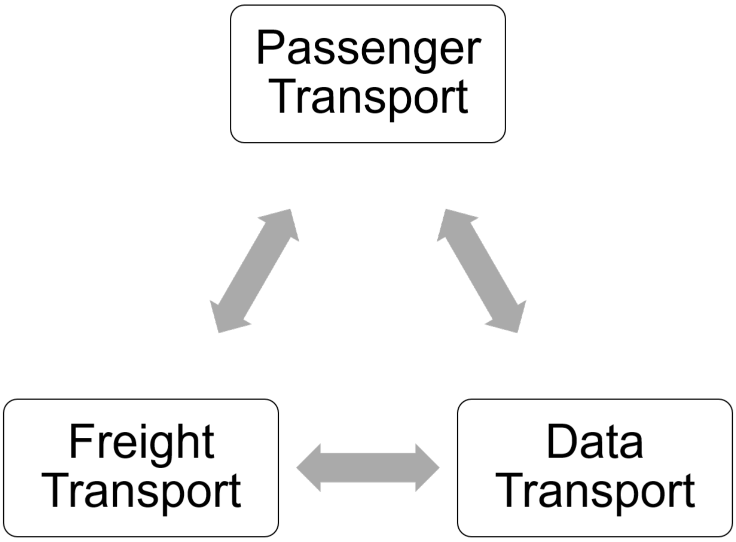


Figure 7 Types of transport

The main idea of substituting physical transport or trips is based on replacing physical activities with virtual activities. Lila & Anjaneyulu (2016) investigate the possibility of substitution and respective effects on trips and traffic. They identify four types of activities, which are being increasingly substituted with their virtual counterparts (Lila & Anjaneyulu 2016, p.420). These types of activities are presented in Table 1.

The overview shows that the substitution of physical transport and physical trips already plays a major role today. The main driver of this development is ICT. The internet in particular gives people the opportunity to move certain activities into a virtual environment. This section is intended to give an overview of the existing literature which investigates the substitution of physical activities and trips. The effects on traffic and mobility are focused on in particular. Especially, the reduction of commuting trips by telework and distributed work is a major field of research. Furthermore, potential traffic reduction due to online shopping, online maintenance and virtual leisure activities

Physical activity	**Virtual activity**
Work • implies trips to office and business meetings	Telework / distributed work • opportunity to work from anywhere and to save business trips
Offline shopping • implies trips to shops for daily items • implies trips to shops for non-daily items	Online shopping / e-commerce • shop and sell online • opportunity to save shopping trips • implies home delivery traffic
Maintenance • implies trips for paying bills • implies trips for banking transactions • implies trips for ticket booking • ...	Online maintenance • pay bills online • online banking • online ticket booking • opportunity to save trips for maintenance activities
Leisure • implies trips to theaters / clubs • implies trips to restaurants • implies trips to friends • ...	Online leisure / teleleisure • stream movies online • order food online • meet friends online • opportunity to save trips for leisure activities

Table 1 Substitution of physical activities with virtual activities (modified, based on Lila & Anjaneyulu 2016, p. 420)

are partially examined.

Lila & Anjaneyulu (2016) focus on the substitution of passenger trips and passenger transport. The distinction of physical activities depicted in Table 1 fits well with the distinction of passenger transport by Bolik et al. (1982, p. 13). They distinguish passenger transport by the purpose of travel into six types. When aggregated, these types can be grouped as commuter traffic, including trips to educational institutions and business trips, shopping traffic and leisure traffic, including holiday traffic. The distinction of passenger transport according to Bolik et al. (1982, p. 13) is depicted in Figure 8. Table 1 shows how all of these physical transport types can be partly substituted. As mentioned before and shown in Figure 7, freight transport can also be affected by data transport. Therefore, potential substitution effects on freight transport as well as respective effects on traffic and mobility are also part of the literature review. One opportunity to enable the substitution of physical freight transport is the use of distributed manufacturing or production near the place of use. Table 2 represents this potential and supplements Table 1, which is based on

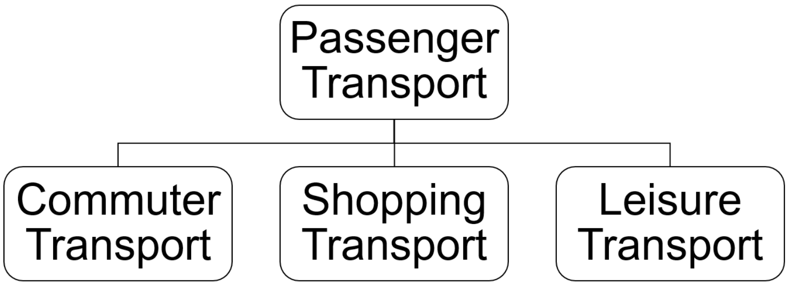


Figure 8 Types of passenger transport distinguished by the purpose of travel (own illustration based on Bolik et al. 1982, p. 13)

Lila & Anjaneyulu (2016) and focuses on passenger transport only. The following literature review of the substitution of physical transport focuses on passenger as well as freight transport.

Physical activity	**Virtual activity**
Physical freight transport (conventional production & logistics)	Virtual freight transport (distributed manufacturing)
• implies long delivery distances	• send digital twins instead of physical goods
• implies long supply chains	• distributed production / production near the place of use (for example using 3D Printing)
	• opportunity to save delivery distances
	• implies transport of production materials

Table 2 Substitution of physical freight transport with data and distributed production

2.3.1. Distributed Work

A large field of research in the existing literature concerns distributed work. In this context, telework and telecommuting are often investigated. Telework is an important aspect when it comes to the substitution of physical transport. It has already been intensively researched for several years. Nilles (1988) conducted early research on the topic of telework and defined telecommuting as the partial or total substitution of daily commuting using telecommunication (Nilles 1988, p. 301). In this context, telecommuting can be differentiated into home-based telecommuting and regional center telecommuting (Nilles 1988, pp. 301-302). Regional center telecommuting can occur in three forms. According to Nilles (1988, pp. 301-302), satellite centers are a typical form of regional center telecommuting. These centers are facilities of certain companies, which only provide workspace for their own staff in distributed locations. In contrast, local centers serve as distributed facilities for telecommuters from different organizations. So-called neighborhood centers are smaller facilities, which only can host a small number of telecommuters. These centers can serve as small satellite centers as well as small local centers (Nilles 1988, pp. 301-302).

Gareis & Kordey (1999) and van Lier et al. (2014) define the concept of telework. According to van Lier et al. (2014, p. 245), telework describes remote working activities away from the office headquarters location. The concept often implies flexible working times. Gareis & Kordey (1999, p. 269) divide telework into mobile telework, alternating home-based telework, permanent home-based telework and center-based telework. The latter corresponds to the concept of regional center telecommuting, which is described by Nilles (1988, pp. 301-302).

Telework is often also denoted as distributed work in the scientific literature. According to Pyöriä (2011, p. 388), telework is a specific type of distributed work. Spinuzzi (2007, p. 268) and Pigg (2014, p. 71) define distributed work as "coordinative work that enables sociotechnical networks to hold together and form dense interconnections among and across work activities that have traditionally been separated by temporal, spatial, or disciplinary boundaries" (Spinuzzi 2007, p. 268).

A review of the literature which investigates distributed work identifies four research clusters (see Table 3). The first research cluster examines the effects of distributed work on traffic, transport demand and mobility. Lila & Anjaneyulu (2016) examine the extent of participation in virtual activities, which may substitute physical activities and corresponding trips. Telework is one activity among others which is investigated. The considered activities were already shown in Table 1. In particular, the relationship between ICT, virtual activities and travel patterns are investigated using survey data from the urban area of Bangalore. The results of Lila & Anjaneyulu (2016) indicate that ICT leads to an increase in leisure activities, which also implies an increase in total trips made by individuals. These results are not very representative of telework, as telework is

Research cluster	**Publications**
Effects of distributed work on traffic, transport demand and mobility	Nilles (1988), Choo & Mokhtarian (2007), Helminen & Ristimäki (2007), Dissanayake & Morikawa (2008), Allen et al. (2015), Lila & Anjaneyulu (2016), Lila & Anjaneyulu (2017), Melo & de Abreu e Silva (2017), Chakrabarti (2018), Akbari & Hopkins (2019), Hopkins & McKay (2019), Elldér (2020), Vakilian & Edrisi (2020), Stiles et al. (2021)
Effects of distributed work on sustainability	van Lier et al. (2012), van Lier et al. (2014), Larson & Zhao (2017), Hofer et al. (2018), Moglia et al. (2021)
Effects of distributed work on spatial trends and land use	Gareis & Kordey (1999), Safirova (2002), Shieh & Searle (2013), Moeckel (2017)
Factors influencing distributed work	Pyöriä (2011), Alizadeh & Sipe (2013), Nijland & Dijst (2015), Ismail et al. (2019), Zhang et al. (2020), Nguyen (2021)

Table 3 Literature review of distributed work & transport

only one of many activities considered. Therefore, another study was conducted.

Lila & Anjaneyulu (2017) explicitly investigate the effects of telework on the transport network of Bangalore. For this investigation, survey data from workers in the urban area is analyzed using factor analysis, structural equation modeling and transport modeling. The results show that driving distances can be reduced by up to 3.2% and travel times can be reduced by up to 6% with the implementation of telework (Lila & Anjaneyulu 2017, p. 10).

Vakilian & Edrisi (2020) also examine the effects of telework on transport networks. Furthermore, factors influencing telework are part of the investigations. Data is collected using a survey in Tehran and analyzed using a logistic regression model. Vakilian & Edrisi (2020) find, that telework has significant effects on traffic and travel times. Vice versa, it is stated, that traffic and travel times also affect the demand for transport and telework.

Hopkins & McKay (2019) investigate telework and traffic in the context of smart cities using literature review and survey data of Melbourne. They find that especially younger people under the age of 35 have a positive attitude towards telework. According to Hopkins & McKay (2019, p. 9), the greatest benefits of telework are flexibility and the reduction of travel times and costs. The biggest constraint of telework, is insufficient technological support (Hopkins & McKay 2019, p. 11). Two examples of this lack of support are slow internet connections and the absence of printing facilities. Hopkins & McKay (2019, p. 13) also find that an average worker in Melbourne spends 115 minutes commuting per day. Due to the promotion of telework, the number of commuters in Melbourne could be reduced by 42% according to Hopkins & McKay (2019, p. 13). Such a reduction would have drastic effects on traffic in the city (Hopkins & McKay 2019, p. 13).

Stiles et al. (2021) examine the effects of telework on traffic, congestion and crashes in the context of the COVID-19 pandemic. For the investigation, real-time data of street networks in the United States are evaluated using a multinomial logistic regression model. The results show that traffic volumes declined by more than 60% due to stay-at-home policies during the pandemic. In this context, one of the biggest stay-at-home policies is telework. Besides traffic volumes, Stiles et al. (2021) also examine crash statistics during the mentioned time period. They show that the total number of crashes decreased while the number of fatal crashes increased (Stiles et al. 2021, pp. 6-7). One possible explanation for the increase in fatal crashes is higher road speed, which can be induced by less traffic volume on streets.

The investigations of Akbari & Hopkins (2019) deal with the traffic behavior of workers in Vietnam as well as attitudes towards telework. In the city of Ho Chi Minh, most workers use motorcycles or bicycles to commute. Only a minority uses cars or public transport (Akbari & Hopkins 2019, p. 12). It is stated that an increase in traffic is counterproductive for sustainable and livable cities. Akbari & Hopkins (2019, p. 14) find that 41 % of the respondents have permission to telecommute, and 74% want the opportunity to, at least partially, work from anywhere. Similar to Hopkins & McKay (2019), the results show that greater flexibility and the reduction of travel are the biggest benefits of telework (Akbari & Hopkins 2019, p. 19). Quantification of potential travel time and distance reduction is missing.

Chakrabarti (2018) examines telecommuting as a travel demand management strategy to reduce vehicle miles traveled. This investigation is based on the U.S. National Household Travel Survey of 2009 and regression models. Chakrabarti (2018) focuses on the effects of telecommuting on noncar mobility. The results of the investigation indicate that frequent telecommuting is associated with 15% more walking trips per week and a higher probability of physical activity (Chakrabarti 2018, pp. 7-10). Overall, Chakrabarti (2018, pp. 1) finds that telecommuting can increase non-motorized travel.

Allen et al. (2015) conduct an extensive literature review of telework and telecommuting. One focus is on traffic effects. They conclude that telecommuting can reduce urban traffic, especially at peak times (Allen et al. 2015, p. 56). In general, telecommuting has the potential to decrease overall traffic volume and emissions (Allen et al. 2015, p. 56).

Elldér (2020) investigates how telework influences daily travel in Sweden. Data comes from the Swedish National Travel Survey and is evaluated using logistic regression. According to Elldér (2020, pp. 6-7), telecommuters are less likely to travel overall. Furthermore, the trip length of telecommuters is shorter compared with people who do not have the opportunity to telework. Elldér (2020, pp. 6-7) concludes that telework leads to reduced travel demand, more use of active transport modes and congestion relief. The results also show that part-time teleworkers generate more trips than non-teleworkers (Elldér 2020, pp. 6)

The investigations of Melo & de Abreu e Silva (2017) take a similar approach. They examine telework and household commuting patterns in Great Britain using econometric analysis. In contrast to other publications, the focus is on the travel distances and times of households. The findings of (Melo & de Abreu e Silva 2017, p. 11) indicate that the weekly commuting distance traveled by teleworkers is longer compared with the distance of non-teleworkers. This result seems to be surprising at first sight. A detailed look at the results shows that the mentioned differences are only statistically significant for part-time teleworkers who work from home once or twice a week (Melo & de Abreu e Silva 2017, p. 11). This fact could explain the differences because part-time teleworkers can decrease the number of commuting trips per week. If teleworkers live far away from their working place, their total commuting distances per week can still exceed the distances of non-teleworkers. Melo & de Abreu e Silva (2017, pp. 14-15) also find that frequent teleworkers tend to have shorter commuting times per week compared with non-teleworkers.

Older research from Dissanayake & Morikawa (2008) focuses on the impacts of center-based telecommuting on travel behavior and air quality in developing countries. They use the city of Bangkok as an example for the investigations. In the studied environment, five satellite center-based telecommuting facilities in suburbs are considered. The used method for the investigation is a nested logit model. The results indicate that telecommuting policies can reduce private vehicle usage by 18-20% (Dissanayake & Morikawa 2008, p. 892).

Choo & Mokhtarian (2007) investigate the impact of telecommunication in general on travel behavior using structural equation modeling. Data comes from the U.S. Federal Highway Administration. The results indicate that increased use of telecommunication corresponds to increased travel demand (Choo & Mokhtarian 2007, pp. 13-14). Similar to Lila & Anjaneyulu (2016), the results are not representative of telecommuting because telecommunication in general is the subject of investigation.

The investigations of Helminen & Ristimäki (2007) study the relationships between telework, commuting distance and commuting frequency in Finland by analyzing national survey data. According to the results of Helminen & Ristimäki (2007, p. 341), home-based telework reduces the amount of commuting by 0.7%.

The second research cluster investigates the effects of distributed work on sustainability. This cluster is highly connected to the research which examines traffic effects but has a greater focus on emissions and the environment.

Moglia et al. (2021) examine the connection between telework and sustainability in the context of the sustainable development goals. SWOT analysis is used. Overall, Moglia et al. (2021, p. 9) find links between telework and 9 different SDG (Sustainable Development Goals). The first link shows that telework can contribute to good health and well-being (SDG 3). Especially, during the COVID-19 pandemic, telework reduced social contact and thus protected against infection (Moglia et al. 2021, p. 9). The results also indicate that telework promotes quality education (SDG 4). According to Moglia et al. (2021, p. 11) telework and ICT can increase access to education and promote lifelong learning. Another linked aspect is gender equality (SDG 5). According to the authors, "telework has the potential to promote increased diversity and social sustainability in terms of employees' ability to access flexible work arrangements" (Moglia et al. 2021, p. 11). As stated by Moglia et al. (2021, p. 11), women are more likely to access flexible work arrangements. Therefore, telework might help women, but also men, to better coordinate parenthood and career expectations (Moglia et al. 2021, p. 12). SDG 8 concerns decent work as well as economic growth and is also clearly linked to telework (Moglia et al. 2021, p. 12). Other sustainable development goals which are influenced by telework are SDG 9 (Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation), SDG 10 (Reduce inequality within and among countries), SDG 11 (Sustainable cities and communities), SDG 12 (Ensure sustainable consumption and production patterns), and SDG 13 (Take urgent action to combat climate change and its impacts) (Moglia et al. 2021, pp. 12-17).

Investigations by van Lier et al. (2012) examine the impact of teleworking on the external environmental transport costs linked to the mobility of employees. The authors use the city of Brussels as an example and generate data using a survey. The results indicate that telework can have beneficial effects on climate change, air pollution, up and downstream processes and noise (van Lier et al. 2012, p. 249). In particular, external transport costs can be reduced and avoided according to van Lier et al. (2012, p. 249).

Later work by van Lier et al. (2014) focuses on the impacts of telework on sustainable mobility. They compare external environmental costs of centralized work with decentralized work and teleworking from home taking into account modal shifts. SWOT analysis is used to compare the external costs. The findings show "that teleworking at home can offer significant external transport cost savings" (van Lier et al. 2014, p. 262). Two main reasons for these external cost savings are the reduction of commuting distances and congestion.

Hofer et al. (2018) compare different types of work. They use agent-based modeling for different urban car traffic scenarios to investigate the effects on CO_2 emissions. In one of the compared scenarios, telework is assumed. The results of Hofer et al. (2018, pp. 7-8) indicate that telework reduces traffic, especially during peak hours. Furthermore, it can reduce emissions by reducing congestion and stop-and-go traffic (Hofer et al. 2018, pp. 7-8). Emissions can be reduced by around 18% according to Hofer et al. (2018, p. 8).

Larson & Zhao (2017) show the relationship between telework, urban form, energy consumption and greenhouse gas emissions using a numerical simulation. The authors conclude that telecommuting benefits not only telecommuters, but also non-telecommuters by reducing congestion on the roads (Larson & Zhao 2017, p. 22). According to Larson & Zhao (2017, p. 23), the energy implications of telework are not obvious. Commuting energy can be reduced in most cases, but total energy demands are uncertain. One possible reason for that is budget savings of households, which are caused by the reduction of commuting distances. These savings may induce other activities and thus pose rebound effects on energy consumption.

The third research cluster identified in Table 3 deals with the effects of distributed work on spatial trends and land use. These effects are also interesting for this dissertation as land use is highly related to transport and mobility, especially in urban areas where space is limited.
The investigations by Moeckel (2017) are representative of this cluster. This publication presents a model to simulate the decision to telework, travel demand and the potential relocation of households on the basis of travel time budgets. Moeckel (2017, p. 212) concludes, that time budgets of households for transport change only slowly over time. Thus, fewer commuting trips to work can increase the number of non-work trips. Furthermore, Moeckel (2017, p. 212) states that telecommuting may influence the location choice of households and urban sprawl.
Shieh & Searle (2013) examine the relationship between telework and spatial trends in Australian cities. They focus on different teleworking environments and their impact on urban planning.
Further work by Gareis & Kordey (1999) and Safirova (2002) also examines effects of telecommuting on urban land use patterns as well as urban and regional development. According to Gareis & Kordey (1999, p.272), companies offering telework are most likely located in urban areas. Employees have the opportunity to live in peripheral locations, where quality of life is higher, despite working in urban areas, due to telework. Nevertheless, telework over longer distances is still rarely practiced according to Gareis & Kordey (1999, p.273). One reason for that may be part-time teleworking, which requires commuting at least some of the time. Telework also impacts the demand for office space and can be a driver for the innovative allocation of work premises. Thus, the demand for office space can be reduced due to the potentials of telework (Gareis & Kordey 1999, p.274). The reduction of required office space is also driven by high rents in densely populated areas. Yet there are limits for the reduction of office space. One example of these limits is the willingness of employees to share their desk (Gareis & Kordey 1999, p.275). Telework influences not only the demand for commercial but also residential land use. According to Gareis & Kordey (1999, p.275), households of teleworkers need more space and potentially additional rooms for working. This increased demand for space is more likely to be satisfied in rural areas where more space is available. The authors state that "urban sprawl and suburbanization are likely not only to continue, but accelerate as a result of widespread adoption of telework" (Gareis & Kordey 1999, p.275). The conclusions of Gareis & Kordey (1999) are wide-ranging, but it must be taken into account that the results were published in 1999 and may no longer be applicable.

Another research cluster examines factors influencing distributed work. Nguyen (2021), Zhang et al. (2020), Pyöriä (2011), Ismail et al. (2019) and Nijland & Dijst (2015) deal with this subject.

In particular, Nguyen (2021) examines factors influencing telework in Vietnam in the context of the COVID-19 pandemic. According to the authors, fear of the pandemic was the main driver for the positive perception of home-based telework. Furthermore, raising employees' awareness of environmental and traffic-related benefits can contribute to keeping some approved and sustainable work habits even after the pandemic and normalizing flexible working arrangements (Nguyen 2021, p. 26).

Zhang et al. (2020) focus on the individual, personal and demographic factors influencing the acceptance of telework in the context of work-life conflicts. The German microcensus of 2010 is used as the data basis. The authors find three significant patterns. The results indicate that parents are less likely to telework compared with workers without children. In the group of individuals without children, singles are more likely to telework than married individuals. Furthermore, the study finds that females are more likely to telework compared with males (Zhang et al. 2020, p. 64).

Pyöriä (2011) describe the beneficial and disadvantageous factors of distributed work and telework. According to the authors, a lack of culture of teleworking is a disadvantage, which hampers the expansion of flexible work arrangements (Pyöriä 2011, p. 390). Example benefits of telework are the reduction of commuting distances and decreased costs of running office premises (Pyöriä 2011, p. 393).

Ismail et al. (2019) also identify important factors influencing the practice of telework. The authors conclude that the number of young children workers have, the frequency of face-to-face communication in work, and the frequency of using email for work are significant factors to predict if certain individuals are likely to perform telework (Ismail et al. 2019, p. 21).

Summary & Link to this Dissertation

The review of the literature shows that commuting distances and frequencies can be reduced by telecommuting. In particular, the more recent literature underlines this potential. At peak times telework can reduce traffic, especially in urban areas. The COVID-19 pandemic has clearly been a driving force behind the rise of telework and telecommuting in recent years. It must be considered that distributed work and telework can also lead to certain rebound effects. Some literature describes potential scenarios whereby telework can reduce commuting traffic at first sight. Subsequently, the decreased traffic on streets can induce other types of traffic due to increased accessibility and lower congestion rates. Some publications also conclude that travel time budgets are constant. Thus, reduced commuting trips may be equalized by increases in other trips. The literature review also shows that telework can enable employees to live further away from their workplace. This can lead to urban sprawl. Thus, especially part-time teleworkers could compensate the decreased number of weekly trips with longer trip lengths to the workplace. Furthermore, living in rural areas can increase the length of other trips, for example to shopping facilities. Overall, the short-term benefits of telework are well investigated. However, it is questionable what long-term impact this will have on traffic. Mobility and traffic pose a complex system, where long-term rebound effects may occur. For this reason, there is a need for further research to evaluate these interrelations on a long-term systemic level.

This dissertation examines the system of urban mobility and urban logistics and tries to identify such long-term effects. The focus is on the impacts of partial substitution of physical freight transport. Nevertheless, passenger transport and primarily commuter transport are essential components of the system. Thus, the potential to substitute commuter transport with telework may impact the system of urban mobility and urban traffic. The literature review of telework and distributed work, in general, shows that the short-term effects of substituting commuter transport are extensively studied. These insights should be used as input for the system model of urban mobility and logistics, which is developed in this dissertation. Furthermore, the system model tries to identify the long-term effects of substituting physical transport, which are less examined in the reviewed literature of distributed work. Thus, this research gap is intended to be closed.

2.3.2. Online Shopping

The previous section showed how commuting can be substituted due to telework. But trips to work are not the only physical activities that can be substituted and have effects on traffic. As shown in Figure 8, Bolik et al. (1982, p. 13) distinguish traffic by the purpose of travel. Besides commuter traffic, shopping traffic is an important component of overall passenger traffic. For this dissertation, transport-related effects of online shopping are of particular interest. Besides passenger transport demand, freight transport is also affected by online shopping. For the system model, which is presented in chapter 6 of the dissertation, environmental impacts of online shopping and related changes in transport are also relevant. These three research clusters can also be identified in the literature review concerning online shopping and transport. Table 4 presents relevant publications on these clusters.

Research cluster	Publications
Relationship between online shopping and individuals' shopping transport demand	Farag et al. (2007), Zhou & Wang (2014), Edrisi & Ganjipour (2017), Suel & Polak (2017), Lee et al. (2017), Suel & Polak (2018), Wadud & Chen (2018), Peng (2019), Shi et al. (2019), Xi et al. (2020), López Soler et al. (2021), Bjørgen et al. (2021), Bönisch et al. (2021), Colaço & de Abreu e Silva (2021), Le et al. (2021), Shi et al. (2021)
Relationship between online shopping and shopping transport demand including passenger and freight transport	Cullinane (2009), Rotem-Mindali & Weltevreden (2013), Francke & Visser (2015), Reiffer et al. (2021)
Environmental impacts of online shopping and related changes in transport	Smidfelt Rosqvist & Winslott Hiselius (2016), Hischier (2018), Buldeo Rai et al. (2019), Buldeo Rai (2021)

Table 4 Literature review of online shopping & transport

As mentioned, the first research cluster deals with the association between online shopping and shopping transport demand. The cluster also examines the relationship between online and local in-store shopping. Early investigations by Farag et al. (2007) examine these relationships in the

Netherlands using survey data. In particular, they use structural equation modeling to examine the relationship between online and in-store shopping. The authors' results indicate that people who frequently search online, tend to make more non-daily shopping trips (Farag et al. 2007, p. 136). Furthermore, the frequency of online shopping is positively correlated to the frequency of local in-store shopping (Farag et al. 2007, p. 136). These results are surprising according to the authors, as they expected a negative correlation and a decrease in shopping trips due to increased online shopping. Instead of this substitution effect, Farag et al. (2007) find more of a complementary relationship.

Zhou & Wang (2014) also examine the relationship between online shopping and shopping trips by analyzing data from the National Household Travel Survey in the United States. The authors expect that online shopping could reduce shopping trips on the one hand. On the other hand, Zhou & Wang (2014) also consider that online shopping could increase trips due to the need of experiencing goods to be ordered online in reality. Similar to Farag et al. (2007), Zhou & Wang (2014, pp. 2-3) also use structural equation modeling as a method of investigation. This investigation of bidirectional impacts indicates an asymmetric relationship between online shopping and shopping trips (Zhou & Wang 2014, p. 8). In particular, Zhou & Wang (2014, p. 8) find that online shopping promotes shopping trips, while shopping trips tend to reduce online shopping propensity.

Edrisi & Ganjipour (2017) investigate the relationship between online shopping and shopping trips in Tehran, Iran also using a structural equation model. The findings are similar to the previous studies. Edrisi & Ganjipour (2017, p. 6) also find a positive effect of online shopping on shopping trips. This finding supports the hypothesis of a complementary relationship between online shopping and shopping trips.

Suel & Polak (2017) focus on the association between online shopping and shopping trips in the context of grocery shopping in London. For that, discrete choice models are developed. The findings show that online grocery shopping has the potential to significantly reduce trips to grocery stores Suel & Polak (2017, p. 160). In contrast to Farag et al. (2007), Zhou & Wang (2014) and Edrisi & Ganjipour (2017), Suel & Polak (2017) find a substitutive relationship. It has to be noted that Suel & Polak (2017) only focus on grocery shopping, while the other authors focus on online shopping in general.

Research by Lee et al. (2017) examines the relationship between online and in-store shopping frequencies in California using survey data. Despite assuming that online shopping may reduce in-store shopping frequencies and physical shopping trips, Lee et al. (2017, p. 48) find a positive correlation between the two variables.

Wadud & Chen (2018) investigate impacts of physical shopping on traffic and congestion in megacities using GPS tracking data. The results of Wadud & Chen (2018, p. 128) show that average speed increases by around 18% when in-store shopping opportunities are restricted. This study shows that substituting physical in-store shopping has a great potential for reducing shopping traffic. It still has to be examined how this potential can be achieved, especially as some papers indicate a positive correlation between online shopping and shopping trips.

Peng (2019) states that online shopping may have various effects on transport. On the one hand, online shopping causes home delivery transport but on the other hand, it may reduce shopping trips and thus passenger transport. The research by Peng (2019) examines a popular online shopping event in China and the impacts on transport. The results indicate that online shopping frequency increased by around 60% during the investigated event. Furthermore, traffic congestion dropped by 1.7 % during peaks and 1% during non-peak hours (Peng 2019, p. 1). Thus, Peng (2019) finds a negative correlation between online shopping and shopping trips. Nevertheless, the representative nature of the investigation of only one online shopping event is limited and implies a need for further research.

Shi et al. (2019) use data from structured interviews in Chengdu, China to investigate if online shopping reduces shopping trips. The authors use different regression models as a method. According to Shi et al. (2019, p. 30), most of the respondents reduced their shopping trips due to online shopping. Thus, a substitution effect of online shopping on shopping trip frequency is identified.

The research of Xi et al. (2020) examines the impacts of same-day delivery online shopping on in-store shopping trips. They use retrospective survey data in Nanjing, China and a quasi-longitudinal research design. According to the results of Xi et al. (2020, p. 43), same-day delivery online shopping reduces local shopping trips. Nevertheless, Xi et al. (2020, p. 43) expect that same-day delivery online shopping will not significantly reduce personal automobile traffic because active transport modes are predominantly used for shopping in the study.

López Soler et al. (2021) examine the relationship between online shopping and transport demand in the European Union using machine learning methods. They find that online shopping positively correlates to travel times and travel distances in general (López Soler et al. 2021, p. 16). A possible explanation for these positive correlations is the correlation between budgets for shopping and transport.

Similar to Suel & Polak (2017), Bjørgen et al. (2021) examine the relationship between online grocery shopping and shopping trips. For this investigation, survey data from Norway is analyzed. Bjørgen et al. (2021, pp. 3-4) find that online grocery shopping is associated with fewer physical shopping trips and reduced car use. Thus, a substitution effect is identified. Bjørgen et al. (2021) state that this substitution effect should be considered for city and transport planning in the future.

The literature review so far indicates that research is at odds when it comes to the relationship between online shopping and transport demand. Therefore, Bönisch et al. (2021) examines if this relationship is complementary or substitutive. The authors use latent class analysis for the city of Munich to answer their research question. Similar to other publications reviewed above, Bönisch et al. (2021, pp. 10-12) find that people who frequently use their car, also tend to use online shopping more frequently. According to Bönisch et al. (2021, pp. 10-12), available time and a positive attitude towards in-store shopping promote local in-store shopping activities. The relationship is not present for daily need shopping. This could explain deviations from the results of the presented literature, which focuses on grocery shopping.

Colaço & de Abreu e Silva (2021) acknowledge that the academic literature provides mixed results for the relationship between online shopping, in-store shopping, and shopping trips. According to the authors, "several studies point to the complementarity between online and in-store shopping, while others suggest substitution, modification, or neutrality" (Colaço & de Abreu e Silva 2021, p. 1). To better explore the relationship, Colaço & de Abreu e Silva (2021) analyze survey data from

Lisbon, Portugal using structural equation modeling. The results indicate that an online shopping preference is positively correlated with online shopping frequency (Colaço & de Abreu e Silva 2021, p. 7). Furthermore, Colaço & de Abreu e Silva (2021, p. 7) find a complementary association between online shopping and local in-store shopping on weekends. According to the authors, this effect is especially linked to a younger generation commuting by car (Colaço & de Abreu e Silva 2021, p. 7). Colaço & de Abreu e Silva (2021) expect that this complementary association may change to a substitutive relationship. Reasons for such a change may be the increasing service quality of home delivery and high rents in central urban areas (Colaço & de Abreu e Silva 2021, p. 1).

Shi et al. (2021) focus on the relationship between online shopping and shopping trip frequency of car owners. The authors assume that car owners are less likely to substitute their shopping trips with online shopping because they have a high degree of mobility and easy access to local shopping stores. To examine this hypothesis, Shi et al. (2021) analyze survey data from Chengdu, China. According to the results, 44% of the respondents reduced their number of shopping trips after purchasing online (Shi et al. 2021, p. 6). Only 14% increased their shopping trip frequency after shopping online (Shi et al. 2021, p. 6). Thus, the results indicate a substitutive relationship between online shopping and shopping trips. According to the authors, shopping trip frequency is less likely to decrease for car owners compared with people who do not own a car (Shi et al. 2021, p. 6). Considering these results, it is questionable if policies which promote online shopping can solve the problem of urban car traffic.

Suel & Polak (2018) and Le et al. (2021) conduct a literature review to better understand the association between online shopping and physical shopping trip frequencies. These literature reviews may help to gain a holistic view on the research cluster.

According to Suel & Polak (2018, p. 4), four types of relationships between online shopping and shopping trips can be observed in the results of existing scientific literature. These types are substitution, complementarity, modification, and neutrality (Suel & Polak 2018, p. 4). Thus, the results are at some point contradictory. Suel & Polak (2018) as well as Farag et al. (2006) and Circella & Mokhtarian (2010) conclude that most studies identify a complementarity effect and a positive correlation between online and in-store shopping frequencies. According to Suel & Polak (2018, p. 4), causality is difficult to determine in this context. Suel & Polak (2018, p. 4), Girard et al. (2003), Mokhtarian (2004) and Rotem-Mindali & Salomon (2007) also state that shopping as an activity is manifold. According to them, shopping for groceries may underlie different mechanics than non-daily shopping. Thus, the mobility impacts of different types of shopping may vary. In particular, shopping activities which require a lot of preparation and information gathering may be less likely to be substituted by online shopping Suel & Polak (2018, p. 4). One example of such an activity is the purchase of a car. Suel & Polak (2018, p. 4) also state that online shopping has the potential to open up new shopping opportunities and thus may induce new traffic and transport demand. Due to these complex relationships, further research is necessary to conduct a system-wide analysis and better understand shopping travel demand and behavior, according to Suel & Polak (2018, p. 4) and Bhat et al. (2003).

The research of Le et al. (2021) is another example of a paper examining the relationship between online shopping and in-store shopping trip frequencies using a detailed literature review. In contrast to Suel & Polak (2018), Le et al. (2021) find more evidence that online shopping substitutes for shopping travel. They criticize that most of the studies use survey data "which hinders the distinction between short- and long-term behaviors and between modification, complementarity, and substitution effects" (Le et al. 2021, p. 1). Furthermore, they remark that online shopping for different types of products may imply different effects on transport demand and in-store shopping behavior (Le et al. 2021, p. 1).

The first research cluster presents mixed results. Some publications indicate a complementary relationship between online shopping and an individual's transport demand. Other publications suggest that online shopping can substitute in-store shopping and related trips by individuals. This dissertation considers and examines both possibilities in the system model presented in chapter 6. The relationship depends on the considered product types and time horizons.

The first cluster, which was reviewed above, constitutes useful research and helps to better understand the relationship between online shopping and the shopping transport demand of individuals. However, transport in the context of online shopping is not only determined by passenger but also by freight transport. To evaluate online shopping and its substitution potentials, it is therefore necessary to review a second research cluster which deals with the relationship between online shopping and transport demand, including both passenger and freight transport. The literature review shows that research covering both passenger and freight transport is less common than research dealing with passenger transport only. Selected publications of this second research cluster are presented in Table 4.

Francke & Visser (2015) discuss the impacts of online shopping on passenger and freight transport. The authors identify several impacts of online shopping on transport. According to Francke & Visser (2015, p. 6), online shopping may substitute trips to local shops but also may induce trips to collection points or parcel shops if the delivery is picked up by the customer himself. Furthermore, online shopping may save time for customers because physical shopping trips can be avoided. This gained time may induce other activities which require transport (Francke & Visser 2015, p. 6). Logistics is clearly affected by online shopping. According to Francke & Visser (2015, p. 6), parcels have to be delivered directly to the customer and bundling effects of delivering goods to a central store are dropped. Thus, online shopping increases home delivery transport using delivery vans or other delivery vehicles. Last, online shopping affects the number of local stores, which may have indirect impacts on the shopping behavior of customers (Francke & Visser 2015, p. 6). The authors take a closer look at the impacts of online shopping on logistics. Before online shopping emerged, the main task of logistics was transporting large volumes of bundles of goods in trucks from manufacturers to retailers or B2B (Business-to-Business), according to Francke & Visser (2015, p. 8). After the rise of online shopping, last-mile logistics to the end customer started to play a major role in logistics.

Reiffer et al. (2021) recognize that increased freight traffic in urban areas due to online shopping may affect not only last-mile delivery but also private passenger transport. To better understand the reciprocal effects between online shopping behavior and last-mile deliveries, they create an agent-based travel demand model. The authors' analyses focus on rates of successful deliveries and are therefore not very suitable for the estimation of changes in shopping transport due to online shopping. Cullinane (2009) and Rotem-Mindali & Weltevreden (2013) both conduct a literature review to evaluate these changes.

The objective of Cullinane (2009) is to highlight the complex transport relationships involved in online shopping. In particular, the role of passenger and freight transport in online shopping is examined. Cullinane (2009) concludes that the impact of online shopping on passenger and freight transportation as well as their interrelationship has rarely been studied. Reciprocal effects of freight transport can be distinguished into direct and indirect effects (Cullinane 2009). Direct effects seem to be obvious as freight transport using van delivery can benefit from bundling effects, which means that fewer vehicles are necessary for a certain number of shopping transactions because one van can serve many customers. Indirect effects can be long-term and are, therefore, difficult to evaluate. Gained time for leisure travel due to the reduction of shopping trips is an example rebound effect that may occur. As these indirect effect pose very complex interrelations, there is a need for further research to better understand these effects.

Rotem-Mindali & Weltevreden (2013) also conduct a literature review. They conclude that an increase in freight traffic is induced by online shopping. Still, the decrease of required physical shopping trips due to online shopping is likely to compensate overall trip distances (Rotem-Mindali & Weltevreden 2013, p. 15). Thus, online shopping can contribute to sustainability according to the authors. Still, Rotem-Mindali & Weltevreden (2013, p. 15) criticize that a significant amount of the literature overestimates the substitution effects of online shopping. This overestimation stems from ignoring that shopping activities are most often chained to other activities (Rotem-Mindali & Weltevreden 2013, p. 15).

The second research cluster that examines the relationship between online shopping and both passenger and freight transport contains a limited amount of publications. On the one hand, online shopping may reduce passenger transport. On the other hand, online shopping induces freight transport on the last mile to the end customer. The system model in this dissertation considers both effects and tries to model the complex interrelations.

The third relevant research cluster evaluates environmental impacts of changes in transport due to online shopping. Selected publications of this cluster are summarized in Table 4. The cluster is relatively small compared with the first cluster, which deals with the relationship between online shopping and individuals' shopping transport demand.

Smidfelt Rosqvist & Winslott Hiselius (2016) evaluate the potential of online shopping for reductions in carbon dioxide emissions in passenger transport. The authors state that online shopping may reduce individuals' shopping trips in Sweden. The results indicate that a 22% decrease in CO_2 emissions related to shopping trips compared with 2012 can be achieved (Smidfelt Rosqvist & Winslott Hiselius 2016, p. 6). Furthermore, the authors identify another huge potential of online shopping. According to Smidfelt Rosqvist & Winslott Hiselius (2016, p. 1), online shopping can reduce peoples' dependence on cars, especially in urban areas.

Hischier (2018) compares the environmental impacts of classical in-store shopping, which implies private shopping trips, and online shopping, which implies home delivery transport. Thus, Hischier (2018) considers shopping transport demand including passenger and freight transport. Such an analysis is valuable, especially because research which focuses on both types of transport is relatively rare, as shown in Table 4. The research of Hischier (2018) focuses explicitly on the clothing market and consists of a case study. The findings show that online shopping is not necessarily more sustainable than local in-store shopping, which requires personal shopping trips. The environmental impacts highly depend on the used means of transport (Hischier 2018, p. 1).

Buldeo Rai et al. (2019) examine environmental impacts of multichannel shopping behavior. The object of investigation is a footwear retailer in Belgium offering both online and in-store shopping opportunities for customers. The results show that customers shopping online generate fewer CO_2 emissions compared with other customer types (Buldeo Rai et al. 2019, p. 14). However, when online shoppers combine their online purchases with trips to local stores to use them as a showroom for products, which are ordered later online, external CO_2 costs double compared with traditional in-store shoppers (Buldeo Rai et al. 2019, p. 14). This finding is relevant from an environmental point of view as the literature review indicates that there might be a complementary relationship between online and in-store shopping.

Further research from Buldeo Rai (2021) states that most of the scientific papers dealing with the environmental impacts of different shopping types focus on the impact of purchasing activities, in which in-store purchases are substituted by online shopping. According to the author, such studies conclude in favor of online shopping. Buldeo Rai (2021) complements these articles by taking into account the spatial organization of customers and businesses. The results of Buldeo Rai (2021) indicate that there is no shopping type which is generally preferable due to low environmental impacts. However, the authors identify a list of factors affecting the environmental impacts of shopping activities.

Summary & Link to this Dissertation

Overall, it can be stated that the first research cluster, which focuses on the relationship between online shopping and individuals' shopping transport demand, is being extensively investigated. Nevertheless, divergent results emerge in this research cluster. These divergent results indicate either complementarity, substitution, modification, or neutrality between online and in-store shopping. The review shows that articles which identify a substitutive relationship between online and in-store shopping often focus on shopping for daily needs (e.g., grocery shopping). Shopping for other product types like clothing is linked to a complementary relationship in some papers. It is also questionable if online shopping frequency has a causal effect on in-store shopping frequencies. Some papers reviewed above try to investigate this causal effect using structural equation modeling. Still, it is possible that the correlations of these two shopping types are spurious, which is caused by other variables like budget or overall preference for shopping. People, who like online shopping may also enjoy in-store shopping and people with higher budgets are likely to have higher shopping frequencies both online and in-store. The insights of this research cluster are highly relevant to the system model in this dissertation. This model examines the system of urban mobility and urban logistics. Shopping behavior influences both passenger and freight transport. The discord of the relationship between online and in-store shopping is an essential input for the system model, indicating that the promotion of online shopping does not necessarily substitute shopping transport.

Furthermore, the review shows that publications concerning the second research cluster, which examine both passenger as well as freight transport in the context of online shopping, are relatively rare compared with publications focusing on online shopping and passenger transport only. This is not surprising, as there are complex interrelations between passenger and freight transport. Especially the quantification and comparison of potential substitution effects of individual shopping trips and increased freight transport on the last mile is not sufficiently studied. Thus, the conducted literature review identifies a need for further research for the evaluation of shopping behavior and its effects on overall transport and traffic, including both passenger and freight transport. This dissertation contributes to closing this gap by applying a systems thinking approach to evaluate these complex interrelations. Furthermore, this dissertation analyzes both passenger and freight transport in the context of online shopping from a systemic point of view to better understand the environmental impacts in the system. Further research is required in this field.

2.3.3. Teleleisure and Online Maintenance

Besides working and shopping, leisure and maintenance activities are another big part of people's lives causing transport demand. Leisure and maintenance are also strongly affected by ICT, as new technologies enable new digital leisure activities and new opportunities for maintenance. These new types of digital activities are often referred to as teleleisure and online maintenance in the scientific literature. Examples of teleleisure are online video games, meeting friends in a virtual environment online, or spending time on social networks. During the global COVID-19 pandemic, these activities inevitably gained popularity. The transport substitution potentials of teleleisure and online maintenance follow the same theoretical principles as online shopping and telework. The basic idea is that activities can be carried out from home, reducing the need for transport and the volume of traffic. This part of the literature review aims to examine the relationship between teleleisure, online maintenance and transport demand. It is to be examined if the potential transport substitution effects of teleleisure and online maintenance are visible in reality. Research focusing on the relationship between teleleisure, online maintenance and transport demand is rare. This impression is confirmed by Andreev et al. (2010) stating that the transport substitution potentials of teleleisure have been least studied compared with the potentials of online shopping and telework. Therefore, specialized research clusters cannot be identified. The following section and Table 5 give a brief overview of relevant publications in this research area.

Research cluster	**Publications**
Relationship between teleleisure, online maintenance and transport demand	Mokhtarian et al. (2006), Andreev et al. (2010), Näsi et al. (2012), Streit et al. (2015), Cohen-Blankshtain & Rotem-Mindali (2016), Lila & Anjaneyulu (2016), Lyons et al. (2018), Shukla & Raval (2021)

Table 5 Literature review of teleleisure, online maintenance & transport

Mokhtarian et al. (2006) investigate the impacts of ICT on leisure activities and leisure travel.

According to the authors, the most important impact is the expansion of peoples' leisure activity choice set due to ICT. In detail, teleleisure may have four different types of impacts (Mokhtarian et al. 2006, p. 270). First, teleleisure can replace traditional leisure activities with ICT-based counterparts. This type of impact is likely to reduce transport demand (Mokhtarian et al. 2006, p. 270). Second, ICT may generate completely new activities substituting, augmenting or overlaying other traditional activities (Mokhtarian et al. 2006, p. 274). The third identified type of impact focuses on the time-saving potentials of teleleisure. According to Mokhtarian et al. (2006, p. 278), teleleisure may save time due to the avoidance of travelling to an activity location. These time savings can enable other types of leisure activities, which may induce additional transport demand. This interrelation is a classical rebound effect. Last, ICT can be an enabler of leisure activities because it opens up new opportunities for activity planning using the internet (Mokhtarian et al. 2006, p. 279). Due to the different potential impacts, transport implications are not trivial and can occur in different forms.

The research of Andreev et al. (2010) investigates the impacts of teleleisure and online maintenance on individuals' travel behavior using a literature review of older publications. As mentioned above, Andreev et al. (2010) find that the transport substitution potentials of teleleisure and online maintenance receive little attention in the scientific literature compared with the potentials of online shopping and telework. Andreev et al. (2010, p. 16) also find that the clear majority of reviewed publications indicate a complementary relationship between teleleisure and traditional leisure activities. Thus, leisure transport demand is unlikely to decrease. Compared with the scientific findings on transport impacts of telework and online shopping, these results are relatively unambiguous. When it comes to online maintenance, the findings of the literature review are less unambiguous. Still, Andreev et al. (2010, p. 16) conclude that most of the reviewed papers find a complementary relationship between online maintenance and traditional maintenance activities.

Näsi et al. (2012) focus on the impacts of ICT on leisure activities and the related transport demand in particular among senior citizens in Finland. The authors use survey data and logistic regressions to answer their research questions. They find that older age groups are not homogeneous when it comes to ICT use. Furthermore, the authors find a strong positive correlation between ICT use and the number of different leisure activities among Finnish seniors (Näsi et al. 2012, p. 174). Thus, these results also support the hypothesis of a complementary relationship between teleleisure and traditional leisure activities.

Streit et al. (2015) investigate how individual travel and transport demand in Germany have changed due to ICT. The authors focus on leisure activities and use data from the MOP (German Mobility Panel). The findings indicate that at least people of the young age groups are shifting their leisure habits to home-based teleleisure. This finding may be an indicator of a negative correlation between teleleisure and related transport demand for a younger age group.

Cohen-Blankshtain & Rotem-Mindali (2016) conduct a literature review to examine the relationship between ICT and sustainable urban mobility. In their publication, they investigate teleleisure among other aspects. Leisure transport is very interesting from a sustainability point of view because this type of transport is often carried out by car (Schlich et al. 2004). Cohen-Blankshtain & Rotem-Mindali (2016, p. 12) conclude that a few publications indicate a negative correlation between teleleisure and leisure transport when it comes to communication activities only (van den

Berg et al. 2013). Other publications reviewed by Cohen-Blankshtain & Rotem-Mindali (2016) indicate a complementary relationship (e.g., Carrasco 2011 and Ren & Kwan 2009). Interestingly, Ren & Kwan (2009) distinguish between teleleisure and online maintenance activities. For maintenance, they find a substitutive relationship.

The research of Lila & Anjaneyulu (2016) has already been reviewed in the context of distributed work and transport. Besides the transport demand reduction potentials of telework, Lila & Anjaneyulu (2016) also examine the potentials of teleleisure, online maintenance and ICT in general using structural equation modeling. The findings show that ICT generates more leisure activities and increases the total number of trips made by individuals (Lila & Anjaneyulu 2016, p. 426).

Lyons et al. (2018) investigate the impacts of teleleisure on cities using a brief literature review. According to the authors, the relevance of teleleisure transport is growing as leisure time increased in developed economies during the last half of the twentieth-century (Lyons et al. 2018, p. 3). The conclusions indicate that ICT use is positively correlated with the frequency of teleleisure activities (Lyons et al. 2018, p. 3). However, Lyons et al. (2018, p. 3) also conclude that greater use of ICT is associated with more meetings with friends and family in person.

Shukla & Raval (2021) investigate the impact of virtual accessibility on out-of-home activity and travel in India using a structural equation model. The findings indicate that ICT accessibility is positively correlated with the number of leisure activities (Shukla & Raval 2021, p. 6). However, this effect is not statistically significant. Furthermore, Shukla & Raval (2021, p. 6) find that ICT accessibility decreases the time spent on maintenance activities.

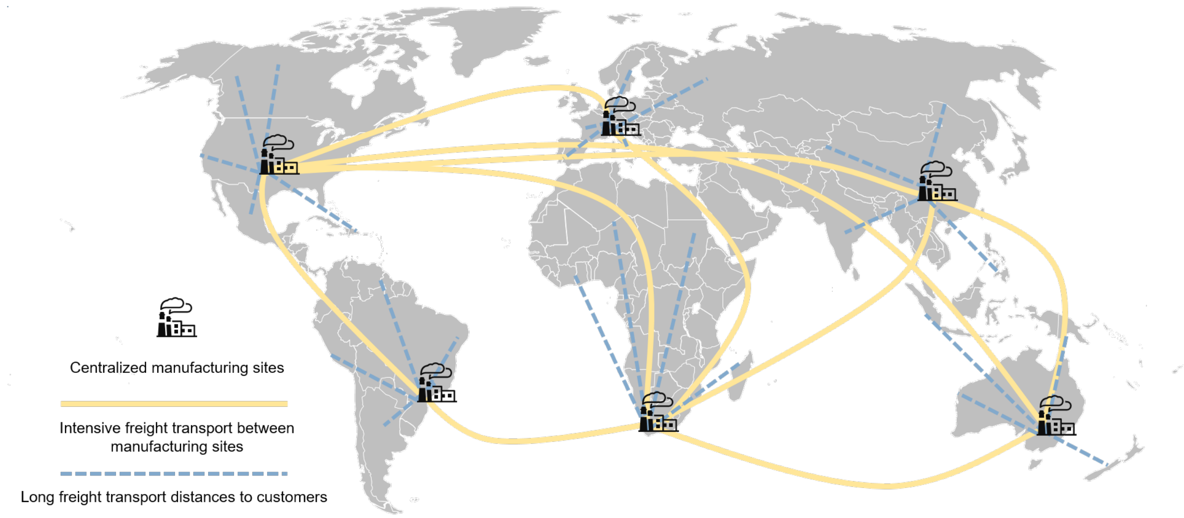
Summary & Link to this Dissertation

The literature review of publications which examine the transport substitution potentials of teleleisure and online maintenance shows that this field is poorly researched compared with the transport substitution potentials of distributed work and online shopping. Thus, a general need for further research in this area is apparent. Still, the findings of the reviewed publications are relatively consistent and unambiguous. The results indicate a complementary relationship between teleleisure enabled by ICT and traditional leisure activities. Thus, there is strong evidence that teleleisure is unlikely to reduce leisure transport demand. Some results even indicate that teleleisure and especially the use of ICT tends to increase the frequency of traditional leisure activities and therefore also leisure transport demand. When it comes to online maintenance, most of the reviewed publications identify a substitutive character, which means that online maintenance may replace traditional maintenance activities. This substitution may also reduce associated transport demand.

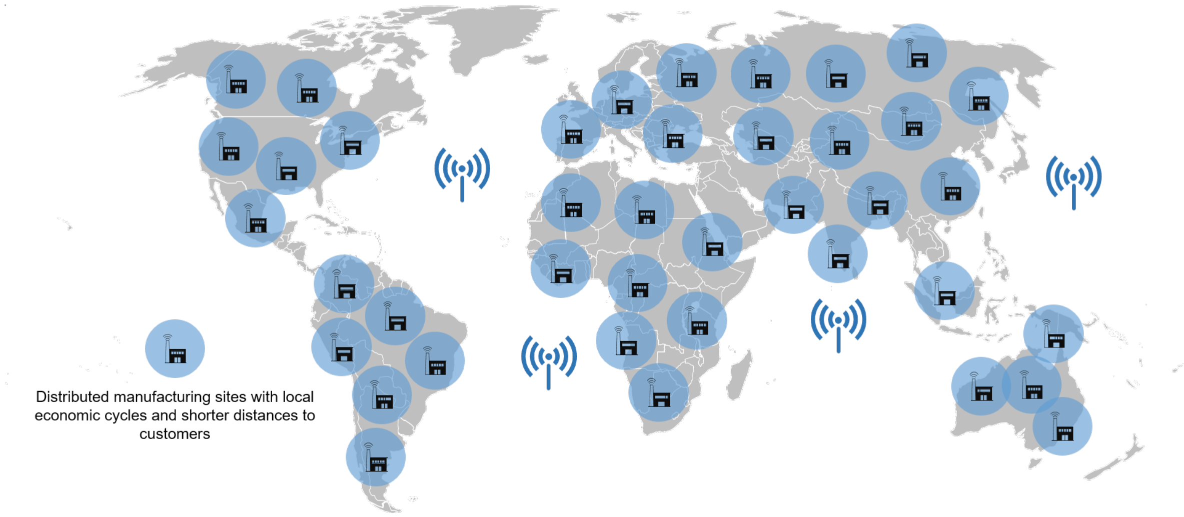
Leisure transport is one crucial component of passenger transport. Thus, the consideration of leisure transport is relevant in the system of urban mobility and logistics. The insights of the literature review serve as input for the system model in this dissertation. In particular, the literature review shows that teleleisure and online maintenance provide new opportunities to substitute related transport. However, some results indicate occurring rebound effects, increasing transport demand. These rebound effects might also occur in other fields of transport. The insights of the review serve as inspiration to consider rebound effects in the system model of this dissertation.

2.3.4. Distributed Manufacturing

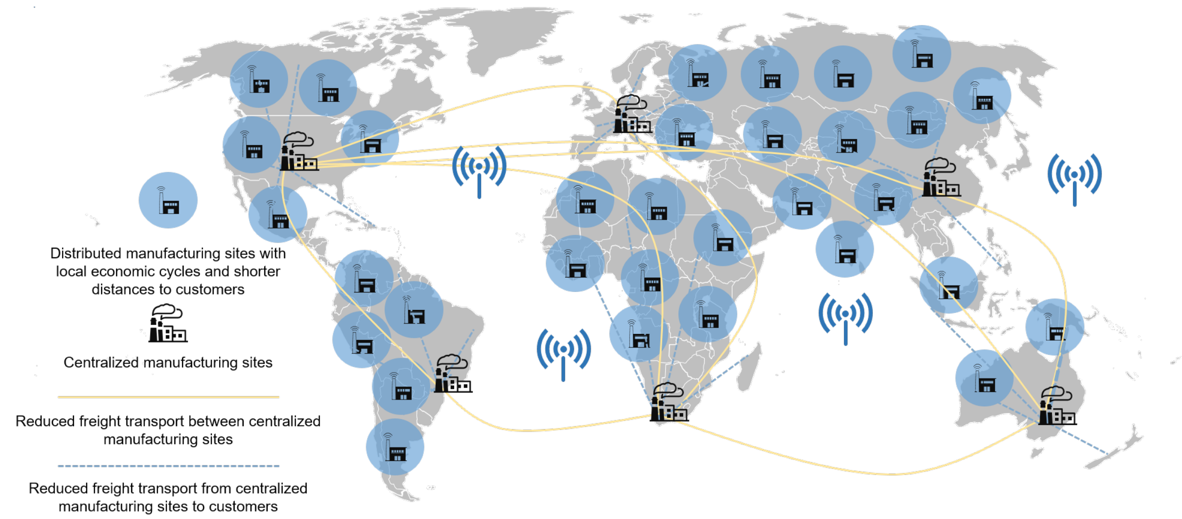
Distributed work, online shopping, online maintenance, and teleleisure pose activities, which have the potential to substitute or complement physical passenger transport under certain circumstances (see Table 1). However, this dissertation focuses on another key aspect of the system of urban mobility and logistics, which is the partial substitution of urban freight transport. The main objective of this dissertation is to examine how physical freight transport can be substituted with data transfer and local production. This approach is referred to in the literature as distributed production or distributed manufacturing. Distributed manufacturing is usually associated with 3DP and AM. In the further course, distributed manufacturing is also referred to as production near the place of use. The goal of this dissertation is to examine how physical freight transport can be substituted using production near the place of use and what impacts this may have on urban mobility. Therefore, it is essential to review existing literature investigating freight transport substitution potentials of distributed manufacturing. Before reviewing relevant publications, it is necessary to define distributed manufacturing and evaluate the characteristics of a decentralized manufacturing system. Lowe (2019, p.39) defines manufacturing as the execution of value-adding steps in the creation of physical products. In this context, distributed manufacturing moves the production process from centralized manufacturing facilities closer to the place, where the product is intended to be used (Lowe 2019, p.39). As products are bought and consumed all over the world, it is intuitive to consider a decentralized manufacturing system, which is spread around the globe. According to Lowe (2019, p.39), decentralized manufacturing systems tend to produce smaller quantities because decentralized manufacturing facilities supply smaller segments of the global market compared with large, centralized manufacturing facilities. Furthermore, Lowe (2019, p.39) states that digital manufacturing technologies such as 3DP are very suitable for decentralized manufacturing because digital twins, which serve as product blueprints, can easily be transferred using ICT. Furthermore, the digital twins can easily be modified and digital manufacturing technologies like 3DP do not require molds or other aspects, which are associated with high fixed costs, in most cases. Thus, the production of small batch sizes and individualized products becomes profitable. Digital manufacturing technologies are usually highly automated compared with their traditional counterparts. Thus, manufacturing costs are largely independent of labor costs, which enables profitable production even in countries where labor costs are comparatively high. This aspect is essential for enabling distributed manufacturing all over the world. Rauch et al. (2016, p. 130) also refers to distributed manufacturing as "glocal" production, which takes place in distributed micro-production facilities. According to the authors, distributed manufacturing is able to meet local needs and to deliver quickly in a sustainable way (Rauch et al. 2016, p. 130). Furthermore, the characteristics of distributed manufacturing enable mass customization of products (Rauch et al. 2016, p. 130). Figure 9 depicts the concepts of centralized and distributed manufacturing, and the differences between the two systems are immediately visible. In centralized manufacturing systems, there typically is a small number of large, centralized manufacturing sites, which produce a certain product. According to (Rauch et al. 2016, p. 131), there are high global flows of goods between these production sites in a centralized manufacturing system. These flows imply high freight transport demands. Furthermore, a centralized manufacturing system typically has long freight transport distances to customers of manufactured products since production takes



(a) Centralized manufacturing system



(b) Distributed manufacturing system



(c) Mixed manufacturing system

Figure 9 Comparison of manufacturing systems place in only a small number of facilities and yet customers all over the world have to be supplied. Rauch et al. (2016, p. 131) states that economies of scale and global competition lead to the production of standardized products in a centralized manufacturing system. The intensive freight transport demand in the system implies a high energy demand and thus is likely to have negative environmental impacts and high transport costs.

The distributed manufacturing system, which is depicted in Figure 9b, contains many manufacturing sites widely distributed all over the world. Products can be easily produced in the facility, which is closest to the customer by transferring the associated digital twin using ICT. Thus, freight transport distances to customers can be reduced which also has positive impacts on the environment due to reduced energy demand for transport. The smaller transport distances to customers are indicated in Figure 9b by the blue circles around the manufacturing facilities, which represent local economic cycles. According to Rauch et al. (2016, p. 131), distributed manufacturing promotes these regional and small-scale economic cycles. In contrast to centralized manufacturing systems, distributed manufacturing systems may promote customization and individualization of manufactured products because digital manufacturing technologies like 3DP are able to produce small quantities profitably due to nearly-constant unit costs (Kunze et al. 2023). Furthermore, distributed manufacturing using digital production technologies is flexible. 3D printers are not designed for the production of only one single product. In fact, 3D printers can produce an almost unlimited amount of shapes and products. Thus, digital decentralized manufacturing facilities are able to produce a wide range of products, even in small quantities. This aspect represents a significant advantage over centralized manufacturing systems using traditional manufacturing technologies. Figure 9b depicts distributed manufacturing on a global scale. However, distributed manufacturing can also be applied on a local scale, for example in a city where certain distributed manufacturing sites serve customers living close by in related areas using production near the place of use. Therefore, the density of distributed manufacturing facilities can be increased.

In reality, it is unlikely that a purely centralized or a purely distributed manufacturing system will emerge, as some products are very suitable for digital distributed production, while others, in particular products with many components consisting of different materials, still require centralized manufacturing. It is more likely that a combination of distributed and centralized manufacturing will emerge in the future. In Figure 9c such a combination is referred to as a mixed manufacturing system. Distributed manufacturing sites can produce a part of the products, which were originally produced in large, centralized manufacturing sites. As mentioned before, some products still have to be produced in these large factories. The production shift may partly reduce freight transport of centralized manufacturing on the global scale. These reductions are indicated by the thinner connections in Figure 9c.

The concept of distributed manufacturing implies changes in logistics, supply chains and freight transport. The aim of this section is to further review the scientific literature in this field. Table 6 shows selected and relevant publications dealing with distributed manufacturing and freight transport in the widest sense. As a result of the literature review process, two different research clusters can be identified. While the first cluster focuses on impacts of distributed and additive manufacturing on freight transport on a global scale, the smaller second research cluster investigates freight transport impacts on an urban scale.

Research Cluster	Publications
Impacts of distributed and additive manufacturing on freight transport, logistics and supply chains on a global scale	Silva & Rezende (2013), Khajavi et al. (2014), Matt et al. (2015) , Rauch et al. (2015), Chen (2016), Pour et al. (2016), Rauch et al. (2016), Attaran (2017), Durach et al. (2017), Daduna (2019), Lowe (2019), Szymczyk et al. (2019), Akbari & Ha (2020), Liu et al. (2020)
Impacts of distributed and additive manufacturing on freight transport, logistics and supply chains on an urban scale	Kunze (2016), Mckinnon (2016), Taniguchi et al. (2016), Chaberek-Karwacka (2017)

Table 6 Literature review of distributed manufacturing & transport

Silva & Rezende (2013) examine future impacts of distributed additive manufacturing on global logistics. They state that material development is crucial for the expansion of AM into production (Silva & Rezende 2013, p. 281). Furthermore, AM may reduce logistics activities as products can be locally produced (Silva & Rezende 2013, p. 281). The authors of the study further assume that supply chains could be shortened drastically as products can flow directly from designers or producers to customers without the intervention of retailers (Silva & Rezende 2013, p. 282). This assumption of the authors can be considered from another perspective. In the future, retailers could use 3DP to manufacture products by themselves and thus make producers obsolete. Nevertheless, Silva & Rezende (2013, p. 282) assume that AM is more likely to rather complement than replace traditional manufacturing and supply chains.

Khajavi et al. (2014) investigate the impacts of AM in a distributed manufacturing system on spare parts logistics and the spare parts supply chain using a case study. The authors compare the production of aeronautics spare parts for the United States Navy in a distributed and centralized manufacturing system. Khajavi et al. (2014, p. 53) conclude that AM in a distributed manufacturing system can reduce transport distances and transport costs, which depend on replenishment policies. According to Khajavi et al. (2014, p. 50), production costs of distributed manufacturing exceed the costs of centralized production in the examined case study. However, distributed spare parts production may become beneficial as 3D printers become "less capital intensive, more autonomous and offer shorter production cycles" (Khajavi et al. 2014, p. 50). It should be noted that the reviewed study took place in 2014. Due to technological developments in AM, distributed manufacturing may be more attractive today.

Matt et al. (2015) present drivers and impacts of distributed manufacturing. According to the authors, transport distances can be reduced in a distributed manufacturing system by moving production closer to the customer (Matt et al. 2015, p. 185). Sustainability, rising logistics costs, mass customization, customer proximity, limited resources, and regionalism are identified as drivers of distributed manufacturing (Matt et al. 2015, pp. 186-188).

Rauch et al. (2015) examine sustainability aspects of distributed manufacturing systems. They identify the same drivers of distributed manufacturing as Matt et al. (2015). Rauch et al. (2015, p. 547) conclude that distributed manufacturing can drastically reduce long-distance transport on roads, at sea, and in the air. Thus, transport emissions can be reduced and local economic cycles can be promoted. Furthermore, Rauch et al. (2015, p. 548) identify four arguments on different levels for sustainable distributed manufacturing. On the economic level, distributed manufacturing can be beneficial due to reductions in logistics costs, shorter delivery times, and the production of individualized products. On the ecological level, traffic and transport emissions can be reduced due to production near the place of use. Distributed manufacturing may have positive impacts on the social level because local manufacturing can increase local employment and customers can be involved in the product development process. Last but not least, the institutional level may promote distributed manufacturing due to ecological incentives (Rauch et al. 2015, p. 548).

Chen (2016) investigates the impacts of additive manufacturing on international supply chains using system dynamics. The results of Chen (2016, p. 14) indicate that the rise of additive manufacturing will shrink worldwide freight transport volume. Besides transport volumes, transport costs will be reduced (Chen 2016, p. 14). Furthermore, the final manufacturing sites are likely to shift to the end of the supply chain and thus closer to the customer (Chen 2016, p. 14).

The research of Pour et al. (2016) follows a similar approach by examining the impacts of additive manufacturing on production and logistics systems using a systematic literature analysis. The great potential to manufacture products near the place of use and close to the customer is the main conclusion of Pour et al. (2016). This potential is enabled in particular by the ability of additive manufacturing to produce parts without the use of auxiliary equipment such as jigs, tools, and coolants (Huang et al. 2013, p. 1194).

Attaran (2017) provides another publication examining the altering effects of additive manufacturing on supply chains and logistics. According to Attaran (2017, p. 194), additive manufacturing has the potential to reduce supply chain complexity. The technology enables the consolidation of components into a single product which reduces inventory complexity and assembly steps (Attaran 2017, p. 194). The conclusions of Attaran (2017, p. 196) indicate that the impacts of distributed additive manufacturing on global supply chains may be disruptive as the technology has the potential to reduce the need for high-volume production facilities and low-level assembly workers. Thus, supply chain costs can be reduced. Since additive manufacturing can take place all over the world, long freight transport distances in the supply chain become obsolete (Attaran 2017, p. 196). Furthermore, distributed additive manufacturing has the potential to reduce lead times and logistics costs due to production near the place of use and close to the customer (Attaran 2017, p. 196). According to the authors, storage of materials for AM and 3DP could emerge as a new sector in logistics (Attaran 2017, p. 196). Other benefits of distributed additive manufacturing are a shorter time-to-market, reduced production waste, more efficient packaging and improved sustainability (Attaran 2017, pp. 197-198).

Durach et al. (2017) examine the impacts of additive manufacturing on supply chains using a survey study conducted with a panel of experts from industry and academia. The authors conclude that the supply chain structure may shift to production at home using 3DP by customers (Durach et al. 2017, p. 16). Local manufacturing of companies is also likely to move close to the customers who can be integrated into the product development process. Such a co-creation can promote individualized products and mass customization (Durach et al. 2017, pp. 17-18). In the context of logistics, additive manufacturing is likely to reduce transport costs and warehousing needs (Durach et al. 2017, p. 19). Furthermore, the authors state that additive manufacturing has the potential to increase supply chain agility by allowing quicker responses to market demands and feedback of customers (Durach et al. 2017, p. 20).

Research by Daduna (2019) also evaluates the disruptive impacts of additive manufacturing on logistics. The author states that the agility of additive manufacturing, which is also mentioned by Durach et al. (2017), is one of the main drivers of distributed production using 3DP. Similar to most of the studies already reviewed, Daduna (2019, p. 2772) predicts that required transport and warehousing services will be drastically reduced in a distributed manufacturing system where production sites can be located close to the customer. Furthermore, certain production steps in different supplier tiers can be eliminated or consumed into the holistic 3DP process. Daduna (2019) conclude that additive manufacturing may have positive impacts on spare parts logistics as spare parts can be produced on demand, near the place of use and in small lot sizes with short lead times. In the publication, a scenario is described whereby retailers, who only import CAD files of certain products, take over the production (Daduna 2019, p. 2772). Thus, the supply chain is drastically shortened. This scenario shows great similarities to the concept of the 3D printing shop, which is explained later in this dissertation (see subsection 2.3.5).

Szymczyk et al. (2019) focus on the substitution of the physical transport of products by the transfer of digital product files and associated impacts on logistics. They identify eight effects of AM implementation on logistics. First, shorter delivery times can be achieved due to production near the place of use and a decreasing number of manufacturing operations per product (Szymczyk et al. 2019, p. 755). Second, production can be relocated to the domestic countries of inventory which also leads to a reduction of transport costs and distances if local customers have to be supplied (Szymczyk et al. 2019, p. 755). Another potential effect which is identified by Szymczyk et al. (2019, p. 755) is the opportunity to produce complex and customer-specific parts and products. Other effects not directly related to transport substitution are changing relationships between manufacturers and retailers, low-volume production at costs, decreasing supplier risks, reduction of product weight and volume as well as improved agility in production (Szymczyk et al. 2019, p. 755).

Akbari & Ha (2020) investigate the impacts of additive manufacturing on the Vietnamese transport industry using an exploratory study. The results show that distributed additive manufacturing may reduce traffic and pollution, especially in emerging markets such as Vietnam (Akbari & Ha 2020, p. 9).

Research by Liu et al. (2020) uses a case study to investigate impacts of distributed manufacturing systems on logistics from an entrepreneurial point of view. Liu et al. (2020) conclude that additive manufacturing has the potential to move manufacturing closer to the customer and to integrate customers into the manufacturing process.

The literature already reviewed and summarized focuses on the impact of distributed manufacturing systems and additive manufacturing on global supply chains and logistics. Since traffic and transport are major issues, especially in cities, it is essential to investigate the potential of distributed manufacturing for transport substitution at the urban level as well. The second identified research cluster in Table 6 deals with these potentials. Table 6 indicates that this research cluster is smaller than the cluster investigating transport substitution potentials of distributed manufacturing on the global scale.

Kunze (2016) uses a qualitative systemic model to evaluate the impacts of distributed additive manufacturing on urban logistics. In particular, the sensitivity model developed by Vester (2019) is used as the method. According to Kunze (2016, p. 293), AM has the potential to transform the present physical logistics to information logistics by transferring digital twins, for example in the form of CAD files, and producing near the place of use instead of sending the already produced goods over long distances. In urban logistics, the location of the 3D printers used for production near the place of use is pivotal. Kunze (2016, p. 294) assumes that the majority of private households are unlikely to operate their own 3D printers for production at home as the technology is relatively expensive and a farm of 3D printers is needed to produce different materials and thus different products. Instead, local centers distributed around the city could offer 3DP services for the production near the place of use and thus create a new business model in urban logistics. Kunze (2016, p. 294) compares these distributed 3DP centers with the former post office structure. The author notes that the substitution of physical goods transport with data transfer and production near the place of use still requires the transport of production materials. Thus, a complete substitution of physical freight transport seems to be impossible. Nevertheless, partial substitution can be achieved as production materials can be transported in larger quantities due to storage opportunities and bundling effects (Kunze 2016, p. 293). Overall, a freight transport substitution potential of distributed additive manufacturing in urban logistics is indicated.

Mckinnon (2016) investigates the possible impacts of distributed additive manufacturing on last-mile logistics in an exploratory study. According to the author, AM has the potential to transform city logistics if its adoption rate is sufficient (Mckinnon 2016, p. 625). However, Mckinnon (2016, p. 625) identifies three constraints that may inhibit this high adoption rate of AM in urban logistics. First, government regulation could pose a constraint. Furthermore, Mckinnon (2016, p. 625) assumes that a lack of economies of scale of 3DP implies higher unit costs in comparison with traditional manufacturing. Third, the author doubts that the added value of additive manufactured products is high enough to induce high adoption rates (Mckinnon 2016, p. 625). It is concluded that AM is likely to reduce delivery times as production can be performed near the place of use (Mckinnon 2016, p. 626). Overall, AM in urban last-mile logistics may "fundamentally reduce the volume of product moved and the vehicle capacity required to transport it" (Mckinnon 2016, p. 626). These potentials can only be exploited for products which can be manufactured using AM. Mckinnon (2016, p. 626) assumes that the amount of these products is limited. It has to be noted that the study of Mckinnon (2016) was conducted in 2016. Since then, AM and 3DP technologies have developed, enabling the production of a wider range of products.

Taniguchi et al. (2016) investigate new opportunities and challenges for city logistics. In this context, additive manufacturing is identified as one opportunity among many. The authors describe AM and 3DP as an emerging manufacturing technology that can be used to create individualized products on demand at distributed locations such as retail stores or even within the homes of customers (Taniguchi et al. 2016, p. 9). Furthermore, AM has the potential to change the structure of manufacturing and supply chains (Taniguchi et al. 2016, p. 9). According to the authors, the technology can be used commercially for mass production in retailing, for example in 3D printing shops and for personal use at home (Taniguchi et al. 2016, p. 9). When it comes to freight transport substitution potentials of distributed AM, Taniguchi et al. (2016) share similar findings with other publications in the reviewed research cluster. They assume that AM can reduce freight transport and especially the distribution of products on the last mile in urban areas (Taniguchi et al. 2016, p. 9). Similar to Kunze (2016), Taniguchi et al. (2016) identify the need for material transport which poses a limitation for the substitution of physical goods transport.

Chaberek-Karwacka (2017) investigate the influence of new information technologies in general on urban logistics and urban mobility using a literature review, expert interviews and real-life examples. According to the authors, 3DP may affect urban logistics until 2030 in two possible scenarios. In the first scenario, people are printing a lot of products at home and thus reduce travel demand for shopping (Chaberek-Karwacka 2017, p. 90). In the second scenario, people do not own 3D printers due to aesthetic and economic concerns. Therefore, products are manufactured in local 3D printing shops and consumers have to travel to print their personalized designs, which can be purchased from databases of suppliers like Amazon or Google, at these local shops (Chaberek-Karwacka 2017, p. 90). Both scenarios may reduce passenger and freight transport.

Summary & Link to this Dissertation

The literature review shows that there is literature dealing with the impacts of distributed additive manufacturing on freight transport, logistics, and supply chains on the global as well as the urban scale. Results and conclusions are largely unambiguous. The vast majority of the reviewed publications indicate that distributed AM has the potential to disrupt logistics and supply chains by moving production closer to customers and the place of use. Thus, delivery distances and home delivery fulfillment traffic may be reduced in the future. It is a difficult task to prove this effect as distributed additive manufacturing is not yet widely adopted in logistics. Therefore, relevant data, which is required to evaluate transport substitution potentials of distributed AM, is not available. This lack of data is apparent in the reviewed publications. Most of them only identify the potentials in the discussion without conducting a quantitative or qualitative evaluation. Here, a gap in the scientific literature is visible. Further research is needed to systematically evaluate and quantify the transport substitution potential of distributed AM. This dissertation tries to fill the gap by simulating and quantifying home delivery fulfillment transport of distributed AM in Munich. In particular, different scenarios of home delivery are analyzed and compared to identify differences in home delivery distances of vans due to distributed AM. Furthermore, this dissertation intends to analyze the impacts of distributed AM on a systemic level.

Publications investigating the effects of distributed AM on global logistics and supply chains often completely ignore material transport, which necessarily also accrues in the other system. Thus, a lot of publications overestimate the substitution of freight transport in distributed manufacturing. Indeed, production materials may be transported more efficiently due to better warehousing opportunities and transport bundling effects. Still, material transport should be considered in future studies. Rauch et al. (2015) offers an implicit solution for the problem of material transport in distributed manufacturing systems. The so-called local economic cycles, which are also depicted in Figure 9, contain not only local customers but also local suppliers. In the best case, materials can be produced in the local economic cycle where products are manufactured and customers are located. Thus, the transport of materials and products can be minimized. In reality, material production depends on many aspects like the local availability of raw materials in the ground and production infrastructure. Therefore, location-independent material production is limited.

It has to be noted that distributed manufacturing can be enabled not only by AM and 3DP, but also by any other automated production technology meeting the requirements of distributed and local production. However, the characteristics including versatility, automation, and almost constant unit costs even at low production quantities predestine AM for distributed manufacturing. For this reason, the existing scientific literature and this dissertation consider AM and 3DP for distributed manufacturing. Furthermore, this dissertation assumes that the emergence of a purely distributed manufacturing system is unlikely since some products require a specific production and assembly process that can not be ensured in distributed manufacturing facilities. Instead, mixed manufacturing systems will likely emerge in the future, especially if the 3DP technologies develop.

Distributed AM has another great potential, that is not largely addressed in the existing literature. This potential is more than relevant in today's world. As already mentioned, distributed AM may shorten supply chains. Thus, shortages and other problems in global supply chains can be prevented. The global COVID 19 pandemic has clearly uncovered uncertainties in these supply chains as pre-products and raw materials could not be delivered. It can be assumed that global crisis such as pandemics and wars may be a driver for the adoption of distributed AM and local economic cycles as customers and countries can increase their independence and reliability in production. In addition, distributed AM might be applied to a local and urban scale by manufacturing products at the customer's home or in local 3D printing shops. In conclusion, the literature review of distributed manufacturing reveals various research gaps. Some of them are intended to be closed through the results of this dissertation.

2.3.5. Distributed Manufacturing in the 3D Printing Shop

The concept of distributed additive manufacturing can be applied to the urban scale in the future. So-called 3D printing shops can perform similar tasks to local copy shops. In opposite to copy shops, local 3D printing shops can be used to manufacture ordered three-dimensional products near the customers. DHL Customer Solutions & Innovation (2016, p. 22) introduced and examined the concept of the 3D printing shop. The concept of the 3D printing shop plays an important role in the following simulations (section 5.1) and system modeling approach (section 6.1). For this reason, the assumed concept is explained and graphically presented in Figure 10. The figure shows that a 3D printing shop can be combined with a classical parcel shop. Thus, the facility can not only be used to send or receive parcels, but also to locally 3D print products, which were ordered online. The basis for this is a digital twin containing production data, that is used as an input for 3D printers. 3D printing shops can also offer 3D scanning. Thus, customers have the opportunity to digitize existing products and to create digital twins. 3D printing shops should provide a wide range of additive manufacturing technologies (see subsection 2.2.3) and materials in order to ensure the capability of printing as many products as possible. Another way to increase the range of printable products in 3D printing shops is to perform simple assembly activities of components. Thus, multi-material products consisting of different components can be manufactured in local 3D printing shops.

Figure 10 The concept of the 3D printing shop

Local 3D printing of products has the potential to complement and partly substitute existing shopping activities such as traditional offline and online shopping. Furthermore, 3D printing shops could provide new opportunities when it comes to last-mile logistics. If a dense infrastructure of 3D printing shops in urban areas were to exist, customers would have the opportunity to reach these shops within short distance using active means of transport such as walking or cycling and pick up their orders. Thus, 3D printing shops can contribute to mixed use areas and concepts such as the 15-minute city according to Moreno et al. (2021) providing a high degree of accessibility.

Furthermore, local production in 3D printing shops would enable home delivery using vans or other means of freight transport directly from the facility. In contrast to classical home delivery for online shopping, 3D printing shops serve as depots which are located much closer to the customers than classical CEP depots. Thus, long approaches from classical CEP depots might be partly replaced with shorter approaches from 3D printing shops. To enable the direct delivery from local 3D printing shops to customers, the shops have to provide parking spaces for their own delivery vehicles. In this case, these vehicles can perform delivery tours directly from the 3D printing shop to the customers and back.

3D printing services representing 3D printing shops already exist today. Customers can upload digital twins of desired products online. Then, 3D printing services manufacture the product for the customers and ship it to the their homes. However, these services are not yet widespread. Thus, the concept of distributed AM has not yet been transferred to the urban scale. This dissertation examines a potential transfer of distributed AM to the urban scale and changes in urban home delivery traffic due to distributed AM in local 3D printing shops. Furthermore, the impacts of distributed AM in local 3D printing shops on the system of urban mobility and urban logistics are examined.

2.4. System Analysis of Urban Mobility and Logistics

This dissertation applies system modeling and system analysis to evaluate the impacts of distributed AM on the system of urban mobility and logistics. For this reason, it is relevant to analyze existing scientific literature in this field. The non-exhaustive literature analysis identifies four research clusters presented in Table 7. The first identified research cluster examines passenger transport using systems thinking approaches. Zulauf & Schneider (1999) use systems thinking to investigate the systemic mechanisms of congestion and traffic jams in German cities with a focus on individual car transport. Wulfhorst (2003) uses both systems thinking, and a system dynamics approach to examine land use and passenger transport interactions. Priester et al. (2014) use systems thinking to evaluate the potential for sustainable development in urban mobility and passenger transport. Moradi & Vagnoni (2018) examine a similar field and apply a multi-level perspective analysis of urban mobility. Research by Fontoura et al. (2019) applies systems thinking to evaluate urban mobility policies in Brazil. The analysis of the first research cluster shows that systems thinking is an approach that is regularly used to examine the complex system of urban passenger transport and mobility.

Research Cluster	**Publications**
Using systems thinking to examine passenger transport	Zulauf & Schneider (1999), Wulfhorst (2003), Priester et al. (2014), Moradi & Vagnoni (2018), Fontoura et al. (2019)
Using system dynamics to examine passenger transport	Wulfhorst (2003) , Shafiei et al. (2013) , Melkonyan et al. (2020), Suryani et al. (2021)
Using systems thinking to examine freight transport	Jereb et al. (2013) , Kunze et al. (2016) , Baporikar (2020), Kunze & Frommer (2021)
Using system dynamics to examine freight transport	Angerhofer & Angelides (2000) , Lai et al. (2003) , Tako & Robinson (2012), Dong et al. (2019), Zenezini & de Marco (2020)

Table 7 Literature review of system analysis of urban mobility and logistics

The second identified research cluster contains papers using system dynamics the investigate passenger transport. Shafiei et al. (2013) examine how system dynamics can be applied to simulate sustainable passenger transport and mobility. Melkonyan et al. (2020) use system dynamics to evaluate integrated urban mobility policies for the Rhine-Ruhr metropolitan region in Germany. Suryani et al. (2021) model urban mobility using a system dynamic approach to reduce traffic congestion. The second research cluster indicates that system dynamics is a proven method for

modeling, simulating, and evaluating urban passenger transport and mobility.
Besides passenger transport, freight transport is another research field for system analysis. The third cluster contains research using systems thinking to examine freight transport and urban logistics. Jereb et al. (2013) apply systems thinking to identify specific supply chain risks. Kunze et al. (2016) apply systems thinking, represented by the sensitivity model of Vester (2019), to city logistics. They extend their model with a system dynamics approach. Baporikar (2020) uses systems thinking to support management decisions in logistics. Kunze & Frommer (2021) apply the sensitivity model of Vester (2019) to assess future scenarios of sustainable urban freight transport.
The last research cluster presents system dynamics approaches to model and analyze freight transport and urban logistics. Angerhofer & Angelides (2000) use system modeling and system dynamics to support supply chain management. Lai et al. (2003) apply system dynamics with a focus on just-in-time logistics. Tako & Robinson (2012) apply discrete event simulation and system dynamics in both a logistics and a supply chain context. Research by Dong et al. (2019) focuses on underground logistics systems and applies system dynamics to understand the mechanisms in this complex system. Zenezini & de Marco (2020) apply system dynamics to city logistics.

Summary & Link to this Dissertation

Table 7 shows that both systems thinking and system dynamics represent proven methods for modeling, analyzing, simulating, and evaluating the complex systems of urban mobility and urban logistics. However, very few papers in the existing literature apply system analysis approaches that combine passenger and freight transport. Passenger transport and freight transport are interconnected. One example of this interrelation is online and offline shopping. Online shopping may affect freight transport through the need for home delivery and passenger transport through changes in shopping behavior. The existing literature analysis shows a research gap in the integrated and combined system analysis of passenger and freight transport. This dissertation tries to close the identified gap by applying a systems thinking approach to the complex system of urban mobility and urban logistics. Furthermore, the system analysis includes distributed and local AM as an innovative and new technology in urban logistics which also may affect passenger transport. The integration of distributed AM in the system model of urban mobility and logistics is a new approach representing a scientific contribution.

3. Top-Level Research Design

This chapter presents the top-level research design and the work plan of this dissertation. The top-level research design is illustrated as a BPMN diagram in Figure 11. The processes with small boxes containing a + symbolize existing sub-processes in the BPMN diagram. These processes contain the methodological approaches of the following research studies and are further described in section 4.1, section 5.1, and section 6.1. The figure depicts the research process consisting of different work packages. These packages were processed in parallel during the Ph.D. project. However, the work packages have a meaningful order indicated by the positions and steps in Figure 11.

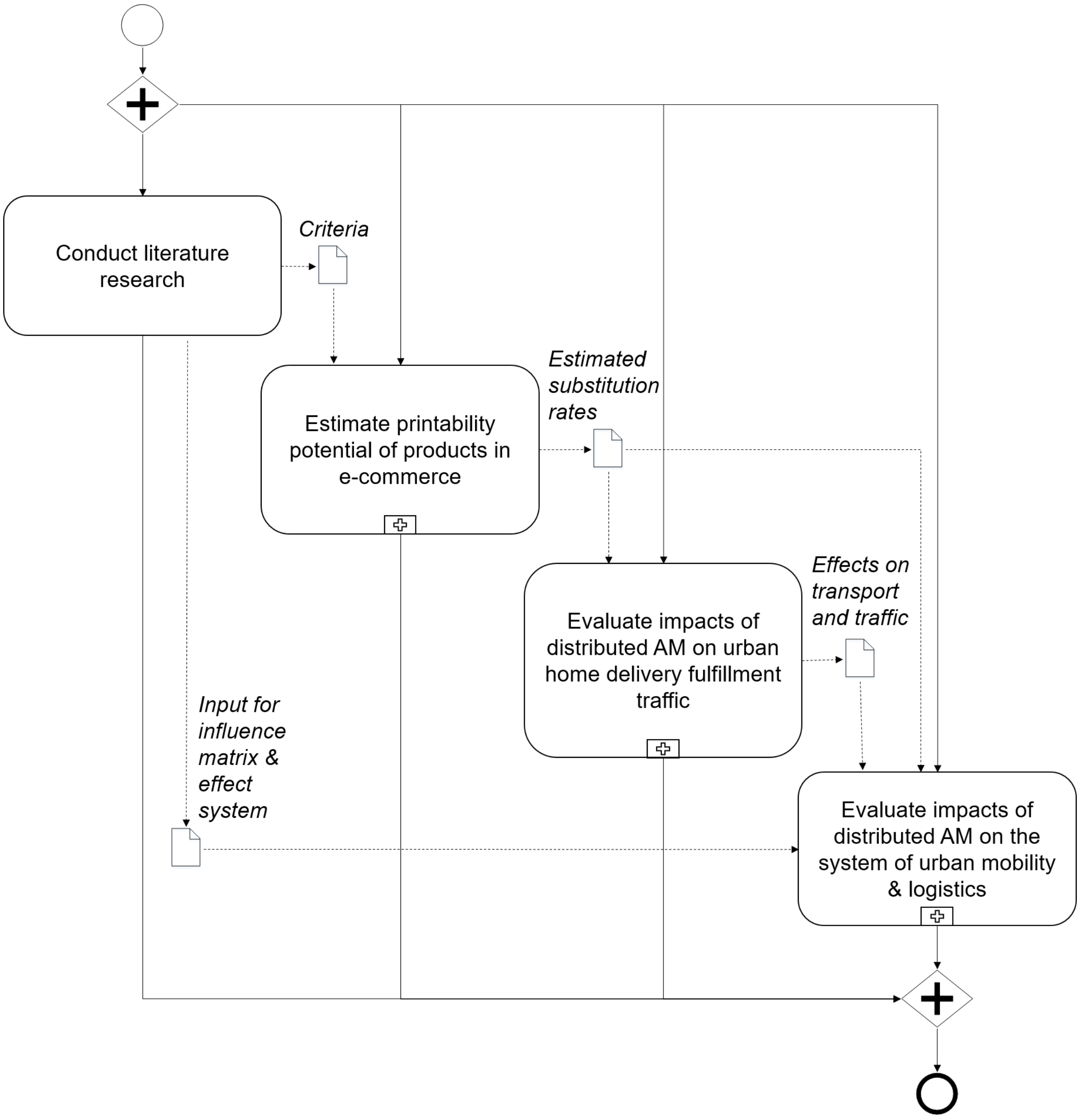


Figure 11 Top-level research design as BPMN diagram

The literature research, presented in chapter 2, forms the basis of the three research studies displayed as processes in Figure 11. In particular, literature dealing with additive manufacturing, the substitution of physical transport, and system analysis is reviewed. The first research study presented in chapter 4 estimates the printability of consumer goods in B2C e-commerce. Furthermore, the study estimates the extent to which classical shipments in urban home delivery can be substituted using distributed AM represented by 3D printing shops or 3D home printing. The evaluation of product printability from a technological point of view is based on a developed criteria catalog (see Figure 14). The literature research identifies decisive criteria for the printability of products, among others. The substitution potential of distributed AM in urban logistics is estimated using market-based potential analysis. The results of the first research study are highly relevant for the following research study since they indicate realistic substitution rates of distributed AM. These substitution rates play a significant role in this dissertation and therefore must be defined. Per definition, the substitution rate represents the percentage of classical home delivery shipments that are substituted with local additive manufacturing of an ordered product. In this context, the first research study identifies substitution rates, which are potentially possible with today's technological capabilities.

These estimated realistic substitution rates serve as input for the second research study, which examines the potential impacts of distributed AM on urban home delivery fulfillment traffic of delivery vans (see chapter 5). The second research study simulates the home delivery traffic of vans for different scenarios. These scenarios assume different infrastructures of distributed AM and different substitution rates. In addition to the estimated substitution rate from today's perspective, identified in the first research study, future substitution rates, which can be enabled through technological developments, are considered. Home delivery fulfillment traffic is simulated and compared to the status quo to identify changes due to the implementation of distributed AM in urban logistics.

The third research study examines the impacts of distributed AM on the system of urban mobility and logistics. This evaluation applies a qualitative systems thinking approach to understand the cybernetic mechanisms in this complex system. A modified version of the sensitivity model developed by Vester (2019) serves as the concrete method for the systems thinking approach. Certain aspects of this sensitivity model are further developed in this dissertation. Thus, not only the impacts of distributed AM on the system of urban mobility and logistics are identified. Furthermore, a methodological extension of the sensitivity model, which can be used in further research, is developed. The third research study uses the results of the other studies and the literature research as inputs. In particular, the influence matrix and the effect system, both part of the modified sensitivity model, determine the effect strengths and directions of the system's variables on each other. The result of the literature research is a basis for this determination. The first research study estimates realistic substitution rates, which are also considered in the systems model. The second research study identifies the effects of distributed AM in cities on urban home delivery fulfillment traffic. These effects are also integrated into the systems model of the third research study. Last, the results of all research studies are summarized and combined to provide recommendations for implementing distributed AM in urban logistics.

Part II

Research Studies

4. Estimating the Printability Potential of Products in E-Commerce

This chapter is intended to investigate and answer RQ1 (To what extent can shipments in B2C logistics be substituted using distributed additive manufacturing near the customer?). In this context, both the technological capability to 3D print products and the market potential of 3D printed products in urban logistics are investigated. Both aspects are essential for the concept of distributed AM and its implementation in urban logistics. For these reasons, the extent to which classical shipments in B2C logistics might be substituted using distributed AM near the customer is investigated in the following. Section 4.1 presents the methodological approach to answer the first research question. The results are presented in section 4.2 and critically discussed in section 4.3.

4.1. Methodological Approach

One prerequisite for the partial substitution of urban home delivery transport with distributed AM is the technological capability to print products and consumer goods, which are ordered and subsequently delivered, near the place of use by AM respectively 3DP technologies. This capability can also be denoted as product printability. For estimating changes in urban home delivery traffic due to distributed AM, it is necessary to estimate the extent of printable products. In particular, the printability of products in B2C e-commerce is of interest as online shopping is a main driver of B2C home delivery traffic and B2C shipments representing 56% of all CEP shipments in Germany 2021 according to Esser & Kurte (2021). Evaluating the printability of consumer goods in e-commerce is a difficult task as in most cases these products are not yet 3D printed and very heterogeneous. Therefore, the extent of printable products can only be estimated. In this dissertation, the estimation of product printability potential is carried out for the German e-commerce market. Furthermore, the potential for substituting classical home delivery with distributed AM near the customer is estimated. As mentioned, the estimation includes products in B2C e-commerce. The printability of these products is estimated based on current technologies. In particular, printability in so-called 3D printing shops, where various AM technologies and materials are available, is estimated.

The methodological approach for the estimation was cooperatively developed with Gaiser (2022) as part of a master's thesis at the University of Applied Sciences Neu-Ulm.

The approach is based on the potential analysis (Holzmüller & Boehm 2007). The potential analysis is often used for product planning (Holzmüller & Boehm 2007, p. 297). According to Servatius (1986) and Holzmüller & Boehm (2007, p. 297), the potential analysis can be distinguished into "potential analysis in the general sense" and "market-based potential analysis" (Holzmüller & Boehm 2007, pp. 297-304). In the further course, the potential analysis in the general sense is referred to as classical potential analysis (see Figure 12). According to Holzmüller & Boehm (2007, p. 297), the classical potential analysis evaluates capabilities and resources of companies to realize new products. Thus, the classical potential analysis provides information on conditions for the feasibility of new product offerings (Herrmann 1998, p. 353). The capabilities of companies to develop and produce new products can be evaluated using the classical potential analysis. However, the classical potential analysis is not suitable for the evaluation of market and sales potential (Holzmüller & Boehm 2007, p. 297). Evaluating market and sales potentials is the task of the market-based potential analysis, which examines markets instead of single companies and their capabilities to develop new products.

The concept of the potential analysis is well transferable to the use case of evaluating printability of B2C products in e-commerce and estimating their market shares (see Figure 12). In the context of AM, the classical potential analysis can be modified and used to evaluate the technological capabilities of existing AM technologies using a criteria catalog (see Figure 14). Thus, the printability of certain products can be determined. The market-based potential analysis can also be transferred to the use case. In this context, the market-based potential analysis can estimate the share of printable products in e-commerce and thus help to answer RQ1 (To what extent can shipments in B2C logistics be substituted using distributed additive manufacturing near the customer?).

The methodological approach for evaluating product printability in B2C e-commerce and estimating the related market shares, which was designed in cooperation with Gaiser (2022), develops the presented methods further by combining the classical with the market-based potential analysis. First, the printability of certain product segments in e-commerce with the technological capabilities of AM is evaluated. This evaluation is the basis for estimating market shares of these printable products and transport substitution potentials in home delivery. In this use case, the results of the classical potential analysis serve as an input for the market-based potential analysis (see Figure 12).

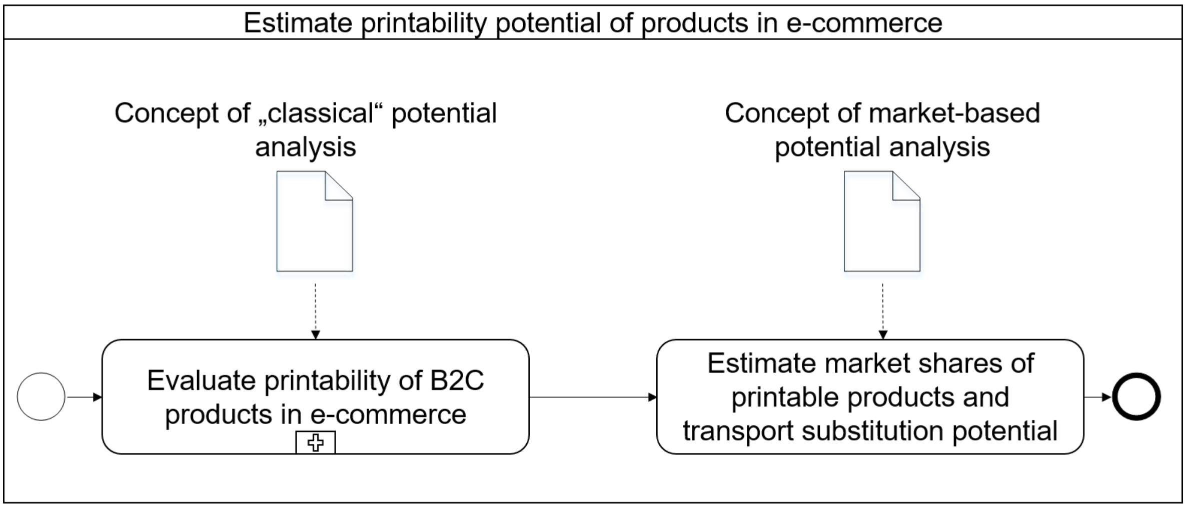


Figure 12 Transfer of the potential analysis to the estimation of product printability and market potential of distributed AM (own illustration inspired by Holzmüller & Boehm 2007 and Gaiser 2022, p. 33, sub-process of Figure 11)

For the market-based potential analysis, five different methods can be applied according to Holzmüller & Boehm (2007). These methods and their corresponding characteristics are displayed in Table 8.

Method	Pros	Cons	Prerequisites
1. Analysis of analogies	• easy to apply • enables estimation of market potential through spatial, temporal or product-related analogies	• quality of results depends on similarity to comparison object	• comparable object or product ✗ • sufficient data on comparable object or product ✗
2. Survey of experts	• easy to apply • no data needed	• results depend on the selection of experts and subjective opinions	• expert panel and resources for the interview ✗
3. Analysis of customer reactions	• provides real feedback from the market	• collection of feedback might be costly	• product, concept or prototype must already exist ✗
4. Analytical estimation methods	• provides quantitative market potential estimations by considering many variables	• estimation results might be sensitive to assumptions and certain variables	• sufficient data on variables ✗
5. Structured estimation methods	• provides estimation of market potential in small steps for segments • reduces complexity for the estimation of market potential as products can be aggregated to product segments	• aggregation of products to product segments leads to less accurate results and predictions	• sufficient data on market shares of segments ✓

✗: Prerequisite not met; ✓: Prerequisite met

Table 8 Assessment of methods for market-based potential analysis

The first optional method for market-based potential analysis is the analysis of analogies (Armstrong 2006, p. 98; Holzmüller & Boehm 2007, p. 305). Analogies enable the comparison of new products with similar markets. Thus, the market potential of the new product can be estimated. According to Holzmüller & Boehm (2007, p. 305), spatial, temporal, and product-related analogies can be developed. One prerequisite for using analogies is the availability of market experience and data (Holzmüller & Boehm 2007, p. 305). For the estimation of product printability in e-commerce using AM and the related market potential, there are no suitable analogies because distributed AM of e-commerce products is a relatively new use case. For this reason, analogies are not an option for the estimations in this dissertation.

The second optional method for market-based potential analysis is the survey of experts (Holzmüller & Boehm 2007, p. 305). Expert interviews have disadvantages making the method not very suitable for estimating the printability and market potential of products in e-commerce. According to Erichson (1979, p. 259) and Holzmüller & Boehm (2007, p. 306), the results of expert surveys highly depend on the selection of experts and subjective opinions. Furthermore, it is difficult to find experts with knowledge in the field of AM for consumer goods in e-commerce. As mentioned before, there are many of these products and the unstructured expert evaluation of every product would require a lot of resources.

The third optional method for market-based potential analysis is the analysis of customer reactions (Holzmüller & Boehm 2007, p. 310). Customer purchase intentions can be determined using this analysis. Subsequently, market potentials can be derived (Holzmüller & Boehm 2007, p. 310). A prerequisite for the analysis of customer reactions is that the development of the examined product is advanced to a certain extent for testing and collecting reactions (Holzmüller & Boehm 2007, p. 310). Today, most products in e-commerce are not yet 3D printed. This makes it difficult to collect customer reactions. Furthermore, the market potential estimation of distributed AM in e-commerce comprises a large number of products, which would make it very complex to collect a sufficient number of reactions. For these reasons, the analysis of customer reactions is not a suitable method for the estimations in this dissertation.

The fourth option for market-based potential analysis is the use of analytical estimation methods (Holzmüller & Boehm 2007, p. 309). These methods resort to time series analysis or econometric forecasting models. An advantage of these methods is that a lot of variables can be considered in the models (Holzmüller & Boehm 2007, p. 309). However, analytical estimation methods strongly depend on the availability of data. Furthermore, analytical estimation methods depend on causal relationships between the variables (Holzmüller & Boehm 2007, p. 309). As the amount of available data for the planned estimations is limited, analytical estimation methods are considered as not suitable for the use case in this dissertation.

The fifth option for market-based potential analysis is the use of structured estimation methods (Holzmüller & Boehm 2007, p. 306). These methods estimate the market potential in small steps for smaller segments. The estimations are subsequently aggregated to the overall market potential of the research object. One specific form of structured estimation method is the so-called market building method (Holzmüller & Boehm 2007, p. 308). This method estimates the market potential as the sum of market potentials of the different segments. The estimation of smaller segments is very suitable for the use case in this dissertation as e-commerce comprises a wide range of products and product segments. Furthermore, the segmentation and the estimation of these segments in small steps reduces complexity in the potential analysis as products can be aggregated to product segments. This aggregation only allows rough estimations, according to Holzmüller & Boehm (2007, p. 307). Thus, segmentation and aggregation in structured estimation methods lead to a trade-off between reducing complexity and improving the accuracy of the results. This trade-off is accepted as structured estimation methods enable the evaluation of a big market with many products and product segments. Furthermore, rough estimation results are sufficient for the use case in this dissertation as they are intended to give only an indication of how many products in e-commerce can be produced using AM from today's perspective and how many classical home delivery tours might be substituted using distributed AM near the customer. Thus, structured estimation methods, and especially the market building method, are considered suitable and are chosen for these research tasks (see last column of Table 8). Therefore, the potential analysis of product printability in e-commerce is based on the market building method. Besides product segmentation, which is an essential part of this method, a criteria catalog is used to evaluate the printability of the segments. The criteria catalog thus represents the classical potential analysis and complements the structured estimation method assessing the market-based potential (see Figure 12). The approach for evaluating printability of product segments is depicted as a BPMN diagram in Figure 13. Figure 13 is a sub-process of Figure 12.

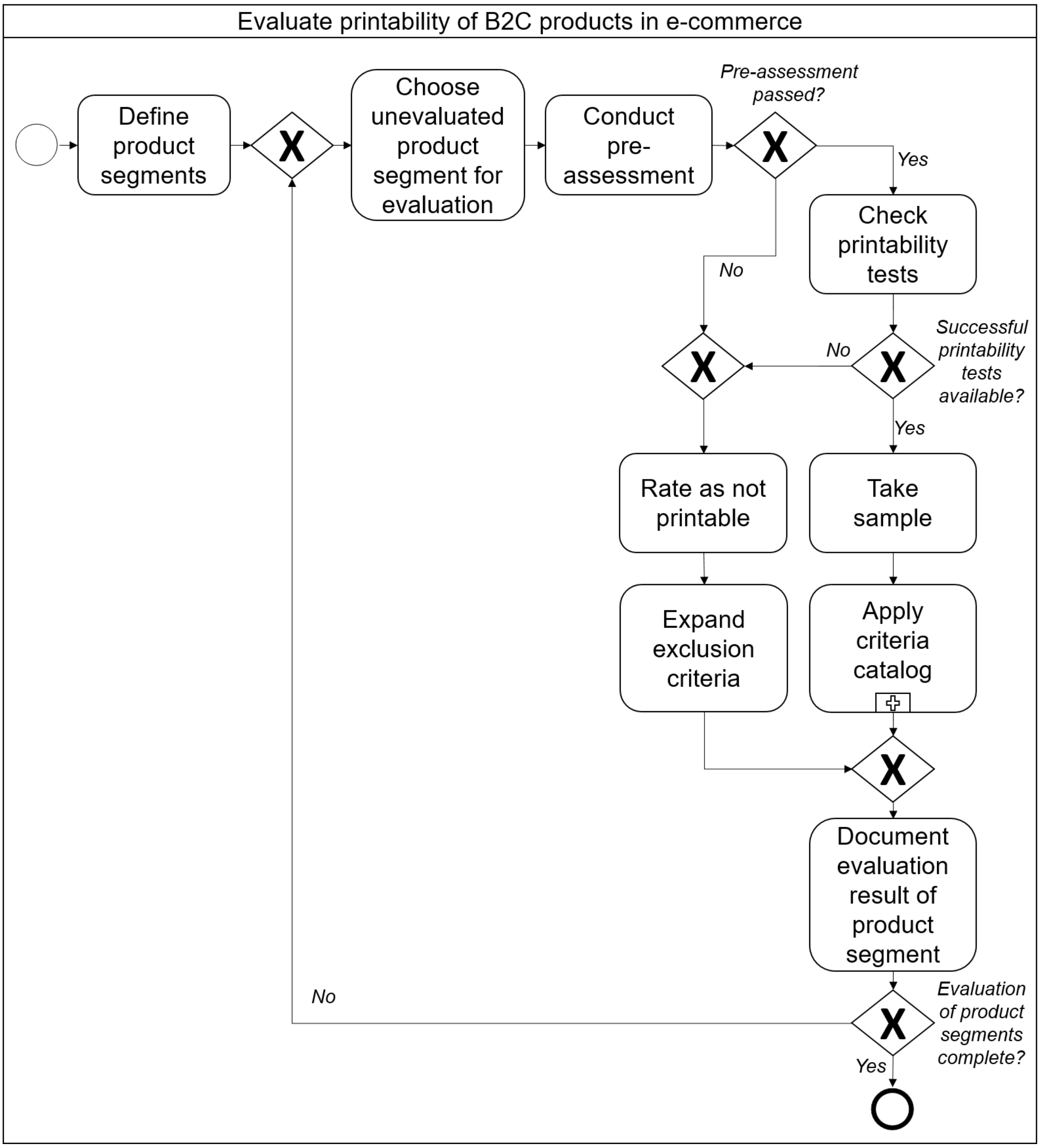


Figure 13 Methodological approach for the printability evaluation of product segments (revised process of first draft, which was cooperatively developed with Gaiser 2022, p. 42)

In e-commerce, countless products are offered for sale online. Therefore, evaluating every product on every platform with limited resources is impossible. The definition of product segments reduces complexity and thus enables an estimation of printability in e-commerce. Therefore, the definition of product segments is the first substep in Figure 13 (*define product segments*). The product segments are determined according to Manner-Romberg et al. (2014, p. 6). This segmentation offers the advantage of available data on the shipment volumes of the individual segments. Thus, the market potential of AM for B2C e-commerce products and the extent of possible substitutions of classical home delivery can be subsequently estimated. The product segments according to Manner-Romberg et al. (2014, p. 6) are presented in Table 9.

After defining the product segments, one segment is chosen for the evaluation (*choose unevaluated product segment for evaluation*).

Subsequently, a pre-assessment is conducted for the chosen product segment (*conduct pre-assessment*). This pre-assessment classifies certain product segments as not printable on the basis of exclusion criteria which were either predefined or identified during the process of evaluating product segments. The goal of the pre-assessment is to identify product segments that are clearly not printable from today's perspective. The pre-assessment substep is inspired by Knofius et al. (2016), who use exclusion criteria to determine the printability of parts in service logistics, and by Kunze et al. (2021), who use an ex-ante check for the printability of spare parts. Furthermore, the pre-assessment is designed to save time in the evaluation process by filtering out certain product segments. If the pre-assessment is not passed, the examined product segment is classified as not printable (*rate as not printable*) and the exclusion criteria can be expanded if necessary (*expand exclusion criteria*).

If the pre-assessment is passed, it is checked if there are successful 3DP use cases or printability tests of the examined product segment in practice or in the literature (*check printability tests*). Thus, printability is evaluated from a purely technological point of view. If there are no successful printability tests, the examined product segment is considered as not printable (*rate as not printable*) and the exclusion criteria can be extended (*expand exclusion criteria*).

The technological printability alone is not sufficient for evaluating the potential of distributed AM. The printability should also be evaluated in a non-experimental environment to examine if additive manufacturing of a certain product segment is reasonable. Therefore, the printability evaluation continues if the check for successful printability tests is positive. As product segments may contain many different products, a representative sample has to be determined (*take sample*). This task is difficult and may strongly influence the results of the printability evaluation. According to Handelsverband Deutschland (2022, p. 28), Amazon is responsible for 54% of all online retail sales and is therefore the biggest player in e-commerce. For this reason, Amazon is most representative compared with other e-commerce platforms. Thus, Amazon is a suitable source for the generation of product samples. In fact, bestseller lists of the product segments on Amazon are used to generate the samples. The use of bestseller lists prevents a bias, which is caused by personalized ads, and displays the products that are most frequently purchased and shipped within a segment. For every examined product segment, the 100 most purchased products are chosen as a sample. If possible, similar products are aggregated for the evaluation.

Subsequently, the printability of the products in the sample is evaluated in detail using a criteria

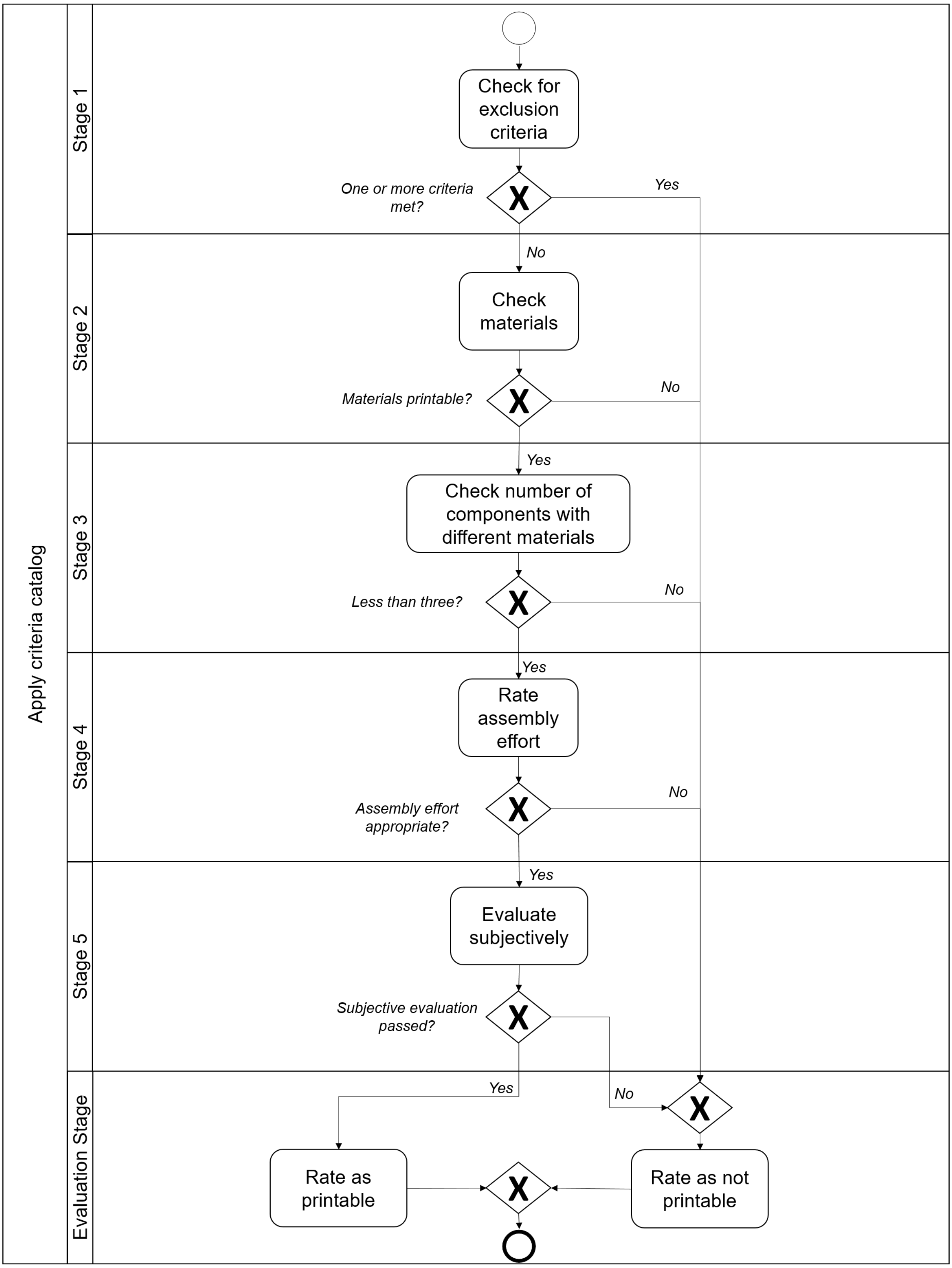


Figure 14 Criteria catalog for the evaluation of printability (revised process of first draft, which was cooperatively developed with Gaiser 2022, p. 45)

catalog (*apply criteria catalog*). This catalog, which was developed in cooperation with Gaiser (2022), is depicted as a BPMN diagram in Figure 14 and is a sub-process of Figure 13.

After the criteria catalog is applied, the results are documented (*document evaluation result of* *product segment*) and the presented process is repeated for all defined product segments.

The presented *criteria catalog* consists of different stages. Each stage evaluates a certain requirement, which has to be fulfilled if the examined product is printable. It must be noted that the criteria catalog is applied to products instead of product segments. This is the main aspect distinguishing the evaluation, based on the criteria catalog, from the pre-assessment, where product segments are checked for exclusion criteria.

In the first stage of the criteria catalog (*check for exclusion criteria*), Gaiser (2022, p. 42) excludes products belonging to the groups of electronic devices, food, adhesive products, text and books, as well as batch products. According to Goh et al. (2021), 3DP is technologically capable of producing electronic devices such as resistors, inductors or even photovoltaics. However, production of these products is complex and rather carried out in the laboratory environment. In addition, the electronic devices in the e-commerce market are most often composed of many electronic parts, which makes their production even more complex. For these reasons, affiliation to the product group of electronic devices is considered as an exclusion criterion. The situation is similar for food. Already today, 3DP can be used for the production of food from a technological point of view (Liu et al. 2017; Sun et al. 2015). Nevertheless, food is excluded from the evaluation as food production using 3DP for consumers is very unusual in today's market. According to Eurostat (2021), only 10% of the people in Germany ordered food from the online platforms of grocery stores. Thus, the potential for substituting food transport from grocery stores to consumers is quite small. The transport of prepared food from food delivery services might be more important. However, these services typically operate in their local environment which means that they already produce near the customer. Due to the overall consideration of the mentioned aspects, affiliation to the product group of food is an exclusion criterion. Texts and books printed using traditional 2D printers and adhesives with specific requirements are not suitable for AM. Therefore, these product groups are also excluded in the first stage.

In the second stage of the criteria catalog, the materials of the products are evaluated (*check materials*). Although AM is capable of using a wide range of materials, there might be some products that need specialized materials. If these materials cannot be used by the common AM technologies, products are classified as not printable.

In the third stage, products are checked for the number of components with different materials (*check number of components with different materials*). Section 2.2.3 showed that AM is capable of printing a wide range of materials. However, it is unusual to print more than two different materials within a single print job according to the current state of technology. MEX has the greatest potential for multi-material 3DP. According to Rafiee et al. (2020, p. 3), MEX can produce multi-material parts through the use of multiple nozzles extruding different materials. Besides MEX, MJT is another common method for multi-material 3DP (Rafiee et al. 2020, p. 23). Other technologies such as PBF struggle when it comes to multi-material printing (Rafiee et al. 2020, p. 23). In practice, most of the MEX printers on the market have a maximum of two nozzles. Thus, a print job using two different materials is enabled in most cases. For these reasons, products consisting of more than two different materials are rated as not printable in the second stage.

In the fourth stage of the catalog, the assembly effort is evaluated (*rate assembly effort*). AM has the advantage of being able to print complex structures. This may drastically reduce assembly effort if the design principles for AM are exploited. Nevertheless, in some cases, 3D printed components have to be assembled, especially if a product consists of multi-material components. In the further course of this dissertation, distributed additive manufacturing is investigated. It is considered that distributed additive manufacturing sites such as 3D Printing shops have lower capacities than centralized factories. Therefore, stage four rates products with the need for high assembly effort as not printable.

In the fifth stage of the criteria catalog, a subjective evaluation of product printability is executed (*evaluate subjectively*). This stage reduces the objective transparency and reproducibility of the results. Nevertheless, the subjective evaluation is reasonable and important because products in e-commerce are heterogeneous and it is hardly possible to develop a criteria catalog that meets the requirements of all these products. The subjective evaluation was conducted by Gaiser (2022). If this evaluation identifies certain aspects which prevent additive manufacturing, the examined product is classified as not printable. If all stages are passed, the examined product is classified as printable in the last stage, which is referred to as *evaluation stage*.

After evaluating the printability of product segments, the overall market potential of additive manufacturing for products in e-commerce has to be estimated (see Figure 12: *estimate market shares of printable products and transport substitution potential*). Therefore, the shares of printable products within a segment have to be multiplied by the market shares of the corresponding product segments in e-commerce and summed. The market shares of the product segments can be derived from the number of shipments. In detail, the estimation of the volume of printable products in e-commerce V is described in Equation 4.1, where s represents the number of shipments of a certain product segment i and p represents the share of printable products within the segment.

$$V = \sum_{i=1}^{n} s_i * p_i \tag{4.1}$$

To determine the number of shipments of certain product segments, data is needed. Research of literature and the internet shows, that it is very difficult to maintain data on these shipment volumes especially for current time periods. Manner-Romberg et al. (2014) published shipment volumes for Germany in 2014. Due to missing alternatives, the data of Manner-Romberg et al. (2014) is used by Gaiser (2022) for the estimations. As overall shipment volumes in e-commerce drastically increased over the last year, the number of shipments are adjusted to the overall B2C shipment volume in Germany 2021. According to Esser & Kurte (2021, p. 20), this volume is 2,268 million shipments. The adjusted shipment volumes for the product segments are displayed in Table 9. As mentioned earlier, the described methodological approach should help to answer RQ1. The evaluation of printable products in e-commerce is an estimation, which creates a certain limitation. Therefore, the methodological approach for this estimation is critically discussed in section 4.3.

Product segment	**Number of shipments in millions***	**Share of shipments***
Clothing	466.9	20.6%
Books	378.0	16.7%
Others	355.8	15.7%
Storage medium for music, videos etc.	200.1	8.8%
Electronics	155.7	6.9%
Household goods and appliances	111.2	4.9%
Shoes	111.2	4.9%
Sports and leisure items	88.9	3.9%
Drugstore items and cosmetics	66.7	2.9%
Food, delicacies, vine	66.7	2.9%
Furniture and decoration	66.7	2.9%
Office supplies	66.7	2.9%
Telecommunication, mobile phone and accessories	66.7	2.9%
Toys	66.7	2.9%
Overall	**2,268.0**	**100.0%**

*Note: Values rounded to one decimal place

Table 9 Adjusted shipment volumes of the product segments in e-commerce

4.2. Results

The estimation of product printability potential in e-commerce is an interesting task. Since the product printability potential in e-commerce represents an indicator for the substitution potential of classical home delivery tours, the results of this estimation can be used as inputs for the simulations of home delivery fulfillment traffic in chapter 5. Thus an appropriate substitution rate for the current state of technology can be determined. Furthermore, the results of the estimation serve as an input for the system model presented in chapter 6.

In the further course of this section, the results of the printability estimation for the defined product segments presented in Table 9 are described separately. These results are based on the application of the criteria catalog depicted in Figure 14. Subsequently, the generated results are used to estimate the overall market potential of 3D printed products in German B2C e-commerce.

Thus, the share of shipments that can be substituted using distributed AM near the customer is estimated.

4.2.1. Estimation of Product Segment Printability

As mentioned, B2C e-commerce products are segmented according to Manner-Romberg et al. (2014, p. 6). This segmentation is presented in Table 9 and additionally provides market shares of product segments in the German e-commerce market. This information is essential for estimating market shares of 3D printable products in e-commerce as the following step. In the following sections, the printability evaluations for the different product segments, that were cooperatively carried out within the framework of the master's thesis of Gaiser (2022), are briefly presented and described. The product segments are presented in order of market shares.

Clothing

The first examined product segment is clothing. According to Sitotaw et al. (2020) and the literature review of Gaiser (2022, p. 46), 3DP is capable of printing flexible structures and materials with similar properties to textiles. Printability tests of 3D printed clothes with special designs do exist in the academic literature. Light-weight polymers or polymer composites are mainly used for 3D printing of cloth-like structures (Sitotaw et al. 2020, p. 4; Valtas & Sun 2016).
According to Gaiser (2022, p. 46) and Sitotaw et al. (2020, p. 4), the number of materials for 3D printing of cloth-like structures is limited due to a lack of comfort and flexibility. In most cases MEX, VPP or PBF are used to produce textile-like mesh structures (Sitotaw et al. 2020, p. 12). Gaiser (2022, p. 48) concludes, that the technology of 3DP/AM is not yet mature and productive enough to completely substitute conventional production of clothing today. Still, Sitotaw et al. (2020, pp. 15-16) attests market potential for 3D printed clothing in the future if technological and economic hurdles are overcome. By applying the criteria catalog, Gaiser (2022) classifies the product segment of clothing as not printable at the present time. In particular, stage two and stage three eliminate the product segment since materials for additive manufacturing of clothing need further technological development. For this reason, (Gaiser 2022, p. 48) adds textile materials for 3DP to the set of exclusion criteria.

Books

Books are produced using conventional two-dimensional printers. Thus, there are no printability tests or practical use-cases for 3DP of books or text. For this reason, the criteria catalog is not applied to the product segment. Thus, books are classified as not printable and books, literature and text are added to the set of exclusion criteria (Gaiser 2022, p. 42). Still, the transport and delivery of books can be partly substituted using ICT in another way by downloading e-books.

Others

The product segmentation of Manner-Romberg et al. (2014, p. 6) considers "others" as a segment. This product segment is not defined. Thus, an evaluation of this segment is not possible. To provide a critical printability estimation, the segment is classified as not printable.

Electronics

According to the literature research of Gaiser (2022, p. 52), printability tests for electronics do exist in scientific literature. Rudolph et al. (2018) completely printed an electric engine using multi-material AM. This process is capable of processing iron, copper, and ceramic at the same time. Besides this application, some components for the electronics industry such as heat exchangers or coils were already additively manufactured using 3DP. However, customer electronics and entertainment electronics usually represent complex devices consisting of many components. According to the literature research of Gaiser (2022, p. 52), there are no successful printability tests for such devices at present. According to Gaiser (2022, p. 52), the market potential for products in the segment of electronics is limited to individual components and accessories. These products only represent a small fraction of the segment. Thus, the product segment of electronics is classified as not printable (Gaiser 2022, p. 52). The segment is eliminated by the third stage of the criteria catalog because most products of the segment are complex and consist of many components with different materials. Gaiser (2022, p. 52) adds electronics to the set of exclusion criteria.

Storage medium for music, videos, etc.

Storage media for music or videos usually contain electronics which represent an exclusion criterion. Furthermore, there are no successful printability tests in the literature or practical use cases for 3DP of digital storage media. For these reasons the product segment is classified as not printable and added to the set of exclusion criteria (Gaiser 2022, p. 42).

Household goods and appliances

The literature research of Gaiser (2022) identifies successful printability tests for household goods and appliances. Thus, the developed criteria catalog is applied to this heterogeneous product segment. For the evaluation, a sample consisting of the 100 most purchased items of the product segment on Amazon is taken (Gaiser 2022, p. 54).

The evaluation of the product segment reveals that one-third of the sample is classified as not printable due to the exclusion criteria of electronics. Close to 16% of the sample products are classified as not printable due to materials that can not be processed in 3DP and AM (Gaiser 2022, p. 54). Close to 10% of the sample products are classified as not printable due to the high effort involved in assembly of components (Gaiser 2022, p. 54). Close to 11% of the sample products are eliminated by Gaiser (2022) in the subjective evaluation. The printability estimation results of the considered product segment is presented in Figure 15 (Gaiser 2022, p. 54).

Shoes

The product segmentation of Manner-Romberg et al. (2014, p. 6), distinguishes shoes from clothing. Thus, shoes represent their own product segment. According to the literature research of Gaiser (2022, pp. 48-49), printability tests for additively manufactured shoes do exist. Occasionally, there are shoe models on the market that are completely 3D printed. These models are usually designer or sports shoes (Gaiser 2022, p. 49). In general, the use of 3DP is not unusual in shoe production. However, in most cases, individual shoe components are 3D printed only (Gaiser 2022, p. 49). Many brands use 3DP for the production of midsoles with complex structures. The production of individual components using 3DP implies the need for assembly. The assembly of shoe components is elaborate since it contains gluing and sewing. Therefore, Gaiser (2022, p. 50) classifies the product segment of shoes as not printable for the mass market with today's technological possibilities although some specific models are already additively manufactured.

Sports and leisure items

The product segment of sports and leisure items is very diverse. The literature research of Gaiser (2022) shows that there are various printability tests for this product segment not only in the literature but also in practice. Some example applications are shin pads, helmets and wheel hubs (Gaiser 2022, p. 55). Due to the diversity of the product segment, a sample for the product segment is taken from the bestseller list on Amazon. Subsequently, the developed criteria catalog is applied to this sample. On-third of the products in the sample are classified as not printable due to the defined exclusion criteria of electronics (Gaiser 2022, p. 55). In addition, 43% of the products in the sample consist of textile materials and are therefore also classified as not printable (Gaiser 2022, p. 55). Further 7% of the products in the sample are eliminated due to the subjective evaluation by Gaiser (2022, p. 55). The printability estimation results of the considered product segment is presented in Figure 15.

Drugstore items and cosmetics

For the product segment of drugstore items and cosmetics, there are no existing printability tests in scientific literature. Furthermore, there are no practical use-cases for 3DP ingredients of cosmetics. For these reasons, the developed criteria catalog is not applied to the segment. Although single components such as packaging may be produced using 3DP, complete products of the segment are classified as not printable. Furthermore, the product segment is added to the set of exclusion criteria (Gaiser 2022, p. 42).

Food, delicacies, vine

There are existing printability tests for 3DP of food in the scientific literature. Sun et al. (2015) describe potential applications. However, 3DP of food is still mostly performed on a laboratory scale. Furthermore, the ingredients that are used for 3DP food are limited. For these reasons, substitution of conventional production of food with 3DP or AM is unlikely. In addition, vine is a liquid and is therefore not printable. The mentioned reasons lead to a pre-assessment that classifies the product segment as not printable. Gaiser (2022, p. 42) adds food and beverages to the set of exclusion criteria.

Furniture and Decoration

The literature research of (Gaiser 2022, p. 54) shows that printability tests for the product segment of furniture and decoration exist. 3DP has been applied to both the production of furniture and decoration. In this segment, the use of 3DP aims to optimize topology (Ntintakis et al. 2019). Furthermore, 3DP for the production of furniture has the potential to process recycled materials (Pringle et al. 2018). The product segment of furniture and decoration is diverse. For this reason, a sample of the product segment is taken and evaluated using the developed criteria catalog by (Gaiser 2022, p. 55). According to this evaluation, close to 27% of the products in the sample are classified as not printable due to the exclusion criteria. Close to 12% of the products in the sample are classified as not printable due to high assembly effort with today's technological capabilities of AM and 3DP. Furthermore, close to 23% of the products in the sample are not printable due to material limitations (Gaiser 2022, p. 55). The products in the sample often consist of glass, wood, or textiles. This makes 3DP not possible according to the requirements in the criteria catalog. The printability estimation results of furniture and decoration are presented in Figure 15.

Office Supplies

The product segment of office supplies usually contains products that are relatively easy to produce. Printability tests and use cases of 3D printed office supplies exist in the literature and in practice (Gaiser 2022, p. 50). To estimate the products in the segment of office supplies, a product sample is generated once again based on the bestseller list on Amazon. The printability estimation of Gaiser (2022, p. 51) shows that close to 6% of the products in the sample are classified as not printable because they consist of many components from different materials with high assembly effort. Further 14% of the products are classified as not printable due to material requirements that can not be fulfilled using 3DP. The analysis of the product segment sample shows that close to 31% of the products contain adhesives which are not printable. After evaluating these products, Gaiser (2022) adds adhesives to the set of exclusion criteria. The printability estimation results of office supplies are presented in Figure 15.

Telecommunication, mobile phone and accessories

Another product segment according to Manner-Romberg et al. (2014, p. 6) is telecommunication, mobile phone and accessories. This product segment is very diverse. Therefore, a sample is generated for the considered product segment by Gaiser (2022, p. 53) based on bestseller lists on Amazon. Since there is no bestseller list available, which contains both mobile phones and mobile phone accessories, the two separate lists for these categories are combined. It is assumed that the order volume of the considered product segment is made up of 50% orders of both categories each. The printability estimation of the product segment is conducted by Gaiser (2022, p. 53) using the criteria catalog. Gaiser (2022, p. 53) classifies all mobile phones in the sample as not printable since these products contain electronics which are part of the exclusion criteria. According to Gaiser (2022, p. 53), close to 73% of the considered accessories also contain electronics and are therefore classified as not printable. Other accessories contain adhesives and are therefore also classified as not printable (Gaiser 2022, p. 53). The overall printability estimation results of telecommunication, mobile phone and accessories are presented in Figure 15.

Toys

According to the literature research of Gaiser (2022, p. 56), there are many successful printability tests and use cases for 3D printed toys. Thus, the developed criteria catalog is applied to a generated sample of the product segment. The evaluation by Gaiser (2022, p. 56) results in 34% of products in the sample which are classified as not printable due to predefined exclusion criteria. Most of these excluded products contain electronics. Close to 20% of the products in the sample are classified as not printable because they consist of many components from different materials with high assembly effort. Close to 39% of the products in the sample are classified as printable since they represent relatively simple plastic parts consisting of few components. The printability estimation results of furniture and decoration are presented in Figure 15. Figure 15 presents the printability estimation results for every considered product segment in e-commerce defined by Manner-Romberg et al. (2014, p. 6) according to Gaiser (2022). In total, the generated samples of product segments contain 718 products which are evaluated by applying the developed criteria catalog (Gaiser 2022, p. 57). As mentioned, similar products in the considered bestseller lists are combined and evaluated together. Thus, resources are saved. The printability estimation results for the sample products that are evaluated using the criteria catalog are presented in Figure 16. 506 examined products of all samples are classified as not printable whereas 192 examined products are classified as printable (Gaiser 2022, p. 57). Once again it has to be noted, that the created criteria catalog only considers technical aspects that are relevant for the printability evaluation of products. Economic aspects are not considered. It also has to be noted, that the printability evaluation of products is based on the current state of 3DP technology and materials. It is very likely that both aspects will develop further in the future. Technological development may increase the number of products that can be 3D printed.

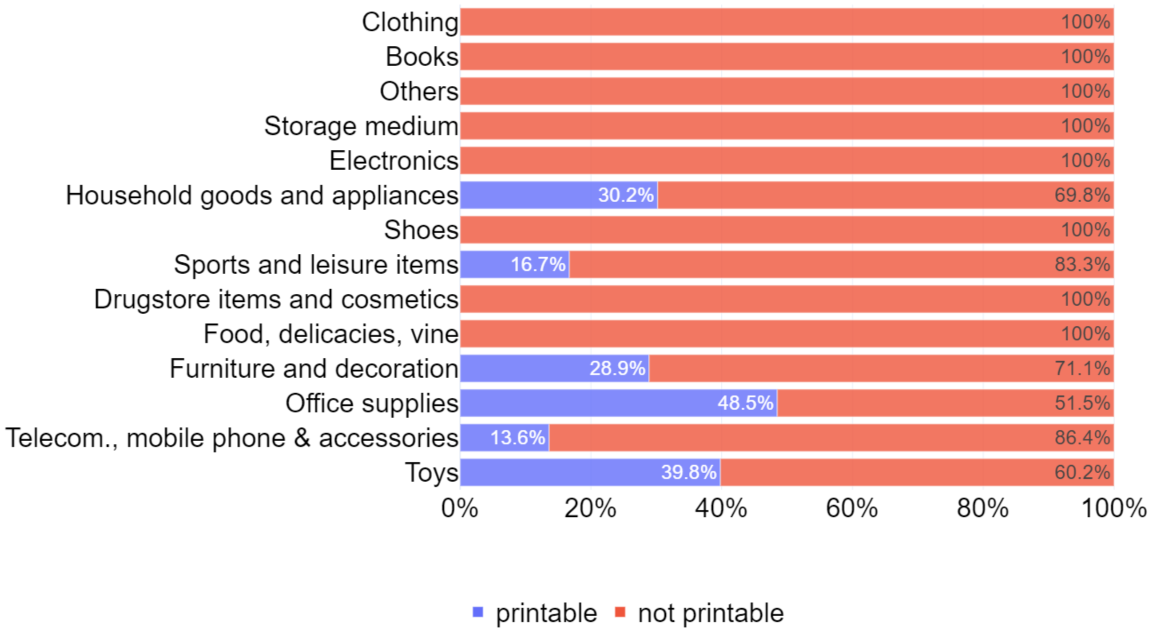


Figure 15 Printability estimation results of product segments, own illustration based on the results of Gaiser (2022, p. 56)

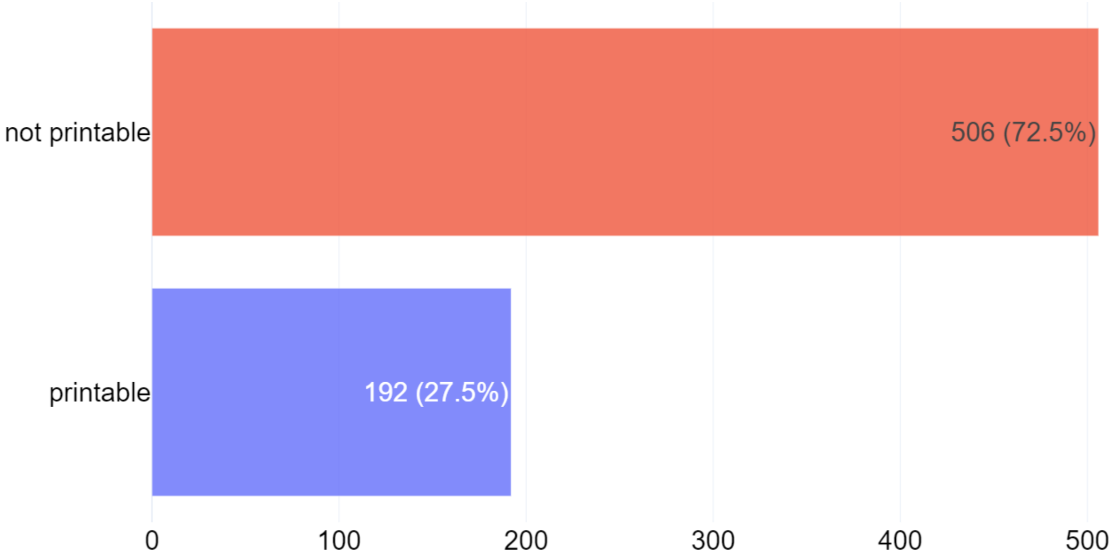


Figure 16 Printability estimation results of products within the generated samples, own illustration based on the results of Gaiser (2022, p. 57)

4.2.2. Estimation of Shipment Printability in E-Commerce

The estimation of product printability provides important information on the technological capabilities and potentials of 3DP in e-commerce. However, the estimation of product segment printability alone doesn't consider market shares of the considered product segments. Thus, the potential for substituting classical shipments and home delivery with distributed AM near the place of use can not be derived from the estimation of product segment printability alone. Data on market shares of e-commerce product segments from Manner-Romberg et al. (2014, p. 6) is combined with the results of the product segment printability estimation. Thus, the number of potentially printable shipments and the corresponding market shares are derived. The number of potentially printable shipments gives important information on the substitution potential of 3DP/AM in logistics. The results of the estimation of printable shipments according to Gaiser (2022, p. 59) are presented in Table 10.

Product segment	**Shipment volume**		**Substitution potential**	
	Share of shipments*	Number of shipments in millions*	Share of printable products*	Number of printable shipments in millions*
Clothing	20.6%	466.9	0.0%	0.0
Books	16.7%	378.0	0.0%	0.0
Others	15.7%	355.8	0.0%	0.0
Storage medium for music, video, etc.	8.8%	200.1	0.0%	0.0
Electronics	6.9%	155.7	0.0%	0.0
Household goods and appliances	4.9%	111.2	30.2%	33.6
Shoes	4.9%	111.2	0.0%	0.0
Sports and leisure items	3.9%	88.9	16.7%	14.9
Drugstore items and cosmetics	2.9%	66.7	0.0%	0.0
Food, delicacies, vine	2.9%	66.7	0.0%	0.0
Furniture and decoration	2.9%	66.7	28.9%	19.3
Office supplies	2.9%	66.7	48.5%	32.4
Telecommunication, mobile phone and accessories	2.9%	66.7	13.6%	9.1
Toys	2.9%	66.7	39.8%	26.5
Overall	**100.0%**	**2,268.0**	**6.0%**	**135.7**

*Values rounded to one decimal place

Table 10 Estimation results of printable shipments based on Gaiser (2022, p. 59)

The results indicate, that approximately 6% of shipments in B2C e-commerce could be 3D printed with current technological capabilities in the environment of a 3D printing shop, where various AM technologies and materials are available. Thus, the physical delivery of these shipments can partly be substituted with the transfer of data and local production using 3DP/AM. In total, 135.7 million shipments in the German B2C e-commerce market are estimated to be printable with current AM technologies. In conclusion, RQ1 (To what extent can shipments in B2C logistics be substituted using distributed additive manufacturing near the customer?) is answered. The extent of printable shipments is estimated to be approximately 6% based on the described assumptions and the available data. The presented results have certain limitations and are therefore critically discussed in section 4.3.

4.3. Critical Discussion

The methodological approach for estimating product printability potential, presented in section 4.1, combines the concepts of classical and market-based potential analysis. This approach is appropriate because both the technological and economic perspectives are considered. Both perspectives are essential for estimating the market potential of distributed AM. Nevertheless, the methodological approach is subject to certain limitations.

The market-based potential analysis uses structured estimation methods to estimate the market potential of additive manufactured products in B2C e-commerce. Table 8 shows a comparison of different methods for the market-based potential analysis. The comparison indicates that structured estimation methods are appropriate for estimating market potential, especially if market information and data are limited. This is the case for the investigations in this dissertation. Although structured estimation methods are appropriate for the estimations in this dissertation, they have certain limitations. Structured estimation methods enable estimations based on product segments. The aggregation of products into product segments decreases the accuracy of the estimation. Furthermore, the used structured estimation method relies on shipment volume data for the product segments. This aspect is the most significant limitation because the used dataset from Manner-Romberg et al. (2014) contains shipment volume data from 2013. Due to a lack of data alternatives, this dataset had to be used and extrapolated to today's shipment volumes. The used dataset implies another problem. The predefined product segments of Manner-Romberg et al. (2014, p. 6) had to be adopted because shipment volume data is only available for this segmentation. The predefined segmentation has to be critically discussed because the criteria according to which the segments were selected are not presented transparently. Furthermore, some product segments tend to overlap. The product segments *clothing* and *shoes* are one example of such an overlap. The product segment *others* is undefined and thus has to be categorized as not printable. This aspect decreases the estimation accuracy.

Besides the market-based potential analysis, the classical potential analysis, which examines technological capabilities, is also subject to limitations. The classical potential analysis uses a criteria catalog to evaluate the printability of the considered product segments. A sample of products is generated for every product segment as input for the criteria catalog. These samples contain the 100 most purchased products of the segments, according to Amazon bestseller lists. Indeed, Amazon has the highest market share in e-commerce worldwide. However, Amazon purchases are not representative of all purchases in the e-commerce market. Moreover, the selection of the 100 most purchased products is not fully representative of each Amazon product segment, especially since some of them are very heterogeneous.

The developed criteria catalog, which evaluates the printability of the generated product samples, implies some further limitations. The criteria catalog examines the most relevant criteria according to literature research and experience from laboratory operations. Thus, the criteria selection is subjective to a certain degree. Since product segments tend to be very heterogeneous, not every criterion fits the evaluation of every product. For this reason, the last stage of the criteria catalog includes a subjective evaluation. Such a subjective evaluation helps to address the peculiarities of products. On the other hand, the printability estimation becomes less transparent.

The methodological approach implies certain limitations to the results. The estimation of product printability potential should not be considered an exact prediction of the number of printable products. The estimation only uses product data from Amazon to represent e-commerce and aggregates products to product segments. Thus, the product printability potential estimation result should be interpreted as an indicator of a rough dimension, which is used as a consolidated input for realistic substitution rates in the following simulations. Furthermore, the results are limited to today's AM technologies. These technologies are constantly evolving. The printability estimation does not consider printing times or printing capacities of 3D printing shops. Furthermore, economic aspects of 3D printing are out of scope. The results do not provide any predictions for product printability in future scenarios. Thus, different future substitution rates have to be assumed for home delivery fulfillment traffic simulations.

In the future, the volume of substituted shipments will likely increase because technologies continue to develop, and product designers are starting to implement additive product design, including complex structures, to reduce the number of required components. Using this additive principle at the start of the design process opens up new possibilities for additive manufacturing in urban logistics. In this way, the future printability potential of products in B2C e-commerce can be increased.

5. Simulating and Evaluating Impacts of Distributed AM on Urban Home Delivery Fulfillment Traffic

This chapter is intended to examine and answer RQ2 (How do home delivery distances in urban areas change due to distributed additive manufacturing represented by 3D printing shops in cities?). The literature review in chapter 2 identifies the potential of distributed AM to reduce physical freight transport in logistics. However, this potential is neither studied in detail nor quantified. Furthermore, existing literature does not examine the freight transport reduction potential of distributed AM on the urban scale. Therefore, the research study in this chapter tries to close this research gap by simulating urban home delivery traffic of vans using Munich as an example. In this context, different scenarios of distributed AM in local 3D printing shops are developed and compared to identify differences in home delivery distances of vans. Section 5.1 presents the corresponding methodological approach. The results are presented in section 5.2 and critically discussed in section 5.3.

5.1. Methodological Approach

This section describes the methodological approach for answering RQ2 (How do home delivery distances in urban areas change due to distributed additive manufacturing represented by 3D printing shops in cities?). By answering this question, the impacts of distributed AM on home delivery fulfillment traffic, which is an important part of urban logistics, can be evaluated. Home delivery is dominated by CEP services, which usually use vans to deliver ordered parcels to their customers. These service providers use tour- and route planning to optimize delivery tours, minimize delivery distances and save costs. The presented approach follows this principle, by simulating and comparing urban home delivery for different scenarios. In particular, the opportunity to manufacture products near the place of use is considered in these scenarios. As mentioned earlier, such a distributed production near the place of use can be performed by the customer at home or by service providers in 3D printing shops, which are distributed all over the urban area (see subsection 2.3.4). Section 5.1.1 gives an overview of the basic assumptions for the simulations. Section 5.1.2 describes the different scenarios simulated. Section 5.1.3 identifies, discusses and eliminates suitable methods for the simulation of home delivery. Section 5.1.4 displays the overall process of the methodological approach for evaluating impacts of distributed AM on home delivery fulfillment traffic.

5.1.1. Basic Assumptions

The simulation of home delivery requires certain assumptions. Especially because distributed production of ordered products near the place of use and near the customer is not established yet in today's logistics. Thus, data is not available from today's perspective and assumptions have to be made. With the help of these assumptions, which are described in the following, future impacts of this new concept on home delivery traffic can be simulated.

Assumption 1: Measurement of home delivery fulfillment traffic

There are many approaches to measuring traffic. According to Steinmeyer (2021), there are different indicators of traffic that can be collected in different ways. Example indicators for the measurement of traffic are frequency of travel, traffic volume, travel speed or route distance (Steinmeyer 2021, p. 36). The goal of the simulations is to compare home delivery traffic in different scenarios. To provide this comparison, traffic has to be measured quantitatively. It is assumed that home delivery fulfillment traffic is determined by the total delivery distances of all delivery vehicles in the simulations. These distances include all ways on the delivery tour including the approach from a parcel depot to the first customer, trips between the customers as well as the return from the last customer to the depot. Total delivery distances were chosen as an indicator for home delivery fulfillment traffic because they are suitable to be calculated as an outcome variable for the simulations and because they are comparable. Furthermore, distance serves as a traffic indicator according to the literature (Steinmeyer 2021, p. 36).

Assumption 2: Means of freight transport for home delivery

In today's logistics, new concepts for home delivery are emerging. In this context, new means of freight transport, such as cargo bikes, are tested and used on a small scale. In the simulations, only delivery vans are considered for home delivery. Thus, only delivery distances covered by vans are simulated and evaluated. These vans are filled at logistics depots and subsequently supply the customers. This assumption reduces complexity and is also reasonable as vans are still predominantly used for home delivery.

Assumption 3: Scenario Approach

As already indicated, a comparison of different scenarios is necessary to evaluate the impacts of distributed AM on home delivery fulfillment traffic. There are many possibilities and variables for the application of distributed AM in last-mile logistics. For this reason, scenarios are created that make assumptions about these variables. Example variables that influence the impacts of distributed AM near the place of use are the density of future 3D printing shops and the substitution rates of traditional home delivery. The considered scenarios for simulation are further described in subsection 5.1.2.

Assumption 4: Geographical Simulation Environment

The investigations and simulations of home delivery fulfillment traffic should be as close to a real use case as possible. Therefore, the urban area of Munich is used as an example and serves as the geographical simulation environment. The street network as well as coordinates of depots and potential customers in the urban area of Munich build the basis for the simulations. Further information on the geospatial data used in the simulations is provided in subsection 5.1.2.

Assumption 5: Simulation on Postal Code Level

The simulation and optimization of home delivery is performed on the postal code level. This assumption is made because the used optimization algorithm has a high computational complexity. Thus, the geographical simulation environment, which contains all addresses in Munich, is divided into many sub-problems on the postal code level and simulations are performed for selected postal code areas. This simplification is further described and discussed in subsection 5.1.4. Further information on the used optimization algorithm and its computational complexity is presented in subsection 5.1.3.

Assumption 6: Simulation Period

A simulation period of one day is assumed. Delivery activities during this period are simulated. In detail, home delivery on a classical workday is simulated and optimized. The simulation tool is capable of considering different traffic situations on different weekdays. Therefore, considering a workday for the simulation is reasonable as home delivery mainly takes place on workdays. Further information on specific time windows for home delivery is presented in subsection 5.1.3.

5.1.2. Simulation Scenarios

In this subsection, the scenarios for the simulation of home delivery are presented. There are three main scenarios, which can be divided into certain sub-scenarios. The characteristics and differences of the scenarios are described in the following. Due to the high computational complexity of the simulations and limited resources, this dissertation considers a limited number of three scenarios. The first scenario represents the status quo with no infrastructure of 3D printing shops. This scenario serves as a baseline scenario and enables the identification of changes in home delivery fulfillment traffic due to distributed AM in 3D printing shops. Furthermore, a scenario with a dense infrastructure of 3D printing shops and a scenario with a sparse infrastructure is considered. Thus, the effects of 3D printing shop density can be examined. The following subsections further describe why the scenarios are chosen.

Scenario 1: Status Quo

Scenario 1 tries to simulate the status quo of today's home delivery in Munich. This scenario assumes that distributed additive manufacturing of ordered products near the place of use is not realized. Furthermore, every ordered parcel is delivered to the home of the associated customer using a delivery van. The delivery tours of the vans start from depots. After the delivery process is completed, vans have to return to the depots from where they started. After returning to the depot, vans can either reload parcels and drive another tour, or end their delivery activity. The parcel delivery bases of the 5 biggest CEP companies around Munich are chosen as depots for the simulation of delivery tours. According to a study of Pitney Bowes (2021), the five biggest CEP service providers by shipment volume in Germany were DHL (48%), Hermes (16%), UPS (12%), DPD (10%) and GLS (7%) in the year 2019. The coordinates of these depots are obtained by running a python script that uses the python package GeoPy[1] to transform addresses into coordinates. These coordinates are presented in the appendix (Table 19). The locations of the considered depots are displayed in Figure 17. Customers in a certain postal code area of Munich are served by the depot of the selected service provider, which has the shortest beeline distance to the middle of the postal code area. As tours are simulated for single postal code areas, this assumption ensures that delivery tours of CEP companies are not split up into many sub-tours with a small number of customers. Further information on the selection and assignment of customers is given in subsection 5.1.4.

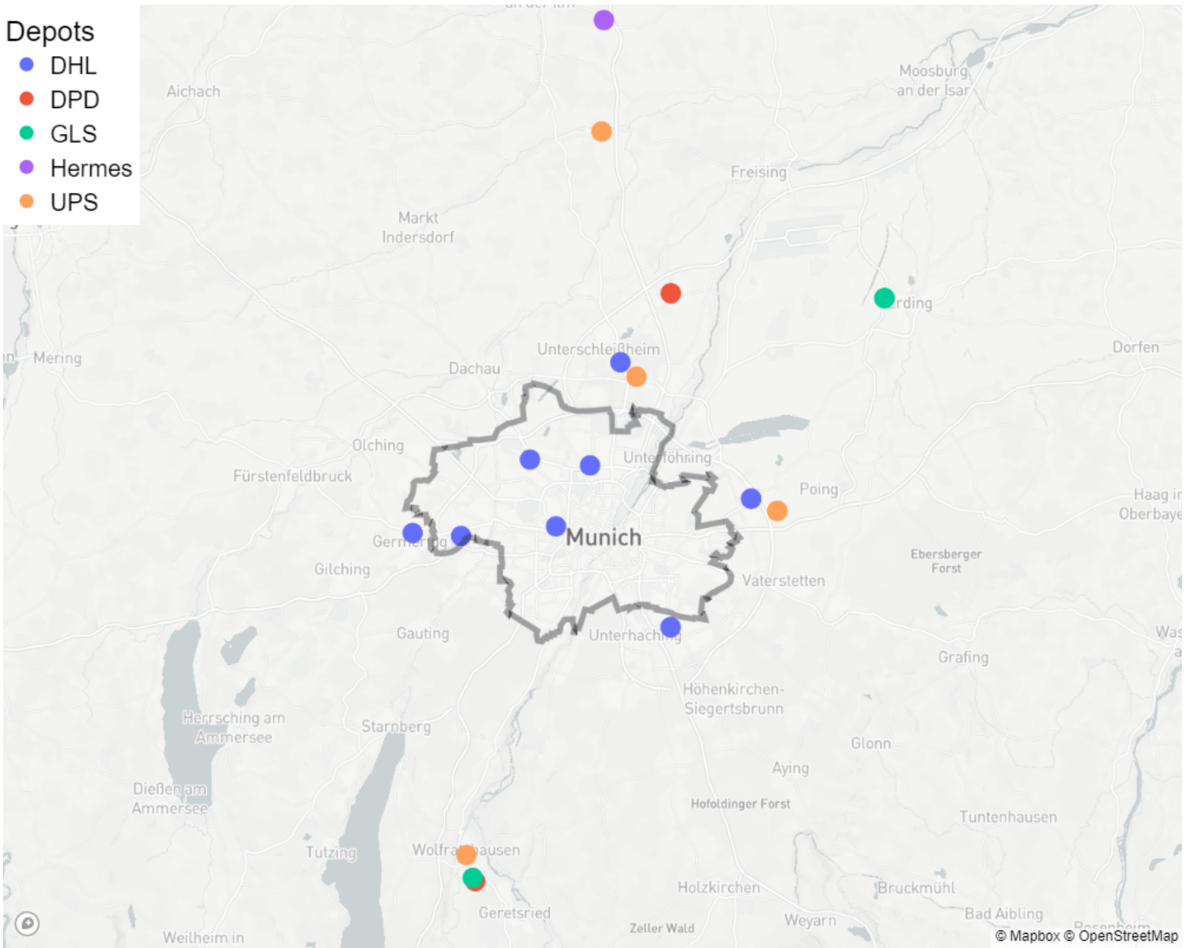


Figure 17 Depot locations

Scenario 2: Dense Infrastructure of 3D Printing Shops

Scenario 2 introduces distributed additive manufacturing of ordered products near the place of use in 3D printing shops. It is assumed that a certain amount of ordered products is produced in such local 3D printing shops. As it is unlikely that all ordered consumer goods are produced using 3DP, a certain amount of products still has to be delivered using classical home delivery from the depots introduced in scenario 1 (see Figure 17). The shares of classical home delivery and pro-

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[1] `https://geopy.readthedocs.io/en/stable/`

duction near the place of use in 3D printing shops in the future are unknown. Therefore, scenario 2 is divided into sub-scenarios which assume different substitution rates for distributed AM in 3D printing shops. Besides scenario 1, which has a substitution rate of 0%, the sub-scenarios of scenario 2 simulate the substitution rates, which are presented in Table 11. The substitution rates are intended to simulate future scenarios with different adoptions of 3DP and different technological capabilities for distributed AM near the place of use. The example substitution rate of 10% means that 10% of the overall orders are processed via a 3D printing shop. The remaining 90% would be processed via classical home delivery in this example. Due to limited computational time, only a limited number of sub-scenarios can be simulated.

Classical home delivery is fulfilled using delivery vans from CEP depots (Figure 17). Scenario 2 assumes that orders which are processed in 3D printing shops are also delivered to the customer via delivery vans. Thus, delivery vans have to drive delivery tours from the 3D printing shops to the customers. Similar to classical home delivery tours, tours from the 3D printing shops have to be circular tours ending at the start. Furthermore, scenario 2 assumes that it is not possible for customers to pick up ordered parcels from the local 3D printing shop. This assumption simplifies the simulation of home delivery traffic and distances, as individual trips to the shops can be made by different means of transport, which makes it difficult to evaluate the effects on traffic.

Scenario 2 assumes a dense infrastructure of 3D printing shops in Munich. It is assumed that 3D printing shops pose a worthwhile business case. Thus, many 3D printing shops are operated in the urban area and proximity to the customers is ensured. In scenario 2, one 3D printing shop is located in the center of every postal code area of Munich. In total, 79 postal code areas are considered. The considered postal code areas and 3D printing shops are listed in the appendix (Table 20). The localization of the 3D printing shops is performed using a developed python script, which uses the package GeoPy[2] to obtain the geographical centers of the considered postal code areas. The locations of 3D printing shops are displayed in Figure 18. The assignment of customers to 3D printing shops is based on postal code areas. This means that customers living in a certain postal code area can only be served by the 3D printing shop that is located in this specific postal code area. Further information on the selection and assignment of customers is given in subsection 5.1.4.

For scenario 2, it is assumed that one 3D printing shop in every postal code area represents a dense infrastructure of 3D printing shops. This assumption is justified by the fact that postal code areas are historically grown. Thus, postal code areas represent an appropriate catchment area. Furthermore, the locations of 3D printing shops can objectively be determined by choosing the center of each postal code area. Thus, a random selection of locations for 3D printing shops is prevented. This is the main reason why one 3D printing shop in each postal code area is considered as dense infrastructure in scenario 2. In further research, infrastructure scenarios with even more 3D printing shops can be examined.

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[2] `https://geopy.readthedocs.io/en/stable/`

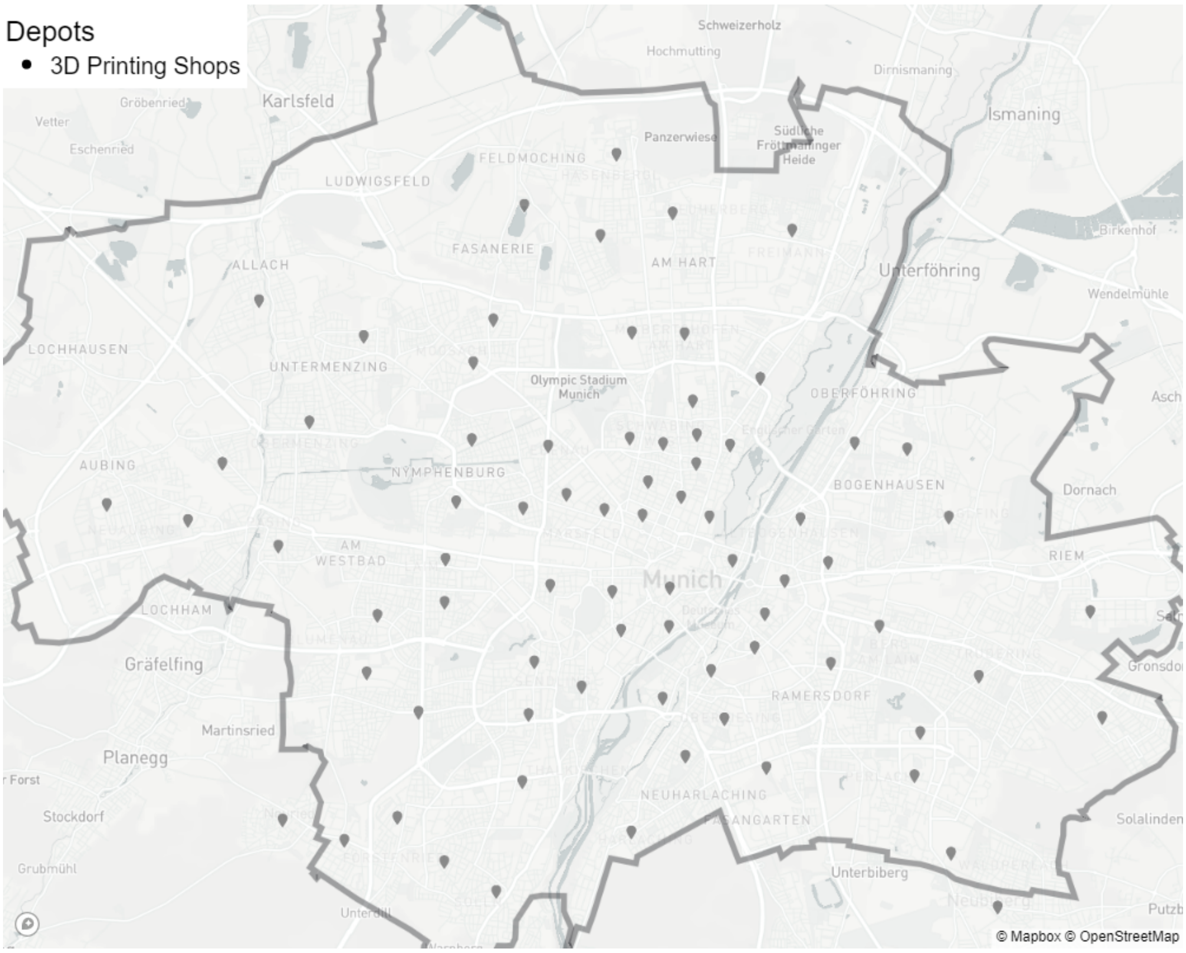

Figure 18 Locations of 3D printing shops in scenario 2

Scenario 3: Sparse Infrastructure of 3D Printing Shops

Similar to scenario 2, scenario 3 also provides distributed AM of orders near the customer in local 3D printing shops. Scenario 3 also assumes that a certain share of ordered products is produced in and delivered from these shops. Thus, classical home delivery and AM in 3D printing shops are assumed to coexist. To examine different substitution rates, scenario 3 is also divided into sub-scenarios (see Table 11). Most of the assumptions which were made in scenario 2 also apply to scenario 3. Again, there is no pick-up option for customers at the 3D printing shop to reduce complexity. All orders produced in these shops have to be delivered via delivery vans. Similar to scenario 2, vans have to drive circular tours starting from and ending at the corresponding 3D printing shop. Classical home delivery is performed from CEP depots just like in scenario 1 and 2.

The main difference between scenario 3 and scenario 2 is the density of 3D printing shops in the urban area of Munich. It is assumed that only a small number of 3D printing shops are worthwhile in the area, because the adoption of AM in urban logistics is smaller compared with scenario 2. A total of four 3D printing shops are assumed for scenario 3. The decision to consider four 3D printing shops as a sparse infrastructure scenario is explained and discussed in the following. The localization of these shops poses a major problem. Simulation results might strongly depend on these locations. Therefore, a random selection of 3D printing shop locations in Munich might pose problems and randomize the simulation results of delivery distances. To prevent random localization of the 3D printing shops, optimization algorithms for location planning can be applied. According to Domschke & Drexl (1996), there are several methods in OR (Operations Research) for optimized location planning. The p-median problem, p-center problem and the FLP (Facility Location Problem), also referred to as WLP (Warehouse Location Problem), are candidates for the determination of optimized locations for 3D printing shops (Domschke & Drexl 1996).

The WLP is a discrete location problem, which has the objective to minimize costs by selecting optimized locations for depots, which should be built to supply customers. The WLP is a classical problem in logistics and is also referred to as UFLP (Uncapacitated Facility Location Problem). The costs compose of fixed costs arising from the opening of new depots and storage, as well as transport costs arising from delivery (Domschke & Drexl 1996, p. 51). Transport costs highly depend on distances from depots to the customers. The WLP chooses optimal locations from a discrete number of options. This implies that the alternative sites have been predetermined (Verter 2011, p. 25). Information on fixed costs for the opening of new 3D printing shops is not available as the concept has not yet been implemented on a large scale. Furthermore, scenario 3 assumes a fixed number of 3D printing shops. For these reasons, the WLP is not used for the localization of 3D printing shops in scenario 3.

The FLP is also referred to as CFLP (Capacitated Facility Location Problem). The UFLP and the CFLP both belong to the group of so-called minisum problems (Eiselt & Marianov 2011, p. 23). The CFLP extends the WLP/UFLP by considering capacity limitations of depots (Verter 2011, p. 26). Depot capacities are not considered in scenario 3. Because of that, and because of missing information on fixed costs, the FLP/CFLP is not used for the localization of 3D printing shops in scenario 3.

Another candidate for the determination of optimized locations for 3D printing shops is the p-center problem (Tansel 2011, p. 82). The basis for solving this problem is a network with nodes representing customers and potential depots as well as edges representing the distances between nodes. Such a network is used to determine one or more (p) central nodes within itself. In the context of logistics, the center can be a location for a depot that supplies customers. The problem aims to find p centers to minimize the distance between the depots and the furthest nodes, which have to be supplied from the associated depot (Tansel 2011, p. 82). Thus, the p-center problem poses a so-called minimax problem (Eiselt & Marianov 2011, p. 61). The p-center problem is a useful approach for the determination of optimized locations for 3D printing shops because information on fixed costs for the opening and operation of a new 3D printing shop is not needed. Only distances between customers and depots as well as related transport costs are considered. Nevertheless, it is questionable if the minimization of distances from depots to the furthest customer is reasonable for the determination of optimized locations for 3D printing shop. If these shops could serve as a logistics hub in cities and future scenarios, which provide a pick-up option for customers, distances from the 3D-printing shops to every customer, not only to the furthest, are of interest. For this reason, a different approach is chosen for location planning.

The p-median problem has the same strengths as the p-center problem and additionally considers the distances between each customer and the depots. Similar to the p-center problem, the basis for solving the p-median problem is a network with nodes and edges. According to Domschke & Drexl (1996, p. 42), the median in such a network is defined as the node i with the minimal $\sigma(i)$, which is defined in Equation 5.1 where V represents the set of all nodes in the network. d_{ij} represents the distance from node i to node j and h_j represents a weight associated with node j.

$$\sigma(i) = \sum_{j \in V} d_{ij} h_j \tag{5.1}$$

Thus, the median of a network is the node with the minimal summed distances to every other node, taking into account node weights. The 1-median problem aims to find this median in the network.

However, the p-median problem is capable of finding more than one optimized location. According to Marianov & Serra (2011, p. 39), "the p-median problem finds the optimal location of exactly p facilities, so that the sum of the distances between customers and their closest facilities, measured along the shortest paths, is minimized". In this definition, facilities are synonymous to depots. Two questions are answered by solving the p-median problem. First, it is determined where to locate the p facilities (the “location” problem). Second, it is decided what customer or demand node is assigned to which facility or depot (the “allocation” problem) (Marianov & Serra 2011, pp. 39-40). The p-median problem is a very suitable location problem if the number of desired depot locations p is predefined. Furthermore, the p-median considers distances from every node/customer to the assigned depot and ignores fixed costs for opening and operating the depots. For these reasons, the p-median problem is chosen to determine the optimal locations for 3D printing shops in scenario 3. The formulation of the p-median problem according to Marianov & Serra (2011, p. 41) and ReVelle & Swain (1970) is presented in Equation 5.2.

$$\min \sum_{i=1}^{n} \sum_{j=1}^{m} h_i d_{ij} x_{ij} \tag{5.2a}$$

subject to

$$\sum_{j=1}^{m} x_{ij} = 1 \qquad \text{for} \quad i = 1, 2, ..., n \tag{5.2b}$$

$$x_{ij} \leq y_i \qquad \text{for} \quad i = 1, 2, ..., n \quad j = 1, 2, ..., m \tag{5.2c}$$

$$\sum_{j=1}^{m} y_j = p \tag{5.2d}$$

$$x_{ij}, y_i \in \{0, 1\} \qquad \text{for} \quad i = 1, 2, ..., n \quad j = 1, 2, ..., m \tag{5.2e}$$

Subscripts, parameters, and variables in formulation 5.2 are defined as follows (Marianov & Serra 2011, p. 42):

i : index of customers/demand nodes
j : index of potential depot sites
m : total number of potential depot locations
n : total number of customers/demand nodes
p : total number of depots to be located
h_i : weight associated to each demand node (representing demand or number of customers)
d_{ij} : distance between customer/demand node i and potential depot at j
x_{ij} : allocation variable equal to 1 if customer/demand node i is assigned to a depot at j, and 0 otherwise
y_j : location variable equal to 1 if there is an open depot at j, and 0 otherwise

Constraint 5.2b assigns each demand node to exactly one depot. Constraint 5.2c allows a demand node i to be allocated to an existing depot only. Constraint 5.2d sets the number of desired depots and constraint 5.2e states that all variables have to be binary.

As mentioned above, the basis for solving the p-median problem is a network. Data to generate such a network comes from the last census of the European Union in 2011[3]. The census provides population data for 100 meter grids all over Europe. The data is filtered by extracting population data for Munich only. For this purpose, the data of the postal code areas already considered in scenario 2 is chosen (see Table 20). The grids represent nodes in the network. The population within each grid poses the weight of the node. Nodes are linked by beelines. Beeline distances between nodes are calculated from the center of the grids.

The computational complexity of the p-median problem is NP-hard, which means that the computational time of the problem can get very high for a big number of nodes and edges. For this reason, the population data is manipulated by aggregating 100 meter grids to 500 meter grids. The population grids of Munich are displayed in Figure 19. The size and color of the dots represent the population size within each grid. To solve the p-median problem for the generated network of Munich, a python script is programmed. This script makes use of the optimizer Gurobi[4]. After implementing the p-median problem in code, the problem is solved and four optimal locations for 3D printing shops in Munich are found. These locations are also displayed as black marks in Figure 19. The coordinates of the 3D printing shops are presented in the appendix (Table 21). As there are only four 3D printing shops in scenario 3, every postal code area is assigned to the closest 3D printing shop according to beeline distance. Further information on the selection and assignment of customers for classical home delivery and 3DP is given in subsection 5.1.4.

Considering four 3D printing shops as a sparse infrastructure of 3D printing shops in scenario 3 is an assumption that needs to be justified. For this reason, several p-median problems are calculated with different numbers of p (3D printing shops) and compared. Since scenario 3 is intended to represent a sparse infrastructure of 3D printing shops, the minimal distance between two 3D printing shops should not be smaller than five kilometers. To still preserve the local character of 3D printing shops, it is assumed that the maximum distance between two 3D printing shops is less than 15 kilometers and that the maximum distance from the center of a population grid to the next 3D printing shop is smaller than 20 kilometers. To find the number of 3D printing shops, that

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[3] https://www.zensus2011.de/DE/Home/home_node.html
[4] https://www.gurobi.com/

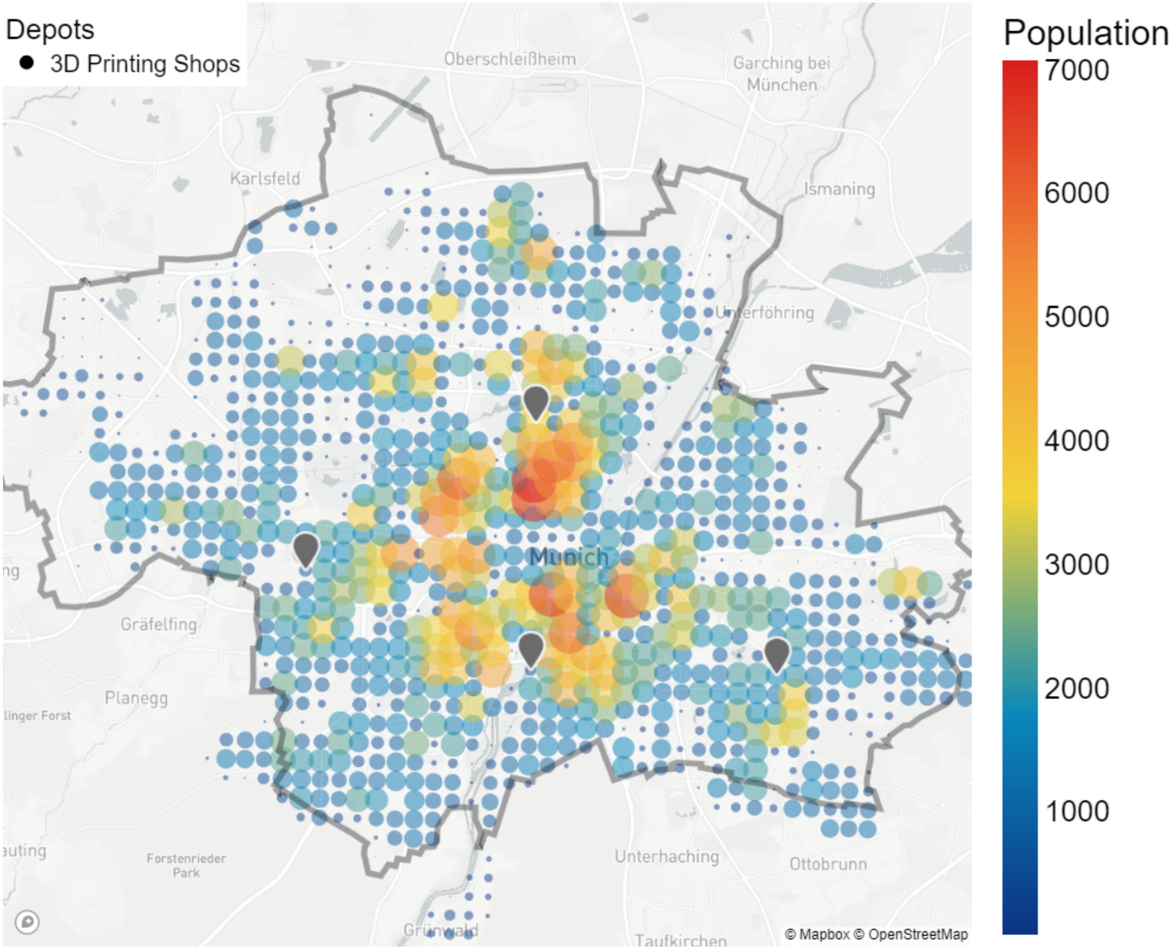

Figure 19 Population of 500 meter grids in Munich and locations of 3D printing shops in scenario 3

fulfills the mentioned requirements, six scenarios with two to seven shops are calculated and considered. An analysis of distances shows that the scenario with four optimized 3D printing shops is the only one fulfilling the assumed requirements. Thus, a scenario with four 3D printing shops represents a sparse infrastructure that still has a local character due to the central localization of facilities and limited distances to customers. Based on the described aspects, the four 3D printing shops depicted in Figure 19 are chosen as the appropriate infrastructure for scenario 3. The location optimization results of the other potential variants for scenario 3 with different numbers of 3D printing shops are displayed in the appendix (see Figure 41-Figure 46).

Table 11 presents a brief summary of the investigated scenarios. For every sub-scenario in Table 11, selected postal code areas are simulated. The simulation of such a postal code area is denoted as variant of a sub-scenario.

Scenario	Infrastructure of 3D Printing Shops	Substitution Rate
Scenario 1	No 3DP	0%
Scenario 2	Dense with one 3DP shop in the center of every postal code area	Various
Sub-scenario 2-1	Dense with one 3DP shop in the center of every postal code area	5%
Sub-scenario 2-2	Dense with one 3DP shop in the center of every postal code area	10%
Sub-scenario 2-3	Dense with one 3DP shop in the center of every postal code area	20%
Sub-scenario 2-4	Dense with one 3DP shop in the center of every postal code area	40%
Sub-scenario 2-5	Dense with one 3DP shop in the center of every postal code area	80%
Scenario 3	Sparse with four 3DP shops in Munich	Various
Sub-scenario 3-1	Sparse with four 3DP shops in Munich	5%
Sub-scenario 3-2	Sparse with four 3DP shops in Munich	10%
Sub-scenario 3-3	Sparse with four 3DP shops in Munich	20%
Sub-scenario 3-4	Sparse with four 3DP shops in Munich	40%
Sub-scenario 3-5	Sparse with four 3DP shops in Munich	80%

Table 11 Summary of scenarios

5.1.3. Simulation Method Selection

There are several methods for optimizing and simulating home delivery. In reality, CEP companies aim to minimize their costs by optimizing home delivery tours and minimizing home delivery distances. This approach should also be taken into account in the simulations. Domschke & Scholl (2010) name three types of problems, which are relevant for tour- and route planning in logistics: TSP (Travelling Salesman Problem), CPP (Chinese Postman Problem) and VRP (Vehicle Routing Problem). This section is intended to present and discuss these problems. Subsequently, the most suitable method for the simulation of home delivery is identified.

Chinese Postman Problem

The CPP is a classical problem in logistics and OR. The problem aims to find the shortest path that visits every edge of a graph or network at least once and poses a closed tour. The basis for solving the CPP is a graph or network with nodes and edges. An example use case for the CPP in practice is postal delivery. In this context, a postman has to go through all streets once (or twice for bigger streets where lanes are separated) to deliver mail to each and every house. The goal of the postman is to find a closed route with minimal distance to save time and costs. Under certain circumstances, the postman has to walk a street more than once. These walks are called unproductive stretches according to Domschke & Scholl (2010, p. 167). Thus, the CPP can also be formulated as an optimization problem, which produces closed tours and minimizes unproductive stretches (Domschke & Scholl 2010, p. 167). Other typical applications that can be optimized with the CPP are garbage collection or street cleaning (Domschke & Scholl 2010, p. 167). According to Domschke & Scholl (2010, p. 167), the CPP can be applied to directed, undirected and mixed graphs or networks.

In theory, solving the CPP is easy. If the graph or network has an eulerian cycle, then this cycle is the solution to the optimization problem (Domschke & Scholl 2010, p. 170). In this case, no unproductive stretches have to be made. If the graph has no eulerian cycle, it has to be extended by adding edges until an eulerian cycle with minimal distance is created (Domschke & Scholl 2010, p. 170). This process is also denoted as minimal cost expansion (Domschke & Scholl 2010, p. 170). In the literature there are several different formulations for the CPP. Eiselt et al. (1995) present a formulation for the UCPP (Undirected Chinese Postman Problem) and DCPP (Directed Chinese Postman Problem). The UCPP assumes that every street/edge is passable from both directions. In contrast, the DCPP considers one-way streets or different lanes for bigger streets.

The UCPP is presented in formulation 5.3 as used by Edmonds & Johnson (1973), Eiselt et al. (1995), or Laporte (2015, p. 54).

$$\min \sum_{(i,j)\in E} c_{ij}x_{ij} \tag{5.3a}$$

subject to

$$\sum_{(i,j)\in E(S)} x_{ij} \geq 1 \quad \text{for} \quad S \subset V, S \quad \text{is odd} \tag{5.3b}$$

$$x_{ij} \geq 0 \qquad \text{for} \quad (i,j) \in E \tag{5.3c}$$

$$x_{ij} \quad \text{integer} \qquad \text{for} \quad (i,j) \in E \tag{5.3d}$$

Subscripts, parameters, and variables in formulation 5.3 are defined as follows:

i : index of first node of a link
j : index of second node of a link
(i,j) : arc/edge from node i to node j
x_{ij} : linking variable equal to 1 if node i is followed by node j, and 0 otherwise
c_{ij} : costs to get from node i to node j (most often depending on distances)
V : set of all nodes
S : subset of nodes
E : set of all arcs/edges
$E(S)$: subset of arcs/edges; $E(s) = \{(i,j) : i \in S, j \in V \setminus S$ or $i \in V \setminus S, j \in S\}$

The CPP is a suitable method for optimizing tours of postmen, who have to go through all edges/streets of a network. For this task, it is assumed that every house in a street must be supplied. Thus, minimizing the distances of tours, which have to include all edges/streets is suitable. For home delivery of consumer goods, this assumption is not applicable. In reality, not every house is supplied by home delivery vans in the period of one day. Thus, some streets do not contain customers for home delivery. In this case, the optimization using the CPP, which has the constraint to cover all streets, can lead to undesired tours. Especially for optimizing home delivery tours on networks with smaller streets containing a low number of houses, the use of the CPP is not suitable. For the optimization of home delivery tours in high-density areas, where streets contain a big number of houses, the use of the CPP is less problematic because there is a higher probability that each street contains at least one customer. Yet, the CPP is not chosen as a suitable method for simulating and evaluating home delivery. Thus, inaccurate simulation results caused by including streets, that do not contain a customer, can be prevented. Furthermore, suitable software for solving the CPP, especially for bigger networks, is rare. This aspect supports the decision of not choosing the CPP for the simulation of home delivery.

Travelling Salesman Problem

The TSP is a classical problem in logistics and OR. In practice, the TSP poses a challenge for an actor (often denoted as a salesman or supplier), who has to visit different locations (often denoted as customers). After visiting all locations, the actor has to return to his starting point. The goal of the TSP is to minimize the distance for the actor, who has to visit all predefined locations. The basis for solving the TSP is a network with nodes representing the locations and edges representing the connections between locations. Furthermore, edge weights in a network represent costs of getting from one node to another. The mathematical formulation of the TSP according to Domschke & Scholl (2010, pp. 99-101) is presented in formulation 5.4.

$$\min \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij} \tag{5.4a}$$

subject to

$$\sum_{j=1}^{n} x_{ij} = 1 \qquad \text{for} \quad i = 1, 2, ..., n \tag{5.4b}$$

$$\sum_{i=1}^{n} x_{ij} = 1 \qquad \text{for} \quad j = 1, 2, ..., n \tag{5.4c}$$

$$x_{ij} \in \{0, 1\} \qquad \text{for} \quad i, j = 1, 2, ..., n \tag{5.4d}$$

$$\sum_{i \in Q} \sum_{j \in Q} x_{ij} \leq |Q| - 1 \quad \text{for all} \quad Q \subset V \text{with} \quad 2 \leq |Q| \tag{5.4e}$$

Subscripts, parameters, and variables in formulation 5.4 are defined as follows:

i : index of first node of a link
j : index of second node of a link
n : total number of nodes
x_{ij} : linking variable equal to 1 if node i is followed by node j, and 0 otherwise
c_{ij} : costs to get from node i to node j (most often depending on distances)
V : set of all nodes
Q : subset of V

The constraints 5.4b and 5.4c ensure that every node is left and reached exactly once. Constraint 5.4d ensures that x_{ij} is either 1 if node i is followed by node j or 0 if there is no connection from node i to node j. Constraint 5.4e is known as the Dantzig-Fulkerson-Johnson-Constraint. This constraint excludes the existence of many sub-tours. Thus, only a circular tour approaching and leaving all nodes exactly once poses a valid result.

The TSP is a suitable method to minimize distances for an actor, who has to visit a series of locations within a tour. For home delivery, vans often have to drive sub-tours, which only contain a few customers, due to the capacity constraints of the vehicles. In this case, vans have to return to their depots. There, they are reloaded and start another sub-tour. In addition, there is usually more than one depot representing a starting and end point for home delivery. These aspects cannot be considered using the TSP. Furthermore, the TSP is not able to take time constraints into account. For these reasons alone, the TSP is not chosen as a suitable method for simulating home delivery.

Vehicle Routing Problem

According to Dantzig & Ramser (1959), the VRP can be considered as a generalization of the TSP, which is capable of considering more constraints such as capacities or time windows. The basis for solving the VRP is a network consisting of nodes (demand nodes and depots) representing locations and edges representing connections between nodes. In the VRP all demand nodes have to be reached and supplied exactly once using closed tours starting and ending at a depot. The goal of the VRP is to minimize delivery costs, which usually strongly depend on distance. A classical use case for the VRP in practice is customer delivery. In this context, delivery vans have to supply customers, which can also be denoted as demand nodes in a network, from one or more depots. Unlike the classical TSP, the VRP considers the demands of nodes/customers, which can be interpreted as parcel size in the example of home delivery, and vehicle capacities. The VRP allows the use of more than one delivery van in parallel. Furthermore, delivery vans have the opportunity to return to depots, reload and drive another tour. A VRP considering capacities is also denoted as CVRP (Capacitated Vehicle Routing Problem). A CVRP, that additionally considers time windows, is referred to as CVRPTW. A mathematical formulation of the CVRPTW according to Domschke & Scholl (2010, p. 207) is presented in formulation 5.5. The formulations 5.5a-5.5e represent the CVRP. The constraints 5.5f-5.5h extend the CVRP to the CVRPTW. The constraints 5.5b and 5.5c ensure that every node is reached and left exactly once. Constraint 5.5d makes sure that vehicle capacities are not exceeded. Furthermore, constraint 5.5d prevents short cycles without the depot. Constraint 5.5e ensures that x_{ij} is either 1 if node i is followed by node j or 0 if there is no connection from node i to node j. Constraint 5.5f ensures compliance with customer time windows. Constraint 5.5g represents time window restrictions resulting from routes and constraint 5.5h ensures that the maximum tour duration is not exceeded.

$$\min \sum_{i=0}^{n} \sum_{j=0}^{n} c_{ij} x_{ij} \tag{5.5a}$$

subject to

$$\sum_{j=0}^{n} x_{ij} = 1 \qquad \text{for} \quad i = 1, 2, ..., n \tag{5.5b}$$

$$\sum_{i=0}^{n} x_{ij} = 1 \qquad \text{for} \quad j = 1, 2, ..., n \tag{5.5c}$$

$$\sum_{i \in Q} \sum_{j \in Q} x_{ij} \leq |Q| - r(Q) \qquad \text{for all} \quad Q \subseteq V - \{0\} \text{with} \quad |Q| \geq 2 \tag{5.5d}$$

$$x_{ij} \in \{0, 1\} \qquad \text{for} \quad i, j = 0, 1, 2, ..., n \tag{5.5e}$$

$$tf_j \leq t_j \leq ts_j \qquad \text{for} \quad j = 1, 2, ..., n \tag{5.5f}$$

$$t_j \geq t_i + sz_i + fzij - (1 - x_{ij})M \qquad \text{for} \quad i = 0, 1, ..., n \quad j = 1, 2, ..., n \tag{5.5g}$$

$$t_j + sz_j + fz_{j0} - (1 - x_{j0})M \leq dur \qquad \text{for} \quad j = 1, 2, ..., n \tag{5.5h}$$

Subscripts, parameters, and variables in formulation 5.5 are defined as follows:

i : index of first node of a link
j : index of second node of a link
n : total number of nodes
x_{ij} : linking variable equal to 1 if node i is followed by node j, and 0 otherwise
c_{ij} : costs to get from node i to node j (most often depending on distances)
V : set of all nodes
Q : subset of V
$r(Q)$: minimal number of tours to fulfill capacity restrictions for a given b and cap; $r(Q) = \lceil \sum_{i \in Q} \frac{b_i}{cap} \rceil$
b_i : demand of node i
cap : capacity of a delivery vehicle
tf_j : earliest possible arrival time at node j
ts_j : latest possible arrival time at node j
t_j : starting time for serving node j
sz_j : time for serving node j
fz_{ij} : travel time from node i to node j
M : sufficiently large number for redundancy condition
dur : latest possible time to finish a tour

The VRP has a few characteristics making it very suitable for optimizing and simulating home delivery. In contrast to classical postman problems such as the CPP, the VRP considers capacity restrictions of vehicles as well as different demands of nodes or customers. Furthermore, the VRP can conduct tour- and route planning for a whole fleet of delivery vehicles, which can be used at the same time.

Thus, sub-tours are possible and delivery vehicles are allowed to return to depots and drive another tour. In real-world home delivery, these aspects are applicable. Furthermore, time windows are relevant for home delivery in practice as customers cannot be supplied at any time and drivers must adhere to specified working hours. Customers typically have different demands, which have effects on the delivery tours. In contrast to the TSP, the VRP is capable of considering these demands. The mentioned advantages, that make the VRP suitable for optimizing and simulating home delivery, are offset by one main disadvantage: The high computational complexity of the VRP. The determination of an optimal solution of the VRP is NP-Hard. Thus, the size of problems that can be optimally solved may be limited (Toth & Vigo 2002). Real-world VRPs often have a large number of nodes. For this reason, commercial solvers often use heuristics to handle a bigger problem size.

After considering the advantages and disadvantages, the VRP is chosen as a suitable method for optimizing and simulating home delivery tours. To handle the high computational complexity of the VRP for simulating and optimizing home delivery tours in Munich, the problem is broken down into many subproblems, which are solved individually. Thus, a VRP is solved on the postal code level for selected postal code areas. Limitations of this simplification are critically discussed in section 5.3.

For simulating home delivery tours and solving the VRPs, the software Siemens XCargo[5] is used.

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[5] `https://xcargo.siemens-digital-logistics.com/home`

This software is capable of solving the VRP in consideration of capacities and time windows. Thus, the CVRPTW is solved in Siemens XCargo. Siemens XCargo is a professional software, which is used both in research and in practice. Furthermore, Siemens XCargo contains street network data of the biggest cities in Europe, including Munich. This is a big advantage because the VRP can be solved on a real-life street network instead of beeline distances. Thus, the results are applicable to the geographical simulation area of Munich. As a proven software, Siemens XCargo is chosen as a suitable tool for the simulations of home delivery tours. The software requires input for certain parameters, which are considered in the CVRPTW. Assumptions are made for these parameters. The assumed parameters are presented in Table 12.

Parameter	**Value**
Loading time at depots, sz_0	$20[min]$
Stop time at customers, $sz_1, ..., sz_n$	$2[min]$
Start of first time window, tf_1	$08:00[hh:mm]$
End of first time window, ts_1	$12:00[hh:mm]$
Start of second time window, tf_2	$12:30[hh:mm]$
End of second time window, $ts_2 = dur$	$18:00[hh:mm]$
Demand volume of customers, $b_1, ..., b_n$	$0.03[m^3]$
Volume capacity of delivery vans, cap	$7.70[m^3]$

Table 12 Parameter assumptions for the simulation and optimization of home delivery tours using the CVRPTW in Siemens XCargo

Loading times at depots are assumed to be 20 minutes. In this time, delivery vans can be loaded. The stop time at every customer is assumed to be two minutes in which packages can be delivered to the door. The time window for home delivery is divided into two sections. After the first section, which goes from 8:00 a.m. to 12:00 p.m., a break for the driver is provided. The second section, which goes from 12:30 p.m. to 6:00 p.m., concludes the home delivery tours for the simulation day. The demand volume of customers is assumed to be equal for every customer. Thus, the demand volume of every customer is $0.03m^3$. The volume capacity of every used delivery van is assumed to be $7.7m^3$, which corresponds approximately to the load volume of the Streetscooter Work L[6].

As mentioned above, the computational complexity of the VRP is NP-Hard. Therefore, complexity should be reduced, to solve bigger problems. Siemens XCargo uses a heuristic to solve bigger problems in a reasonable runtime. The used heuristic is called column generation.

5.1.4. Resulting Evaluation Process

The basic assumptions, simulation scenarios and the simulation method provide a basis for understanding the evaluation process including the simulation. This process poses a sub-process of the holistic methodological approach and is displayed as BPMN diagram in Figure 20.

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[6] `https://www.streetscooter.com/de/`

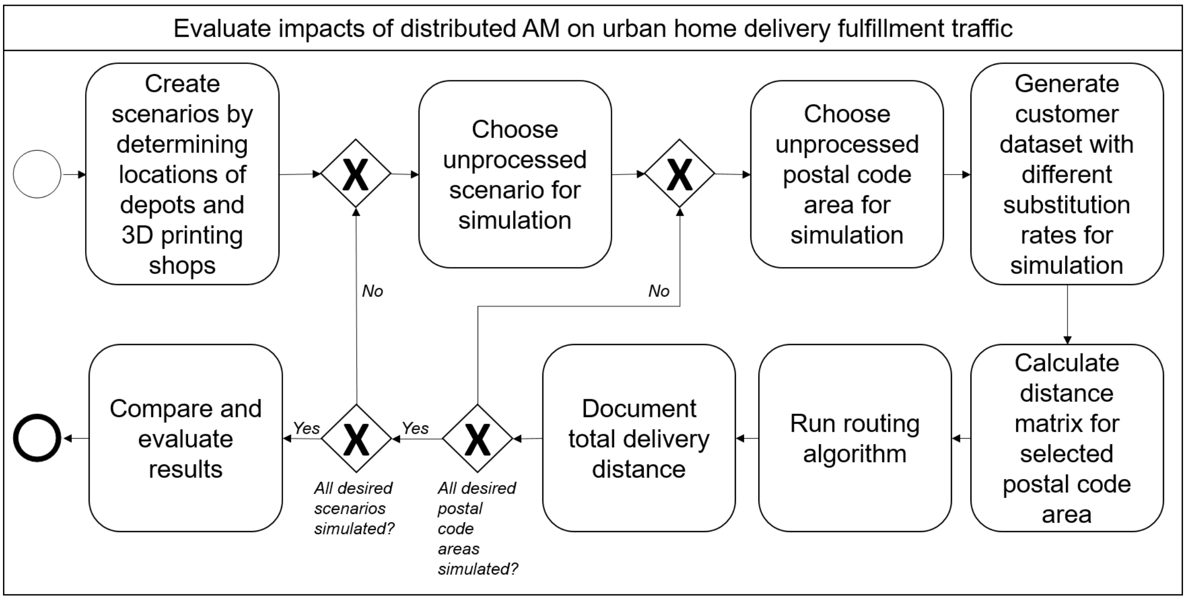

Figure 20 Methodological approach for evaluating impacts of distributed AM on urban home delivery fulfillment traffic (sub-process of Figure 11)

The first step of the process is called *create scenarios by determining locations of depots and 3D printing shops*. Locations of depots and 3D printing shops represent the main distinction between the scenarios. The locations and the process for their determination were already presented and described in subsection 5.1.2.

The following step, which is called *choose unprocessed scenario for simulation*, selects one of the created scenarios. This step is called recursively during the process so that all scenarios are evaluated.

As mentioned in subsection 5.1.3, the computational complexity of the VRP is NP-Hard. Therefore, two possibilities are used to reduce the computational time of the calculations. First, a heuristic is applied to solve the VRP. Second, the big problem for the geographical simulation environment, which contains all addresses in Munich, is divided into many sub-problems on the postal code level. Thus, every postal code area represents a sub-problem. The next step of the process chooses a certain postal code area for the simulation (*choose unprocessed postal code area for simulation*). This step is repeated in a loop within the process to evaluate many postal code areas in the geographical simulation environment of Munich.

For every chosen postal code area, a customer dataset is generated (*generate customer dataset with different substitution rates for simulation*). The basis for the generation of the customer dataset is a dataset of Munich containing all addresses in the city[7]. This address dataset contains street names and house numbers only. Therefore, the dataset is further processed using the python package GeoPy[8] to add postal code areas as well as coordinates to every address. Thus, the dataset can be filtered by postal code area. For home delivery, it is unlikely that every address poses a customer, who needs to be supplied in the simulation period of one day. Therefore, a customer rate is introduced, which determines the share of addresses representing customers.

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[7] `https://opendata.muenchen.de/dataset/adressverzeichnis-der-landeshauptstadt-muenchen`

[8] `https://geopy.readthedocs.io/en/stable/`

For central postal code areas, a customer rate of 50% is assumed. For outer postal code areas, a customer rate of 10% is determined because it is assumed that there are more single-family homes in these outer, less urban areas of Munich. In contrast, inner postal code areas are assumed to contain more buildings with several residential units. A customer rate of 50% means that 50% of the addresses contain customers. The assignment of the simulated postal code areas is presented in Table 13.

Region	Simulated postal code areas
Inner area of Munich	80331, 80333, 80335, 80336, 80337, 80339
Outer area of Munich	80939, 80997, 81249, 81475, 81739, 81929

Table 13 Locations of simulated postal code areas

Depending on the customer rate, a certain amount of addresses is randomly chosen from the address dataset as the customer dataset for the postal code area. A customer address is defined as an address containing one or more customers, who have to be supplied with a parcel during the investigated simulation day. Depending on the scenario, each customer address is assigned to a depot or a 3D printing shop from which they are supplied. In scenario 1, 3D printing shops do not exist. Therefore, every customer address is assigned to and supplied from a CEP depot. As mentioned in subsection 5.1.2, the five biggest CEP service providers by shipment volume in Germany are considered. In 2019, these providers were DHL (48%), Hermes (16%), UPS (12%), DPD (10%) and GLS (7%) (Pitney Bowes 2021). As the five considered CEP providers do not own the entire market share, the shares are normalized to 100%. This normalization represents a simplification for the assignment of customer addresses. The customer addresses are randomly assigned to the CEP providers according to the standardized market shares. Furthermore, the customer addresses, which were assigned to a certain CEP provider, have to be assigned to a depot of the provider. This assignment is based on distances. Thus, a customer address is assigned to the postal code areas closest depot of the assigned CEP provider according to beeline distance. Scenarios 2 and 3 introduce the 3D printing shop. In both scenarios, some of the customer addresses, which were supplied from a CEP depot, are now assigned to and supplied from a 3D printing shop. In scenario 2, every postal code area of Munich contains one 3D printing shop. Thus, some customer addresses are assigned to the printing shop in their postal code area. Scenario 3 considers a sparse infrastructure in Munich with only four 3D printing shops. Here, customer addresses are assigned to and supplied from the closest 3D printing shop according to beeline distance. The sub-scenarios presented in Table 11 determine the percentage and number of customer addresses, which are reassigned from CEP depots to 3D printing shops.

After a customer dataset is generated for a certain scenario and postal code area, a distance matrix is calculated containing the shortest distances between all nodes of the network, which represent the locations of customer addresses, CEP depots and 3D printing shops (*calculate distance matrix for selected postal code area*). The calculation of the distance matrix is executed in the used software Siemens XCargo and constitutes the basis for solving the CVRPTW.

After generating the customer dataset and the distance matrix, the routing algorithm for solving the CVRPTW is executed in Siemens XCargo (*run routing algorithm*). The selection of the simulation method is described in subsection 5.1.3. As mentioned in subsection 5.1.3, Siemens XCargo uses a column generation heuristic as routing algorithm to solve the CVRPTW.

In the next step of the process, the results of the simulation and optimization using the routing algorithm are documented (*document total delivery distance*). Here, the summed delivery distances of the optimized delivery tours are of particular interest, since home delivery fulfillment traffic is assumed to be measured by delivery distances (see subsection 5.1.1).

After documenting the results one loop pass is completed and the described steps can be repeated for further unprocessed scenarios and postal code areas.

As a last step of the process, results of the scenarios are compared and evaluated (*compare and evaluate results*). Thus, changes in home delivery fulfillment traffic can be identified.

5.2. Results

This section presents the results of the simulation and evaluation considering the impacts of distributed AM in urban logistics on urban home delivery fulfillment traffic. As mentioned in section 5.1, home delivery fulfillment traffic is simulated for different scenarios with a differing infrastructure of 3D printing shops (see Table 11). By comparing home delivery distances of vans in these different scenarios, conclusions can be drawn about the impacts of distributed AM on home delivery fulfillment traffic. Section 5.1 suggests that the simulation is not performed for the whole geographical simulation environment of Munich at once. The reason for this is the high computational complexity of the used algorithms in the simulation, which leads to long computation times for big networks. Therefore, the problem of simulating home delivery fulfillment traffic in Munich is decomposed into many sub-problems which simulate home delivery fulfillment traffic for single postal code areas in Munich. The examined and simulated postal code areas are displayed as blue polygons in Figure 21. The complete simulation results for the different postal code areas are documented in the appendix (Table 22). Summarized results with average values of changes in delivery distances for the different scenarios are presented in Table 14. According to the presented results, every scenario is simulated for twelve different postal code areas. To evaluate changes in home delivery fulfillment traffic, differences in tour distances are focused on. The mean percentage difference in total tour distance between sub-scenario 2-1 and the status quo scenario 1 is 0.0228. This means that total tour distances in sub-scenario 2-1 are on average 2.28% longer compared with the baseline scenario 1. The difference is statistically significant at the 1% level. The statistical significance of all differences of means in Table 14 is determined using a one-sample t-test. This test is appropriate as one sample is compared to a percentage difference in tour distances of scenario 1 which is always 0. The percentage difference in mean delivery distance of sub-scenario 2-2 compared with scenario 1 is 0.0246. This result indicates an increase in distances for home delivery which is statistically significant at the 1% level. The simulation results of sub-scenario 2-4, which contains a dense infrastructure of 3D printing shops and a substitution rate of 40%, indicate the first reduction of delivery distances. The percentage difference in mean delivery distance of sub-scenario 2-4 compared with scenario 1 is -0.0027. However, the difference is not statistically significant. The simulation results of the last sub-scenario of scenario 2, which contains a dense infrastructure of 3D printing shops and

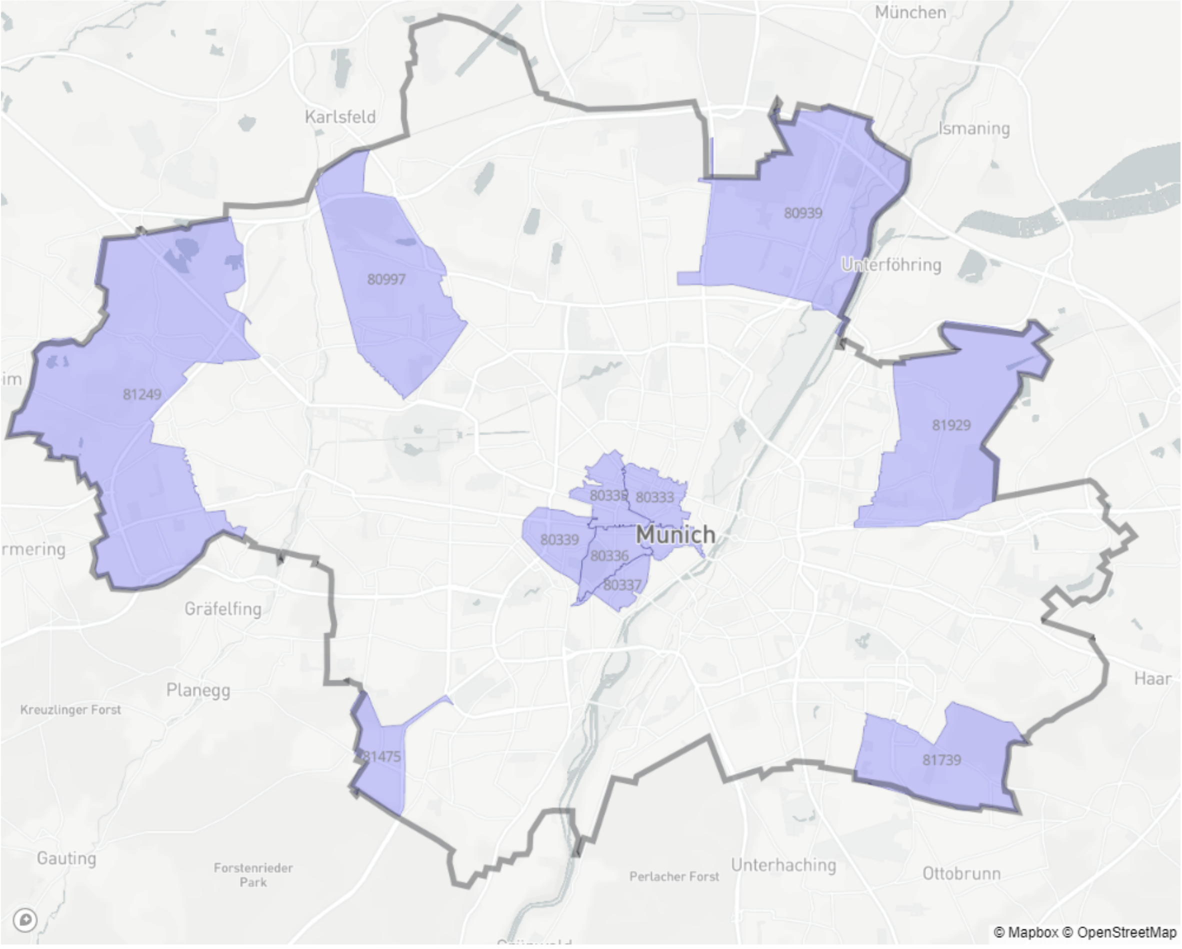


Figure 21 Simulated postal code areas

a substitution rate of 80%, indicate a significant reduction in delivery distances. The percentage difference in mean delivery distance of sub-scenario 2-5 compared with scenario 1 is -0.0722. Thus, the delivery distances in sub-scenario 2-5 are on average 7.22% shorter compared with scenario 1.

In contrast to scenario 2, scenario 3 contains a sparse infrastructure of 3D printing shops with only four facilities. The simulation results for the sub-scenarios 3-1, 3-2, and 3-3 indicate an increase in mean delivery distance compared with scenario 1. These differences are statistically significant at the 1% level. Sub-scenario 3-4, which considers a substitution rate of 40%, shows a percentage difference in mean delivery distance of 0.0326 compared with scenario 1. This difference is statistically significant. Compared with scenario 2, the reduction of home delivery distance in scenario 3 only occurs at a higher substitution rate. Sub-scenario 3-5, which assumes a sparse infrastructure of the 3D printing shop and a substitution rate of 80%, indicates an insignificant reduction of delivery distances.

The presented results seem to be counterintuitive at first glance since we could assume that distributed and local AM of ordered products would lead to a reduction in home delivery fulfillment traffic. However, this is not always the case in the urban area of Munich which is used as an example for the simulations and investigations. The results depend on the assumed substitution rates in the different scenarios. These substitution rates determine the share of ordered prod-

Scenario		Delivery distance in km		Percentage difference in delivery distance compared with scenario 1		
	N	Mean †	SD†	Mean††	SD††	95% CI††
Scenario 1	12	392.09	53.21	0.0	0.0	$[0.0000, 0.0000]$
Sub-scenario 2-1	12	401.42	57.56	0.0228^{***}	0.0126	$[0.0144, 0.0313]$
Sub-scenario 2-2	12	402.33	59.36	0.0246^{***}	0.0175	$[0.0129, 0.0364]$
Sub-scenario 2-3	12	401.47	61.22	0.0218^{***}	0.0223	$[0.0069, 0.0368]$
Sub-scenario 2-4	12	391.87	60.30	-0.0027	0.0240	$[-0.0188, 0.0134]$
Sub-scenario 2-5	12	363.66	49.37	-0.0722^{***}	0.0265	$[-0.0900, -0.0545]$
Sub-scenario 3-1	12	409.10	58.73	0.0424^{***}	0.0138	$[0.0331, 0.0517]$
Sub-scenario 3-2	12	409.41	60.83	0.0425^{***}	0.0215	$[0.0281, 0.0570]$
Sub-scenario 3-3	12	409.02	62.77	0.0409^{***}	0.0248	$[0.0243, 0.0576]$
Sub-scenario 3-4	12	406.03	65.85	0.0326^{**}	0.0414	$[0.0047, 0.0604]$
Sub-scenario 3-5	12	386.38	57.41	-0.0154	0.0465	$[-0.0467, 0.0158]$

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

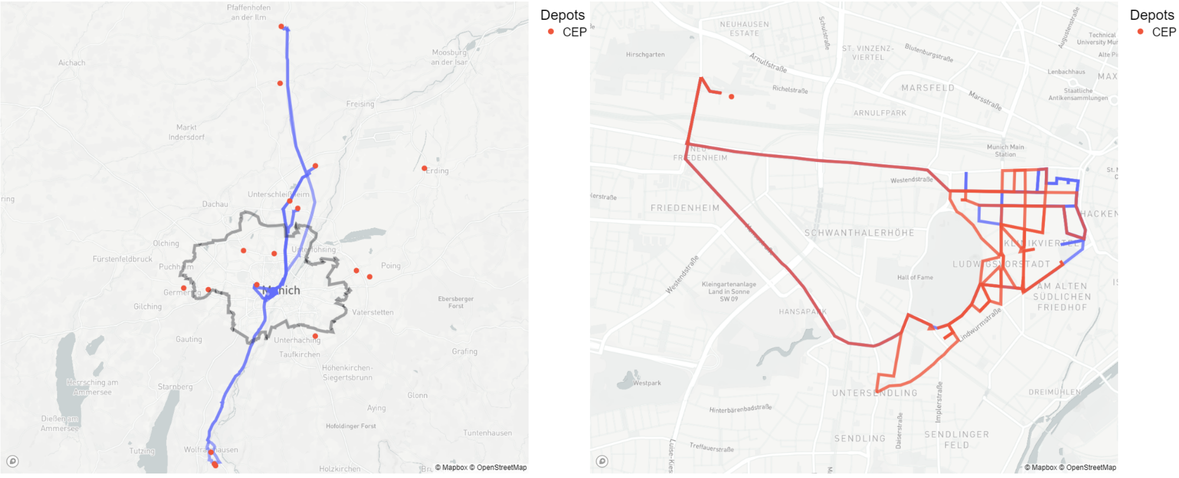
† Values rounded to two decimal places, †† values rounded to four decimal places

Table 14 Aggregated results of home delivery fulfillment traffic simulations

ucts whose classical delivery from CEP depots is substituted with distributed and local AM in 3D printing shops near the customer. In scenarios with lower substitution rates (5% and 10%), additional delivery tours from 3D printing shops to their customers have to be driven. However, the substitution rates are not high enough to substitute the classical delivery tours from CEP depots. Only a few stops from the classical delivery tours are shifted to the delivery tours from the local 3D printing shops. These shifts only have small effects on the delivery distance of a classical tour from a CEP depot.

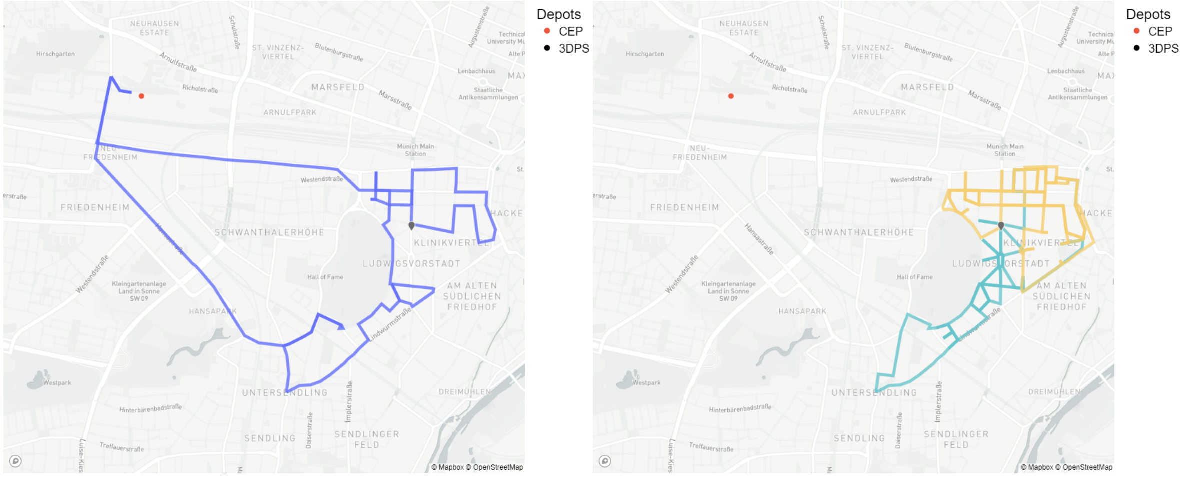
If substitution rates are higher ($20\%, 40\%$ and 80%), some of the classical delivery tours from CEP depots can be replaced completely. In the geographical simulation environment of Munich, many CEP depots are located far away from the city center (see Figure 17). Through the substitution of classical delivery tours from these depots, long approaches from outside the city center to an investigated postal code area within the city can be reduced. Furthermore, long returns from customers to outer CEP depots can be reduced. In most cases, 3D printing shops are located closer to their customers than CEP depots. This effect is particularly visible in scenario 2 where a dense infrastructure of 3D printing shops is assumed. The proximity of 3D printing shops leads to shorter approaches to customers and returns to the facilities. Thus, the substitution of classical delivery tours from CEP depots with delivery tours from 3D printing shops can lead to a reduction of total home delivery distances under certain circumstances.

The mentioned substitution effect between classical delivery tours from CEP depots and delivery tours from 3D printing shops can be demonstrated using the simulated postal code area 80336.



(a) All delivery tours (from CEP depots) in scenario 1

(b) Delivery tours from DHL depots in scenario 1



(c) Delivery tours from DHL depots in scenario 2-5

(d) Delivery tours from 3D printing shop in scenario 2-5

Figure 22 Visualization of resulting delivery tours for postal code area 80336

Figure 22 visualizes the delivery tours resulting from the simulation of home delivery in the postal code area 80336.

Figure 22a shows the delivery tours of scenario 1. All of these tours are operated from classical CEP depots, which are displayed as red circles. Figure 22b zooms in and shows the two delivery tours that are operated from DHL depots. DHL serves the most customers in scenario 1 and therefore has to carry out two tours (red and blue). Figure 22c displays the changes in delivery tours from DHL depots in scenario 2-5 which assumes a substitution rate of 80%. The figure shows that one of the two delivery tours is replaced. Thus, only one delivery tour has to be operated from the DHL depot in scenario 2-5. Figure 22d shows the new tours that emerge from distributed AM in local 3D printing shops. In total, two tours (yellow and turquoise) are carried out from the 3D printing shop in scenario 2-5.

The results presented in Table 14 indicate differences between the dense (2) and sparse (3) infrastructure scenario. In scenario 3, reductions in home delivery distances occur at higher substitution rates compared with scenario 2. In detail, sub-scenario 3-5, which assumes a substitution rate of 80%, is the only sub-scenario with a sparse infrastructure of 3D printing shops that reduces the mean difference in delivery distance compared with scenario 1. However, this difference is not statistically significant. The percentage reduction in the delivery distance for a substitution rate of 40% and 80% is stronger in scenario 2 where a dense infrastructure of 3D printing shops is assumed. Furthermore, the mean delivery distances of the sub-scenarios in scenario 2 are all shorter compared with their counterparts in scenario 3. Table 15 shows the percentage difference in mean delivery distance between scenario 3 and scenario 2 by comparing associated sub-scenarios. The application of a one-sample t-test shows that there are significant percentage differences in delivery distance of scenario 3 compared with scenario 2. At a substitution rate of 5%, the delivery distances in scenario 3 are on average approximately 2% longer compared with scenario 2. Similar differences occur at a substitution rate of 10%. Comparing sub-scenario 2-3 with sub-scenario 3-3 shows that the considered difference is approximately 1.9% on average. At a substitution rate of 40%, the percentage difference starts to grow. The mean of the percentage difference in delivery distance between sub-scenario 3-4 and sub-scenario 2-4 is approximately 3.6%. At a substitution rate of 80% the biggest difference appears. Thus, the delivery distance in sub-scenario 3-5 is on average approximately 6.2% longer compared with the distance of sub-scenario 2-5.

Scenario	**Percentage difference in delivery distance compared with corresponding sub-scenarios of scenario 2**†					
	N	Mean	SD	95% CI	t	Sig.
Sub-scenario 3-1	12	0.0191^{***}	0.0062	$[0.0149, 0.0233]$	10.2204	0.0000
Sub-scenario 3-2	12	0.0174^{***}	0.0060	$[0.0133, 0.0215]$	9.5563	0.0000
Sub-scenario 3-3	12	0.0187^{***}	0.0133	$[0.0098, 0.0277]$	4.6664	0.0009
Sub-scenario 3-4	12	0.0353^{***}	0.0301	$[0.0150, 0.0555]$	3.8818	0.0030
Sub-scenario 3-5	12	0.0618^{***}	0.0535	$[0.0259, 0.0980]$	3.8318	0.0033

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$

† Values rounded to four decimal places

Table 15 Percentage differences in delivery distance between scenario 3 and scenario 2

The comparisons in Table 14 and Table 15 show that the infrastructure of 3D printing shops affects delivery distances in the simulations. The investigated scenario with a dense infrastructure of 3D printing shops has significantly shorter delivery distances than the scenario with a sparse infrastructure of 3D printing shops. This tendency is valid and statistically significant for all sub-scenarios and all considered substitution rates.

The differences in delivery distance between scenario 3 and scenario 2 can be explained by the distances from 3D printing shops to customers. In the scenario, with a dense infrastructure of 3D printing shops, the proximity between 3D printing shops and customers is greater. Thus, the approaches to the customers and the returns to the shops after a delivery tour is completed are shorter. Table 14 also indicates that the variance and standard deviation of delivery distances are greater in scenario 3 than in scenario 2. This difference can also be explained by the number of 3D printing shops. In scenario 3, some simulated postal code areas are close to a 3D printing shop and some are far away. Thus, the distances of approaches and returns vary. In opposite, scenario 2 assumes that there is one 3D printing shop in the center of every postal code area. Thus, certain proximity from the 3D printing shops to the customers is given in every considered postal code area and the distances of approaches and returns have a smaller variance.

The findings of section 4.2 can be combined with the presented simulation results to estimate changes in home delivery fulfillment traffic due to the introduction of 3D printing shops in urban logistics. The estimation of printability potential shows that approximately 6% of the ordered and delivered products in B2C e-commerce can be 3D printed in the environment of a 3D printing shop with current technological capabilities (see Table 10). Thus, a substitution rate of 6% in the simulations seems to be realistic from a technological point of view. Assuming a substitution rate of approximately 6%, the introduction of distributed AM in local 3D printing shops would lead to an increase in home delivery distances and home delivery fulfillment traffic in Munich. In a scenario with a dense infrastructure of 3D printing shops, the increase in home delivery fulfillment traffic is most likely to be smaller compared with a scenario with a sparse infrastructure.

In conclusion, home delivery fulfillment traffic in Munich will likely increase, assuming realistic substitution rates for current technologies in distributed AM. However, given the assumptions, distributed AM in 3D printing shops can reduce home delivery fulfillment traffic in Munich at high substitution rates.

Despite the presented results, the introduction of distributed AM in urban logistics and urban 3D printing shops is likely to happen in the future, given economic conditions and customer demand. First shops that commercially offer B2C 3D printing services already exist occasionally. The presented results help to better understand the consequences of such an introduction. As home delivery fulfillment traffic is likely to increase, it is essential to discuss how 3D printing shops and their infrastructure has to be designed to limit this increase. Thus, introducing and operating the new concepts of distributed AM and 3D printing shops can be performed in a sustainable way. The simulation results are critically discussed in section 5.3. Recommendations for the implementation of distributed AM and 3D printing shops in urban logistics are presented in section 7.4.

5.3. Critical Discussion

The impacts of distributed AM on home delivery fulfillment traffic are examined using a scenario approach (see section 5.1). These scenarios have to be critically discussed. Overall, three scenarios are compared, which either consider dense, sparse or no infrastructure of 3D printing shops. The dense infrastructure scenario assumes one 3D printing shop in every postal code area of Munich. The sparse infrastructure scenario assumes four 3D printing shops throughout Munich. Due to long computation times for the simulations, examining more scenarios is impossible within the scope of this dissertation. Moreover, each scenario contains six sub-scenarios assuming different substitution rates ($0\%, 5\%, 10\%, 20\%, 40\%, 80\%$). Again, the long computation times do not allow further simulations with additional substitution rates.

The dense infrastructure scenario locates one 3D printing shop in the center of each postal code area in Munich using geocoding in GeoPy. The geocoding does not consider if the selected location is available and appropriate to build and operate a 3D printing shop. In reality, it is unlikely that a 3D printing shop can be set up in every selected location. As a simplification, it is assumed that every selected location is available and appropriate. The sparse infrastructure scenario locates four 3D printing shops in Munich using a p-median problem to minimize distances to customers. Population data in 500-meter grids is used as input for this optimization problem. Thus, only the center of each grid is considered a potential location for a 3D printing shop, limiting the optimization's geographical accuracy. The low resolution of the population grids is necessary to solve the p-median problem in reasonable computational time with the available computational power. Furthermore, the population data stems from the last census of the European Union, which was conducted in 2011. In future research, data from the next census should be used to find the optimized locations of 3D printing shops from today's point of view. For the sparse infrastructure scenario, four 3D printing shops are assumed to have sufficient capacity to serve potential customers throughout Munich. This assumption must be critically discussed if a sparse infrastructure scenario is intended to be implemented in cities. A dense infrastructure of 3D printing shops is more likely to meet the capacity requirements.

To evaluate the impacts of distributed AM on home delivery fulfillment traffic, home delivery tours of vans in Munich are simulated. This simulation approach uses optimization to minimize the overall delivery distance. As already explained in subsection 5.1.3, the optimization is conducted using the software Siemens XCargo. The CVRPTW is used as the optimization algorithm. The high computational complexity of the CVRPTW (NP-Hard) implies two limitations. First, the software uses a column generation algorithm as a heuristic for the CVRPTW to generate results in a reasonable amount of time. Second, the CVRPTW optimizes delivery tours on the postal code level. The optimization of delivery tours for the whole city of Munich would contain a huge number of customers represented by nodes. Thus, generating results for the whole city at once is impossible with the available computing power for the defined requirements. The optimization results of delivery tours could be slightly different from the actual tour distances since one delivery van could serve customers of different postal code areas in one tour. Therefore, future research should use higher computing power to simulate larger areas containing more customers in one simulation run to review the results of this dissertation. It is expected that distributed AM in 3D printing shops would sooner lead to reduced home delivery fulfillment traffic if all postal code areas in Munich were simultaneously simulated. The reason for this is the higher number of delivery tours that connect different postal code areas and can potentially be replaced. This hypothesis should be tested in further research.

In order to ensure the statistical significance of resulting differences in home delivery distance between the considered scenarios, the results are statistically evaluated. Before simulating a postal code area, a customer dataset is generated to determine the coordinates of the network nodes to be served. The basis for this generation is a dataset from the city of Munich containing all addresses. According to customer rates, a certain percentage of addresses in a considered postal code area is randomly selected for the dataset. The customer generation process is subject to two simplifications. First, only two different customer rates are considered. Second, the capacity of houses is not considered. Thus, an address of a single-family house has the same probability of serving as a customer location as the address of a populous apartment building. The capacities are only taken into account indirectly via the customer rates of postal code areas. These simplifications limit the results and can be addressed in further research.

The simulation approach assumes that parcels are delivered directly from 3D printing shops to customers. This is only possible if 3D printing shops have their own delivery van that is parked at the shop. If delivery vans first have to approach the 3D printing shop from other depots before driving the delivery tour, the traffic reduction potentials are less likely to be realized. For this reason, urban planners should consider parking spaces for delivery vehicles at 3D printing shops.

Furthermore, the simulation approach measures home delivery fulfillment traffic as the aggregate distance of home delivery tours of vans. However, other possibilities exist to measure home delivery fulfillment traffic, such as travel speed or congestion. The reduction potentials of home delivery fulfillment traffic due to distributed AM mainly occur at high substitution rates because long approaches from CEP depots outside the city center can be substituted. Still, 3D printing shops have to supply their customers in the city center, and delivery vans consume urban space while driving and parking during their delivery activities. For this reason, reducing delivery distance alone does not solve the congestion problem in the city center.

The described assumptions and simplifications limit the results of the simulation approach. Since the simulations of home delivery tours are performed on the street network of Munich, the results can not be automatically generalized. However, the presented methodology can be used to simulate and compare home delivery traffic in other cities. The presented results are subject to the assumptions described in subsection 5.1.1. Thus, the results are only valid if orders are delivered to customers exclusively by vans and if 3D printing shops directly deliver from their location using vans. Other means of freight transport are not considered in the simulations. Pick up options for customers are also not considered. The use of more sustainable means of freight transport is discussed in chapter 6.

Furthermore, there are no continuous results for all substitution rates. Therefore, it is impossible to identify a specific substitution rate above which the use of distributed AM leads to decreased home delivery distance and traffic. Such break-even points depend on multiple aspects, such as proximity to depots.

Besides the quantitative simulation results, the developed methodological approach also represents a result. The resulting approach is intended to be used in further research to simulate and examine different scenarios of home delivery fulfillment traffic. In this context, the approach can be improved by using better input data, especially in the process of generating a customer dataset.

6. Evaluating Impacts of Distributed Additive Manufacturing on the System of Urban Mobility and Urban Logistics

This chapter intends to examine and answer RQ3 (What effects does distributed additive manufacturing have on the system of urban mobility and logistics?). Chapter 5 investigates the impacts of distributed AM on urban home delivery fulfillment traffic. However, home delivery fulfillment traffic is only one component of urban traffic and urban mobility. Therefore, the impacts of distributed AM on the whole system of urban mobility and urban logistics are investigated in this chapter. The literature review in chapter 2 shows that the potentials of distributed AM in urban logistics are rarely examined from a systemic point of view. Furthermore, most of the existing literature examines passenger and freight transport separately. The research study in this chapter tries to close this research gap by modeling and evaluating the complex system of urban mobility and logistics, including distributed AM. The system model is intended to integrate urban passenger and freight transport. In this context, the system model should identify long-term effects of distributed AM, which can not be identified using simulations of home delivery fulfillment traffic. The main goal of the system modeling approach is to identify mechanisms, feedback loops, and potential rebound effects in advance of implementing distributed AM on a large scale in cities. This avoids undesired effects on traffic, environment, and urban health and supports the planning and design of distributed AM in cities.

Section 6.1 describes the methodological approach to answer the third research question. Section 6.2 presents the results, which are subsequently discussed in section 6.3.

6.1. Methodological Approach

Simulating and evaluating the impacts of distributed AM on home delivery traffic is an important task to identify the potential of additive manufacturing in logistics. However, home delivery traffic, which is simulated in chapter 5, represents only one component of the total traffic in an urban environment. To estimate the impacts of distributed AM on urban mobility and urban logistics, a systemic approach is required to understand and capture occurring effects and interactions on and within this complex system. This section presents the methodological approach to answer RQ3 (What effects does distributed additive manufacturing have on the system of urban mobility and logistics?).

6.1.1. Method Selection

The analysis of complex systems is the task of systems science. According to Hieronymi (2013), there are several definitions of systems science. A popular one comes from M'Pherson (1974, p. 229), who defines systems science as "the ordered arrangement of knowledge acquired from the study of systems in the observable world, together with the application of this knowledge to the design of man-made systems". According to Hieronymi (2013, p. 582), a main characteristic of systems science is transdisciplinarity. In contrast to interdisciplinary, transdisciplinarity "involves work in which new shared concepts are needed, and work that bridges theoretical and practical issues" (Hieronymi 2013, p. 582). A significant advantage of systems science is the consideration of complex interrelations between variables within the system instead of simple cause-effect relationships.

Similar to systems science, there are several definitions of a system. Hall (1956) provide a simple definition by describing a system as "a set of objects together with relationships between the objects and between their attributes" (Hall 1956, p. 18). Complex systems are defined by Vester (2019) and Cilliers (1998), among others. Accordingly, complex systems consist of many components which are in dynamic order with each other, interact with each other and form a causal network (Vester 2019, p. 25; Cilliers 1998, pp. 3-4). According to Vester (2019, p. 25), components of a complex system can represent subsystems.

Systems science features several methods for understanding, modeling, and simulating complex systems (Hieronymi 2013, p. 591). Forrester (1994) names and differentiates two of the most popular methods in systems science: System dynamics and systems thinking.

System Dynamics

System dynamics is a qualitative and quantitative approach to the analysis and simulation of complex systems. According to Duggan (2016), system dynamics models are capable of providing conditional, imprecise projections of dynamic behavior. Furthermore, system dynamics models "can accept the complexity, nonlinearity, and feedback loop structures that are inherent in social and physical systems" (Forrester 1994, p. 245). The recursive process of system dynamics according to Forrester (1994, p. 245) is displayed in Figure 23. The second step of the presented process requires specific information and data to formulate mathematical equations, representing the effects of variables on each other. According to Duggan (2016, p. 4), a system dynamics

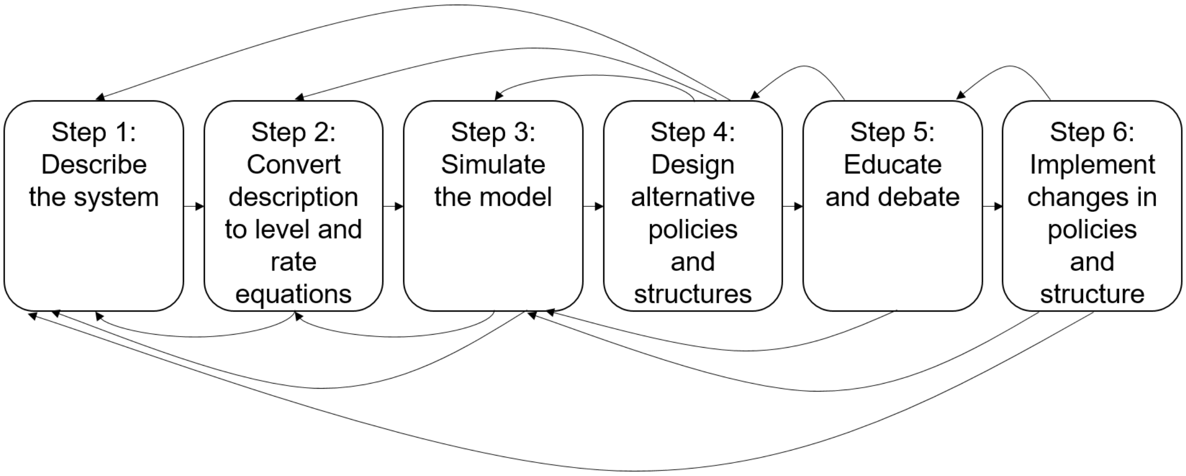
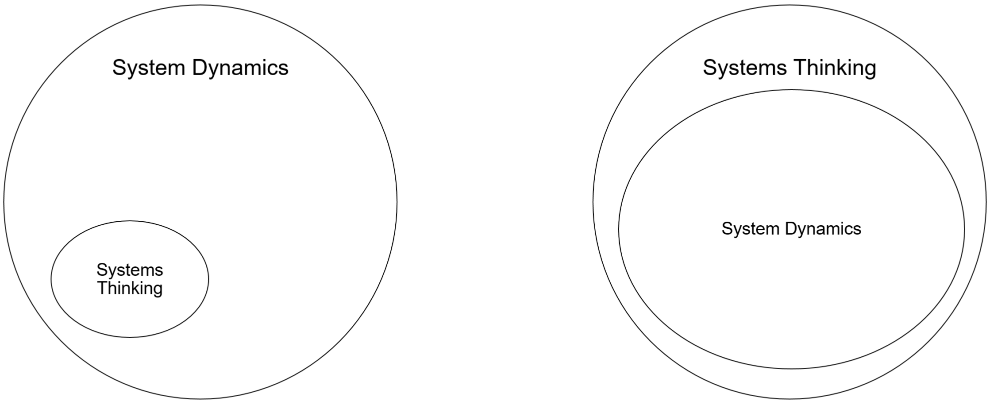


Figure 23 System dynamics process (own illustration based on Forrester 1994, p. 245)



(a) Relationship between systems thinking and system dynamics according to Forrester (1994) (b) Relationship between systems thinking and system dynamics according to Richmond (1994)

Figure 24 Relationship between systems thinking and system dynamics

model consists of stocks and flows. In this context, stocks can only change through input or output flows. System dynamics models are also capable of considering feedback loops (Duggan 2016, p. 14).

System dynamics models try to accurately represent reality by formulating mathematical equations for modeling effects within the system. On the one hand, this modeling approach has an advantage due to the accurate representation of effects. On the other hand, the approach may raise problems because certain aspects of complex systems can hardly be quantified using equations. Furthermore, system dynamics models usually require a good data foundation. If available data is limited, modeling a system using system dynamics may reach limits. Thus, understanding complex systems using system dynamics can be a challenge especially if the investigated system and related effects within this system are difficult to quantify. A method for overcoming the mentioned problems is systems thinking.

Systems Thinking/Sensitivity Model

Systems thinking is a more general concept, which is not uniquely defined in the literature. Forrester (1994, p. 248) considers systems thinking as a subset of system dynamics, which focuses on describing the system only (see step one in Figure 23). Richmond (1994) presents another definition of systems thinking. In contrast to Forrester (1994), Richmond (1994) sees system dynamics as a subset of systems thinking. He defines systems thinking as "the art and science of making reliable inferences about behavior by developing an increasingly deep understanding of underlying structure" (Richmond 1994, p. 193). In this context, systems thinking is seen as both a paradigm for a holistic systemic way of thinking as well as a method (Richmond 1994, p. 193). Figure 24 displays the relationship between systems thinking and system dynamics according to the differing definitions of Forrester (1994) and Richmond (1994). Sweeney & Sterman (2000, p. 2) note that the goal of systems thinking is the ability to represent and assess dynamic complexity. Specific skills for systems thinking according to Sweeney & Sterman (2000, p. 2) include the following:

- Understanding how behavior of systems is influenced by the interaction of its agents over time
- Discovering and representing feedback processes (both positive and negative) in systems
- Identifying relationships between variables in the system (e.g. stock and flow relationships)
- Recognizing delays and understanding related impacts
- Identifying nonlinearities
- Recognizing and challenging the boundaries of models

This dissertation shares the definition of Richmond (1994) by considering systems thinking as a paradigm that also includes a set of methods for analyzing, understanding, modeling, simulating, and improving systems.

One method that can be assigned to systems thinking in addition to system dynamics is Frederic Vester's sensitivity model. The sensitivity model is based on system dynamics but differs in some aspects. While system dynamics tries to quantitatively model relations between stocks and flows using complex equations, the sensitivity model tries to model relationships between variables or system components at a higher level using more nonspecific tendencies. In contrast to the system dynamics, the sensitivity model deliberately reduces the accuracy and uses fuzziness and a higher level of aggregation to recognize patterns in complex systems (Vester 2019, p. 57). This approach is denoted as fuzzy logic by Vester (2019). Furthermore, the sensitivity model is capable of including qualitative variables, which are also denoted as soft factors by Vester (2019). The sensitivity model supports systemic instead of linear thinking by considering feedback and control loops within systems. Vester (2019, pp. 110-111) views systems from a bio-cybernetic point of view as self-regulating organisms. According to Vester (2019, p. 110), the goal of every system is the maintenance and optimization of its own viability. Constant growth in itself should not be a goal of a system because it may endanger its viability. Thus, interventions or policies in a system should always be evaluated in terms of maintaining viability. As a result, unnoticed side effects or rebound effects can be identified (Vester 2019, p. 37).

The mentioned characteristics, especially fuzzy logic, make the sensitivity model very suitable for analyzing, understanding, modeling, simulating, and improving complex systems, which are difficult to quantify using mathematical equations. Furthermore, the sensitivity model is capable of combining quantitative and qualitative variables. The system of urban mobility and urban logistics is complex and difficult to quantify because it is very strongly influenced by the behavior of people. The shopping or mobility behavior of people is difficult to predict. Therefore, a system dynamics approach, which tries to exactly model this behavior using mathematical equations is very likely to lead to a misleading spurious accuracy. For this reason, the sensitivity model is chosen over other methods such as system dynamics for modeling the system of urban mobility and urban logistics and evaluating potential impacts of distributed AM. The process of the sensitivity model is further described in subsection 6.1.2.

6.1.2. Sensitivity Model Process according to Vester (2019)

The process of the sensitivity model has similarities to the systems dynamics process. Both structures are recursive. Thus, the sensitivity model provides regressive, self-correcting work steps. The recursive structure of the sensitivity model according to Vester (2019, p. 199) is depicted in Figure 25. In this illustration, dotted lines represent recursive connections between steps. The recursive structure offers advantages through the possibility of constant adaptation and improvement of the model. Thus, especially the system description and the set of variables can be revised after conducting later steps. Despite the recursive structure, the sensitivity model follows a basic order. The ordered steps are described in the following.

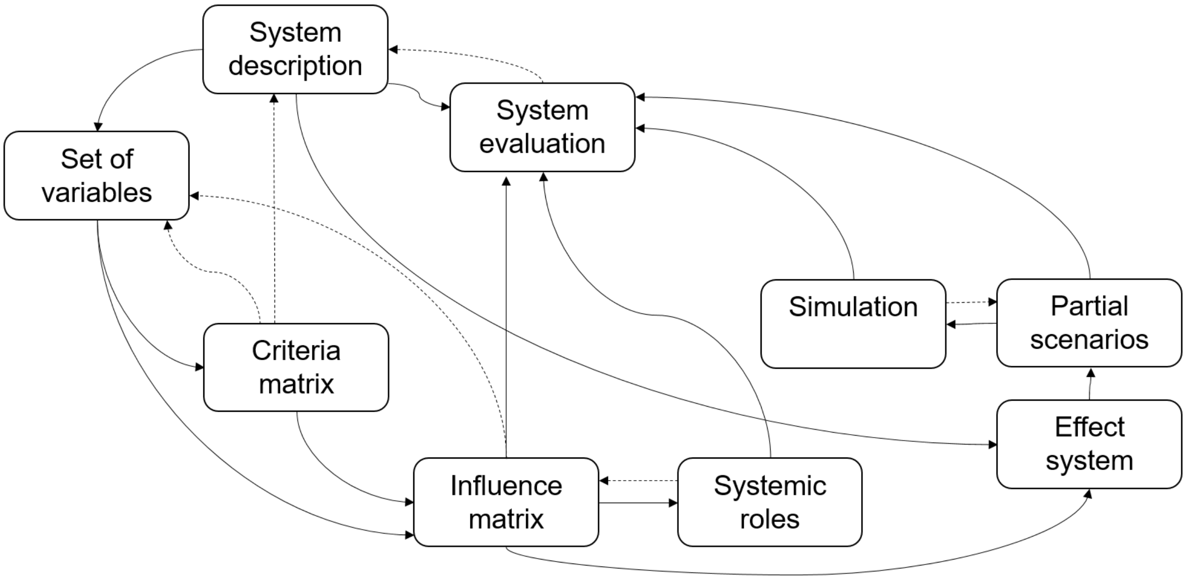


Figure 25 Sensitivity model process (own illustration based on Vester 2019, p. 199)

System Description

The sensitivity model usually starts with describing the investigated system. According to Vester (2019, p. 192), the investigated system should be described in the sense of the overarching goal of increasing viability. Another important aspect of this step is defining system boundaries. In many use cases of the sensitivity model, a graphical system description is developed. According to Vester (2019), it is useful to include many involved stakeholders in the system description especially if policies or interventions, which may have various effects on a considered system, have to be developed and planned. Thus, subgoals for analyzing, modeling, and simulating complex systems can be defined (Vester 2019, p. 192).

Set of Variables

For the examination of a complex system, it is essential to record system-relevant variables. Vester (2019, p. 213) defines variables as variable quantities representing nodes in the system. Cybernetics of the system can be derived from the interactions of these variables. Due to the fuzzy logic, variables can be both quantitative and qualitative in the sensitivity model. According to Vester (2019, p. 213), the terms and aspects collected in the system description can help to identify system-relevant variables. Furthermore, variables should have the same degree of aggregation. Thus, variables are prevented from being over- or underrepresented. To sufficiently describe a system, it is important to record enough but not too many variables to keep an overview of the system and to successfully handle the complexity using fuzzy logic. Vester (2019, pp. 213-214) recommends a size of 20-40 variables for the set. For the further process, it is useful to add a description to each identified variable. Thus, variables are clearly defined from the beginning. Furthermore, it is recommended to choose an indicator for each variable. Thus, the evaluation of influences on the variables is enabled. Similar to the step of the system description, it may be useful to involve experts and stakeholders in the process of identifying system-relevant variables. Thus, different perspectives can be considered.

Criteria Matrix

As mentioned, it is essential to limit the number of variables for handling and modeling complex systems. This limitation implies that only relevant variables are chosen for the set. The sensitivity model provides a method to check if the most important criteria of a complex and viable system are covered. This method is called criteria matrix. According to (Vester 2019, p. 218), the criteria matrix should help to prevent one-sided views on the system by checking if the set of variables fulfills certain predefined criteria. In detail, every variable is checked for the predefined criteria. The set of criteria consists of different spheres of life, and physical and dynamic criteria. A complete list of the considered criteria is presented in Table 16. Every criteria of Table 16 should be represented in the set of variables. Within the matrix, variables can either completely or partially cover criteria. According to (Vester 2019, p. 223), the criteria matrix is used to complement unconsidered variables but also to reduce the set of variables by unimportant or overrepresented aspects. Thus, the criteria matrix can have recursive effects on the set of variables.

Criteria	Description	Examples
Spheres of life		
Economics	Variables describing economic aspects	Jobs, sales
Stakeholders	Variables providing information on stakeholders	Population, market participants
Land use	Variables describing how space is used and where things happen	Residential-, commercial space
Human ecology	Variables describing the state of people	Health, culture, behavior
Environment	Variables describing environmental aspects and resources	Climate, emissions
Infrastructure	Variables describing internal structures and communication channels	Logistics, traffic, media
Regulations	Variables describing the intrinsic order	Laws, corporate hierarchy
Physical criteria		
Matter	Variables which have material character	Buildings, material
Energy	Variables which have energy character	Labor, energy
Information	Variables which have information and communication character	Media, decisions, image
Dynamic criteria		
Flow variable	Variables describing flows of matter, energy or information	Traffic, energy consumption
Structural variable	Variables describing structural aspects	Population density, transport network
Temporal dynamics	Variables changing over time while remaining localized	Products, number of employees
Spatial dynamics	Variables that vary from site to site at any given time	Traffic, structural funding
System relations		
Opens the system through input	Variables opening the system through input from outside	Import, national policies
Opens the system through input	Variables opening the system through output from inside	Export, tax
Controllable from inside	Variables controlled by inner decisions	Life quality, product quality
Controllable from outside	Variables controlled by outer decisions	Climate change, global trends

Table 16 Predefined criteria for the criteria matrix according to Vester (2019, pp. 218-223)

Influence Matrix

In the classical process of the sensitivity model, checking the criteria matrix is followed by the development of a so-called influence matrix. The influence matrix represents the effects of the system variables on each other. In detail, possible influences of every variable on every other variable are considered. According to Vester (2019, p. 226), it is important to only document direct influences between variables. Thus the overrepresentation of effects is avoided.

There are four possible evaluations of influences between variables, which can take values between 0 and 3 (Vester 2019, p. 227):

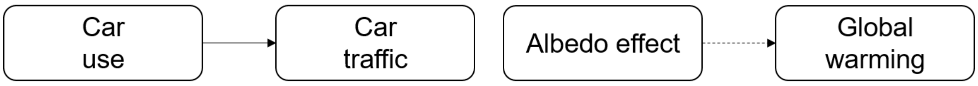
- 0: no or very weak effect
- 1: weak/underproportional effect; a strong change in variable A causes a weak change in variable B
- 2: medium/proportional effect; a change in variable A causes a similarly strong change in variable B
- 3: strong/overproportional effect; a slight change in variable A causes a strong change in variable B

The corresponding values of the effects between variables are documented in the matrix. Vester (2019, p. 232), recommends including affected stakeholders of the system to discuss the effects between variables in the influence matrix. Thus, different perspectives can be considered. If stakeholders are included in the process, Vester (2019) suggests the development of the so-called consensus matrix. In this matrix, the perspectives and opinions of all stakeholders are included and a consensus for every effect strength has to be found.

Systemic Roles

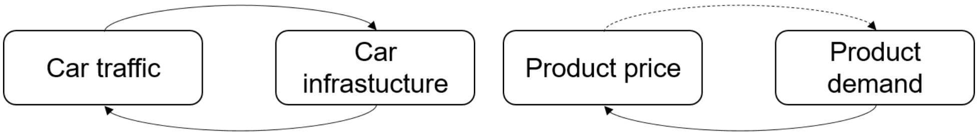
Based on the influence matrix, the systemic roles of the variables can be determined at a relatively early stage. Vester (2019, p. 234) categorizes variables into active, reactive, critical, and buffering variables. The categorization is mainly based on the number of inputs and outputs in the sensitivity model. In SNA (Social Network Analysis) and graph theory, these inputs and outputs are denoted as in-degree and out-degree. In a directed graph, the out-degree of a node represents the number of arcs reaching from the considered node to any other node of the network. The in-degree of a node analogously represents the number of arcs reaching from any other node to the considered node (Bang-Jensen 2010). The degree is defined as the sum of in- and out-degree in a directed network. This concept is well transferable to the sensitivity model as the influence matrix can be displayed as a directed network of variables (representing nodes) with weighted effects (representing weighted arcs or edges) on each other. In- and out-degrees of variables can be read from the influence matrix. In the sensitivity model, in-/out-degrees are represented by the sum of weighted effects reaching to/reaching from a considered variable.

In the sensitivity model, variables with a high degree are considered critical, while variables with



(a) Example of parallel effect

(b) Example of opposite effect



(c) Example of positive feedback loop

(d) Example of negative feedback loop

Figure 26 Examples of effects and feedback loops in thematically different effect systems

a low degree are considered buffering (Vester 2019, p. 234). Variables with a high out-degree and a low in-degree are considered active (Vester 2019, p. 234). Vice versa, variables with a high in-degree and a low out-degree are considered reactive (Vester 2019, p. 234). Furthermore, role categories can be combined. Thus, a variable can be critical-active or buffering-reactive for example. The sensitivity model contains software, which is capable of graphically representing the systemic roles of variables.

Effect System

In the classical process of the sensitivity model, determining systemic roles is followed by creating the so-called effect system. The effect system extends the influence matrix and poses a graphical representation of variables and effects in the system. According to Vester (2019, p. 239), the effect system is intended to identify and visualize effect chains and feedback. Thus, the effect system extends the influence matrix by representing reality in a multidimensional network (Vester 2019, p. 239). The determination of effects in the effect system differs from the determination in the influence matrix, where only effect strengths are considered. In contrast to the influence matrix, the directions of effects are determined in the effect system. There are two different effect directions, that can be displayed in the graphical representation of the effect system. In this context, parallel effects are represented by solid arrows. These parallel effects express rectified changes in related variables, meaning that an increase in the independent variable A leads to an increase in the dependent variable B and vice versa. Opposite effects between variables are represented by dotted arrows. These kinds of effects express opposite changes in related variables, meaning that an increase in the independent variable A leads to a decrease in the dependent variable B and vice versa. Besides single effects, feedback loops can be represented in the effect system (Vester 2019, p. 241). Feedback loops are present when two variables interact with each other. If the effects of two variables on each other are both parallel or both opposite, the relation is referred to as a positive or reinforcing feedback loop (Vester 2019, p. 241). If the two effects are different from each other, the relation is referred to as a negative or stabilizing feedback loop (Vester 2019, p. 241). Examples of parallel and opposite effects, as well as positive and negative feedback loops, are displayed in Figure 26. Positive feedback loops have a self-reinforcing characteristic after a small change is triggered. For this reason, positive feedback loops may endanger the balance of a system. In opposite to positive feedback, negative feedback loops have a buffering effect between two variables and pose a sign for self-regulation (Vester 2019, p. 242). A feedback loop can contain more than two variables. It typically starts with an effect from a certain variable. This effect triggers more direct and indirect effects on other variables. The loop ends with an effect on the variable that started the feedback loop. Thus, the loop is closed. According to Vester (2019), the number of feedback loops provides information on the system's behavior. A low number of feedback loops indicates that a system is dependent on outer influences, while a system with many feedback loops is likely to be independent (Vester 2019, p. 244). Long feedback loops with many variables indicate time-delayed feedback (Vester 2019, p. 244). According to Vester (2019, p. 244), the analysis of feedback loops helps to identify central variables in the system and inner processes as well as subsystems. Systems may contain a big number of feedback loops, which are difficult to identify without tools. Therefore, the software of the sensitivity model automatically generates a list of all feedback loops. Thus, important feedback loops can not only be identified but also easily analyzed.

Partial Scenarios

According to Vester (2019, p. 250), the sensitivity model provides the opportunity to consider and model parts of particular interest within the system as partial scenarios. Partial scenarios are created by isolating a selection of the original variables of the effect system. Furthermore, certain variables can be split into sub-variables and auxiliary variables can be implemented (Vester 2019, p. 250). The partial scenarios provide a lot of information on system behavior and the detailed mechanism of the cybernetics within the investigated system (Vester 2019, p. 250). According to Vester (2019, p. 251), partial scenarios should include between three and ten variables. Partial scenarios with a small number of variables are suitable for simulation (Vester 2019, p. 250). Vester (2019, pp. 251-252) recommends identifying partial scenarios with a pronounced cybernetic character. These scenarios typically contain feedback loops and can be denoted as organs of the system (Vester 2019, pp. 251-252). In particular, partial scenarios containing positive feedback loops are of interest as these represent critical aspects of the system.
According to Vester (2019, p. 252), partial scenarios can be used to test policies. These tests can be executed by changing a variable that is considered a control lever. After triggering the change of a variable, the resulting effects on the other variables of the partial scenario can be analyzed (Vester 2019, p. 252).

Simulation

The purpose of the simulation in the sensitivity model is to gain a deep understanding of system cybernetics (Vester 2019, p. 255). In particular, the effects of changes in variables on the whole system can be investigated. Vester (2019, p. 255) describes the simulation as an interactive tool for the investigation of connected dynamics. In this context, the simulation is suitable for the testing of policies. The simulation is supported by the sensitivity model software. Partial scenarios form the basis of simulations. Vester (2019, pp. 255-256) recommends only simulating partial scenarios instead of the whole system. The simulation of the whole system is usually too time-consuming and contradicts the fuzzy logic. The simulation is beneficial when it comes to a detailed analysis of system components. According to Vester (2019, p. 256), simulation helps to identify and analyze the effects of connected feedback loops as well as time-delayed effects.

The biggest challenge of simulations in the sensitivity model is the transfer of complex interactions of variables to a mathematical model (Vester 2019, p. 258). The sensitivity model software enables the representation of complex effects of one variable on another using a graphical curve instead of mathematical formulations. Thus, complex effects can be represented more comprehensibly. In contrast to the influence matrix, effect strengths are determined depending on the level of a variable. Thus, an example variable A can have a strong effect on variable B, if B is on a low level, and a weak effect, if variable B is on a high level. Initial levels of variables can be determined on a graphical scale in the sensitivity model software. Besides determining graphical functions for effects and initial levels of variables, the user has to determine the simulation time as well as the order of variables and their effects (Vester 2019, pp. 259-260). According to Vester (2019, pp. 261-262), the simulation is executed time step by time step. The resulting changes in variables during the time of simulation are graphically represented in the software.

The simulation in the sensitivity model has limitations. The graphical representation of effects between two variables is indeed less quantitative compared with system dynamics. Still, this representation as well as determining initial levels of variables requires a lot of assumptions. The simulation results are very sensitive to these assumptions. Thus, the predictive quality of simulations is limited in many cases. According to Vester (2019, p. 256), the predictions of simulations are only applicable for short time horizons. Due to the mentioned limitations, the simulation is often neglected in the sensitivity model.

System Evaluation

The system evaluation forms the last step of the sensitivity model. The results of the system description, influence matrix, systemic roles, partial scenarios and simulations can be used to support the evaluation. The system evaluation is a suitable task for answering the examined research question.

6.1.3. Modified Sensitivity Model Process

The sensitivity model process according to Vester (2019), represents a basic framework for modeling, analyzing and simulating complex systems. Figure 25 shows, that the process can be run through recursively. For this dissertation, not every recursive step in the classical process was taken and some methodological aspects of the sensitivity model were adjusted and modified. This section is intended to present the modified sensitivity model process, which was used as a method for answering RQ3 (What effects does distributed additive manufacturing have on the system of urban mobility and logistics?). The modified process is depicted as BPMN diagram in Figure 27. The depicted process starts similarly to the classical sensitivity model process according to Vester (2019) by *describing the system*. After the system description, a first *set of variables*

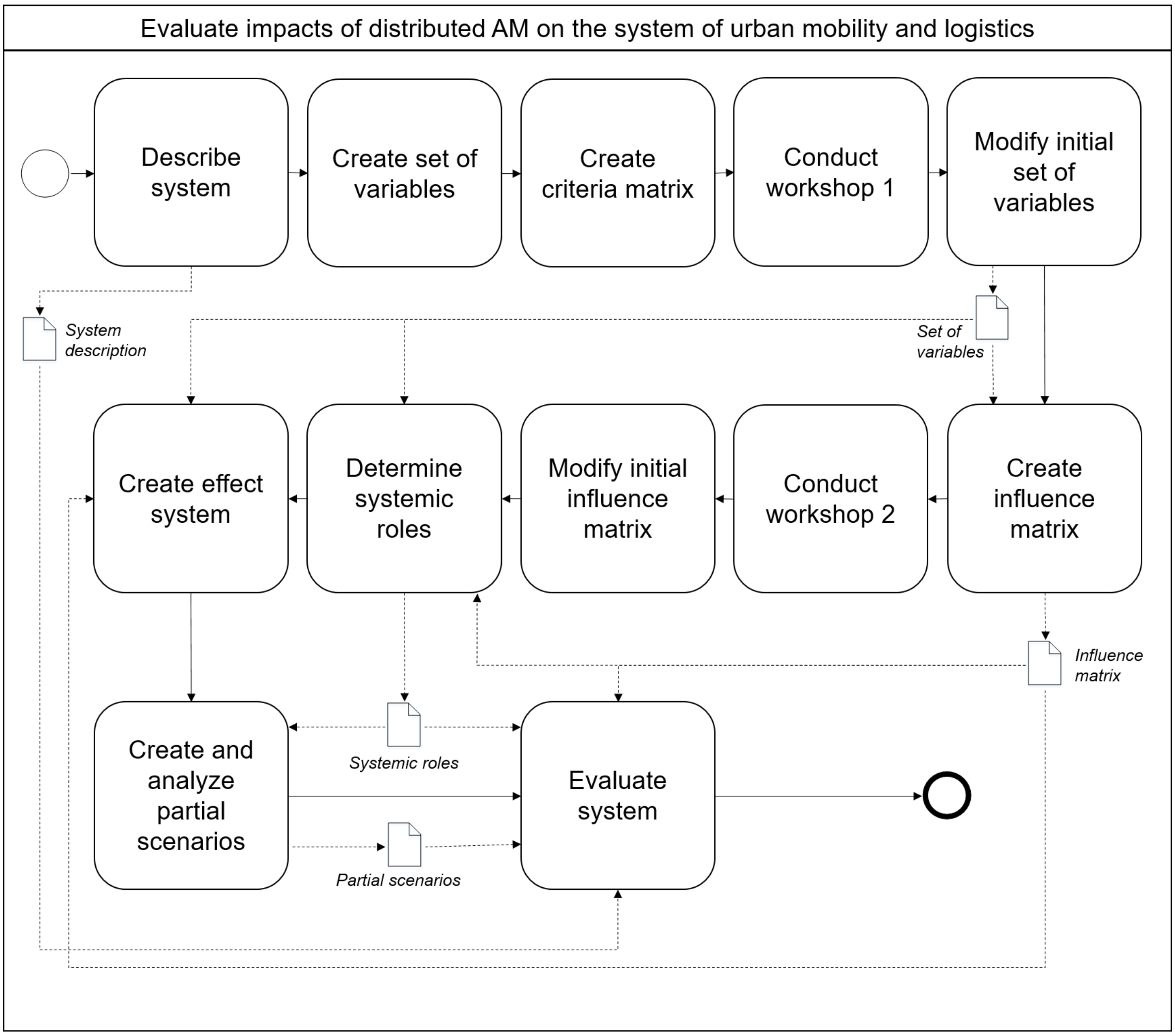


Figure 27 Methodological approach for evaluating impacts of distributed AM on the system of urban mobility and logistics using a modified process of the sensitivity model (sub-process of Figure 11)

and a belonging *criteria matrix* were created in the course of the Ph.D. project. Subsequently, the first difference to the classical sensitivity model process occurs. A *first workshop* is conducted to consolidate and modify the initial set of variables. After this recursive step, the process continues with the classical step of *creating the influence matrix*. Similar to the set of variables, the created influence matrix is reviewed and modified by conducting a *second workshop* with experts. After adjusting the influence matrix, the process continues with the *determination of systemic roles*. Subsequently, an *effect system* is created. Then, *partial scenarios* are created and analyzed. The process concludes with a *system evaluation*, which uses interim results from previous steps as inputs.

The comparison of the processes in Figure 25 and Figure 27 shows, that there are a lot of similarities but also some modifications such as the addition of workshops. These modifications are described and explained in the following.

Modification 1: Workshops

Following the recommendation of Vester (2019) to involve stakeholders or experts in the sensitivity model process, a *first workshop* was conducted to review the created set of variables for relevance and system representativeness. The first workshop was conducted with 12 students of TUM (Technical University of Munich) as part of the lecture Integrated Land-use and Transportation Modeling. In the workshop, the participants were divided into three groups and each group was provided with a brief system description. The task of each group was to create a set of variables to represent the system of urban mobility and logistics including AM based on the given system description. The groups had no information on the original set of variables, which was created before. Thus, the groups were not biased in the process of finding a set of variables. As a result, three new sets of variables were generated.

As a recursive step, the students' sets of variables are compared to the original set. Through this comparison, overlaps and variables, mentioned multiple times, can be identified. These variables of the original set are consolidated. The comparison also enables the identification of variables, which are developed by the student groups but do not exist in the original set of variables. If this is the case, it is checked if the missing variables are relevant and already represented by another variable of the original set. Subsequently, relevant variables are added and the original set of variables is modified. The recursive step, which is represented as the first loop in Figure 27, also implies a modification of the criteria matrix.

As described in subsection 6.1.2, the effect strengths of every variable on every other variable have to be determined on a scale from zero to three in order to create the influence matrix. Determining effect strengths runs the risk of being subjective if done by only one actor. Therefore, it is useful to justify and check the plausibility of the decisions using the research of academic literature.

To further avoid subjectivity and biases in the influence matrix, a *second workshop* is conducted. The participants of this second workshop were experts from academia and practice. The expert panel included three city and traffic planners working for the cities of Munich, Hamburg, and Ulm, one project manager working for a logistics company, as well as two professors at the University of Applied Science Neu-Ulm and TUM working in the fields of logistics and urban mobility. Experts from various cities were deliberately selected to include different perspectives in the influence matrix and to generalize the results as much as possible. During the workshop, effect strengths were discussed in the panel. The goal was to find a consensus in the panel on the discussed effect strengths. The expert panel had no information on the initial influence matrix. Thus, a bias in the process of determining effect strengths can be ruled out as the expert panel was only provided with a brief system description and the investigated variables. As an influence matrix contains a lot of potential effects between variables ($n^2 - n$ potential effects for n variables), it was not possible to discuss all effects in the limited time of a workshop. For this reason, key effects in the system, as well as effects that are not evident, and effects that were difficult to determine during the process of creating the initial influence matrix, were identified and prepared for discussion by the expert panel. The effect strengths determined by the expert panel were subsequently compared with the initial influence matrix. Thus, effect strengths that had the same value in both versions were consolidated. If the effect strengths of the expert panel differed from the initial influence matrix, the panel once again discussed the effect strengths and found a final consensus for the value. Thus, a consensus matrix in the sense of Vester (2019) is created. In a recursive step, the initial influence matrix is modified according to the findings of the second workshop.

Modification 2: Extended Systemic Roles

For this dissertation, the classical systemic roles according to Vester (2019) are extended to gain deeper insights into the behavior of variables. In the classical step according to Vester (2019), the in-degree and out-degree are determined for every variable. From these indicators, a Q-value and a P-value are derived for every variable. In this context, the Q-value represents the quotient of out- and in-degree and the P-value represents the product of in- and out-degree. In SNA, in- and out-degree are indicators for the centrality of nodes in a network. In this context, these indicators belong to a group of centrality measures and are also referred to as in-degree centrality C_{in-D} and out-degree centrality C_{out-D}. Mathematical formulations for in- and out-degree according to Wasserman & Faust (2009, p. 178) are presented in Equation 6.1 and Equation 6.2.

$$C_{in-D}(n_i) = \sum_{j=1}^{g} x_{ji} \tag{6.1}$$

$$C_{out-D}(n_i) = \sum_{j=1}^{g} x_{ij} \tag{6.2}$$

In these formulations, n_i represents the considered node i for which in- or out-degree are calculated. g represents the total number of nodes in the network and x_{ji} represents the arc or edge from node j to node i. If there is no existing arc from node j to node i, x_{ji} equals 0. Else, x_{ji} equals 1 or the weight of the arc, if the considered network is a weighted network.
Based on these formulations the Q-value and P-value according to Vester (2019) are calculated as follows:

$$Q(n_i) = \frac{C_{out-D}(n_i)}{C_{in-D}(n_i)} \tag{6.3}$$

$$P(n_i) = C_{in-D}(n_i) \cdot C_{out-D}(n_i) \tag{6.4}$$

The expressive power of Q-values and P-values in the classical sensitivity model according to Vester (2019) is limited because only the degree centrality is considered for the determination of systemic roles. Some centrality measures of SNA and graph theory can be applied to the determination of systemic role in the sensitivity model. Thus, the sensitivity model is further developed in this dissertation and systemic roles are described and analyzed in a more differentiated manner. Certain centrality measures provide additional information on systemic roles of variables in the system. Thus, a deeper understanding of the behavior of variables can be gained. Centrality measures that are additionally considered to extend the analysis of systemic roles are described and explained in the following.

Closeness centrality is a measure representing the closeness of a considered node to all other reachable nodes within a network. The normalized closeness centrality is defined as the reciprocal of the average shortest path distance from a considered node to all other reachable nodes. A mathematical formulation of the normalized closeness centrality C'_C according to Freeman (1978, p. 226) is presented in Equation 6.5.

$$C'_C(n_i) = \frac{g-1}{\sum_{j=1,j\neq i}^{g} d(n_j, n_i)} \tag{6.5}$$

In this formulation, g represents the number of nodes in the system and $d(n_j, n_j)$ represents the distance of node j to node i. In directed networks, Equation 6.5 is not defined unless the directed network is strongly connected (Wasserman & Faust 2009, p. 200). If a network is disconnected, which means that its graph has more than one connected component, or directed, it is useful to adjust the equation for closeness centrality. Otherwise, isolated nodes may have a high closeness centrality although these nodes are not even reachable from some other nodes. Furthermore, using unadjusted closeness centrality for unconnected directed graphs can lead to distances of ∞ (Wasserman & Faust 2009, p. 200). Using the adjusted closeness centrality, these undesired effects in disconnected networks are avoided. To adjust closeness centrality for unconnected or directed networks, the so-called influence range of a node n_i is considered. The influence range of n_i contains all reachable nodes from the considered node without n_i itself (Wasserman & Faust 2009, p. 200). In this context, J_i is defined as the number of reachable nodes in the influence range from node n_i (Wasserman & Faust 2009, p. 200). The mathematical formulation of the adjusted closeness centrality $C^*_C(n_i)$ according to Wasserman & Faust (2009, p. 201) is presented in Equation 6.6.

$$C^*_C(n_i) = \frac{J_i/g-1}{\sum_{j=1,j\neq i}^{g} d(n_j, n_i)/J_i} \tag{6.6}$$

As mentioned, the closeness centrality can be applied to both directed and undirected networks. Furthermore, closeness centrality can consider the weights of edges between nodes. In the context of closeness, edge weights most often represent distances between nodes.

In a classical social network, closeness centrality can be interpreted as an indicator of how directly a person is connected to all other persons in the network. In this context, nodes with a high closeness centrality are connected to the other nodes via few intermediate nodes. Vice versa, nodes with a low closeness centrality are less directly connected to all other nodes. In a weighted street network, a high closeness centrality is an indicator of low distances to all other nodes and high accessibility.

Due to its properties, closeness centrality is well transferable and applicable to the determination of systemic roles in the sensitivity model. Especially since the influence matrix can be displayed as a network with nodes representing variables and directed edges representing effects/influences. Thus, the influence matrix represents a directed network. Since closeness centrality evaluates the shortest path distances in the system, edge weights, which represent effect strengths in the sensitivity model, should not be considered. Thus, closeness centrality is applied to a directed and unweighted network. In the context of the sensitivity model, closeness centrality can be interpreted as the immediacy with which variables affect or are affected by the system. Closeness centrality in directed networks is based on the average shortest path distance from every other node to the investigated node (see Equation 6.5). This measure provides vulnerable information for the determination of systemic roles in the sensitivity model based on incoming edges. Vice versa, the average shortest path distance from an investigated node to all other nodes (based on outgoing edges) is of interest in the context of the sensitivity model. In academic literature, there is no clear separation between closeness centrality in a directed network based on outgoing and incoming edges. However, (Wasserman & Faust 2009, p. 200) state, that such a separation is essential as both variants may have different results. Thus, closeness centrality is divided in this dissertation. Left closeness centrality $C_{Cl}(n_i)$ and right closeness centrality $C_{Cr}(n_i)$ are defined and differentiated. Left closeness centrality is based on incoming edges only. Thus, the measure is based on the average shortest path distance from every other node to the investigated node. The mathematical formulation of the left closeness centrality is equal to Equation 6.5. A mathematical formulation of the left closeness centrality adjusted to direct and unconnected networks $C^*_{Cl}(n_i)$ is presented in Equation 6.7.

$$C^*_{Cl}(n_i) = \frac{J_i/g-1}{\sum_{j=1,j\neq i}^{g} d(n_j,n_i)/J_i} \tag{6.7}$$

In contrast to left closeness centrality, right closeness centrality is based on outgoing edges. Thus, the measure is based on the average shortest path distance from an investigated node to every other node in the network. The mathematical formulation of the adjusted right closeness centrality is presented in Equation 6.8

$$C^*_{Cr}(n_i) = \frac{J_i/g-1}{\sum_{j=1,j\neq i}^{g} d(n_i,n_j)/J_i} \tag{6.8}$$

Left and right closeness centrality support the interpretation of systemic roles in the sensitivity model. Variables with high left closeness centrality (based on incoming edges) are likely to be more directly affected after changes in the system are triggered compared with variables with a lower left closeness centrality. Furthermore, variables with high left closeness centrality are likely to react faster after changes in the system are triggered. Vice versa, introduced policies are likely to only show effects on variables with low left closeness centrality after a certain time.

Variables with high right closeness centrality (based on outgoing edges) are likely to influence all other variables in the system more directly compared with variables with low right closeness centrality. Thus, policies on variables with high right closeness centrality usually imply fast and direct effects on all other variables in the system. Closeness centrality is a valuable measure for the determination and interpretation of systemic roles since decision-makers can use it to predict the impact immediacy of potential policies. The traditional analysis of systemic roles in the sensitivity model does not provide this kind of information.

Eigenvector centrality is another centrality measure of SNA, that can complement in- and out-degree centrality in the sensitivity model. In the classical sensitivity model according to Vester (2019), variables are classified as active or passive based on in-degree centrality and out-degree centrality only. Thus, this classification only considers direct (first-degree) effects from or on a variable. To conduct a more advanced analysis of activity and passivity, it is essential to consider indirect effects as well. The importance of considering indirect effects is illustrated in the following example.

A variable V may have a high out-degree centrality meaning that V directly affects many other nodes with high effect strengths. If the affected neighbors of V each have a low out-degree centrality, the effects of V fall flat and are transmitted to the system only to a small extent. Still, V would be classified as a very active variable in the classical role determination step of the sensitivity model according to Vester (2019).

To avoid this bias, higher degree effects from and on variables are examined using eigenvector centrality. Eigenvector centrality was introduced by Bonacich (1987). A modified definition of eigenvector centrality C_E according to Bonacich (1987, p. 1172) is presented in Equation 6.9.

$$\lambda C_E(n_i) = \sum_{j=1, j\neq i}^{g} x_{ij} C_E(n_j) \tag{6.9}$$

In Equation 6.9, λ represents a required constant so that the equation has a nonzero solution. Once again, g represents the number of nodes in the network and x_{ij} represents an arc or edge from node n_i to node n_j. If there is no existing arc from node i to node j, x_{ji} equals 0. Else, x_{ij} equals 1 or the weight of the arc, if the considered network is a weighted network.

In matrix notation, eigenvector centrality can be derived as follows (Bonacich 1987, p. 1172).

$$\lambda e = Ae \tag{6.10}$$

In Equation 6.10, A represents an adjacency matrix of a graph or network with the eigenvalue λ and the eigenvector e. The eigenvector centrality C_E for node n_i is the i-th element of the vector e.

The equations show, that the eigenvector centrality of a node depends on the eigenvector centrality of its neighbors. For this reason, eigenvector centrality should be calculated recursively in several steps. Most algorithms use a recursive power iteration method for calculating eigenvector centrality in a network. Equation 6.9 implies that the centrality of a node depends on the centrality of its direct neighbors.

Similar to closeness centrality, eigenvector centrality can be calculated in two different variants for directed networks. Left eigenvector centrality C_{El} is based on incoming edges only. Vice versa, right eigenvector centrality C_{Er}, is based on outgoing edges. Most algorithms use the left eigenvector centrality as a standard. To calculate the right eigenvector centrality, an underlying adjacency matrix can simply be inverted. Left and right eigenvector centrality are defined as follows for the further course of this dissertation (see Equation 6.11 and Equation 6.12).

$$\lambda C_{El}(n_i) = \sum_{j=1, j\neq i}^{g} x_{ji} C_{El}(n_j) \tag{6.11}$$

$$\lambda C_{Er}(n_i) = \sum_{j=1, j\neq i}^{g} x_{ij} C_{Er}(n_j) \tag{6.12}$$

Eigenvector centrality is well applicable to the determination of systemic roles in the sensitivity model. Besides the classical degree centrality measures, the measure poses an advanced option for determining if variables are active or passive. Variables with a relatively high eigenvector centrality strongly influence the other variables not only directly but also indirectly. Vice versa, variables with a relatively low eigenvector centrality are strongly influenced by other variables not only directly but also indirectly. Since the influence matrix uses effect strengths, it is appropriate to use these effect strengths as edge weights. Thus, eigenvector centrality is calculated for the variables in a directed and weighted network.

SNA contains further centrality measures, such as betweenness centrality. However, these further measures usually rely on weighted graphs or networks that include distances between nodes. The network in the sensitivity model does not include distances. Furthermore, the betweenness centrality does not provide useful information for the use case. For these reasons, only closeness and eigenvector centrality are applied to determine the systemic roles of variables.

The goal of extending the measures used to determine systemic roles in the sensitivity model is to better understand variable behavior. The use of advanced centrality measures provides more information on variables compared with the classical determination of systemic roles in the sensitivity model according to Vester (2019). This supports both the selection of relevant variables for partial scenarios and the evaluation of the system.

Modification 3: Abandonment of the Simulation

As already described in subsection 6.1.2, the simulation in the sensitivity model has limitations and highly depends on assumptions for starting values and functions of variables and effects. Furthermore, predictions of the simulations are only applicable for short time horizons (Vester 2019, p. 256). The investigated system of urban mobility and logistics contains many qualitative variables. For these variables, it is difficult to provide a quantification of starting values. Furthermore, effect functions that go beyond the evaluation of effect strengths on a scale from zero to three are both difficult to define and likely to have spurious accuracy. Thus, the simulation in the sensitivity model faces similar problems to system dynamics models. Due to the high dependency on subjective assumptions for starting values and effect functions the simulation is not performed and considered in the modified sensitivity model process for this dissertation. Thus, the system is evaluated based on systemic roles, the influence matrix as well as the partial scenarios.

6.2. Results

This section is intended to present the results of evaluating impacts of distributed AM on the system of urban mobility and urban logistics. As mentioned, home delivery traffic, which was quantitatively simulated and evaluated in chapter 5, is only one component of urban traffic. Therefore, a systemic approach is required to evaluate the impacts of distributed AM on the whole system of urban mobility and urban logistics. Since this system is complex, a qualitative approach is selected to answer RQ3 (What effects does distributed additive manufacturing have on the system of urban mobility and logistics?).

The methodological approach for evaluating systemic impacts of distributed AM is displayed in Figure 27 and derived from the classical sensitivity model of Vester (2019). The following results are structured according to the steps of the modified sensitivity model.

6.2.1. System Description

The investigated system contains aspects of urban mobility and urban logistics according to their definitions in section 2.1. In the context of these definitions, mobility is a generic term that encompasses traffic, transport, and accessibility. These aspects are also part of the investigated system. According to the definition in section 2.1, logistics not only represents the planning, management, coordination, implementation, and control of flows of information and goods but also contains the intention and purpose of transporting freight and information. Thus, the investigated system also contains important aspects of logistics including shopping and purchasing behavior. Furthermore, the investigated system focuses on urban areas. The system explicitly contains the opportunity to use distributed AM in urban logistics. This is a prerequisite to evaluating the impacts of distributed AM on the investigated system. Due to fuzzy logic and a high degree of abstraction, the investigated system may represent any urban area. Nevertheless, the urban area of Munich is once again chosen as an example and object of investigation. The use of one concrete urban area supports the determination of effects and effect strengths.

Logistics activities and freight transport outside the urban area are outside the system boundaries and therefore not considered. Other emerging technologies in urban logistics except for 3DP/AM, which may occur in the future, are also not considered and are outside the system boundaries. The system description is clarified by the set of variables.

6.2.2. Set of Variables

To create an appropriate set of variables for the described system of urban mobility and logistics, four leading questions were developed and answered:

1. How do people and goods move in an urban environment?
2. Which factors control how people and goods move in an urban environment?
3. How do people shop in an urban environment?
4. Which factors control how people shop in an urban environment?

As mentioned in subsection 6.1.2, a set of variables can be created in several iterations. During the Ph.D. project, several iterations were passed through by the author. The last iteration used the first workshop described in subsection 6.1.3 to create the final version of the set of variables. This final version is presented in Table 17 and contains a description of the variables.

Variable	Description of variable	Measurement option
Accessibility via car	Relative accessibility of destinations in the system using cars	Accessibility rate
Accessibility via bus	Relative accessibility of destinations in the system using bus	Accessibility rate
Accessibility via metro/train	Relative accessibility of destinations in the system using metro/train	Accessibility rate
Accessibility via (e-)bike	Relative accessibility of destinations in the system using (e-)bike including walking	Accessibility rate
Car use	Extent of car use on streets in the system	Distance traveled daily by car
Bus use	Extent of bus use on streets in the system	Number of daily trips by bus
Metro/train use	Extent of metro/train use on streets in the system	Number of daily trips by metro/train
(E-)bike use	Extent of (e-)bike use and walking on streets in the system	Distance traveled daily by (e-)bike and walking
Truck use	Extent of truck use on streets in the system. Trucks are defined as delivery vehicles with a total weight over 3.5 tons. Trucks can be used for B2B delivery only	Distance traveled daily by truck
Van use	Extent of van use on streets in the system. Vans are defined as delivery vehicles with a total weight up to 3.5 tons. Vans can be used for both B2B and B2C delivery	Distance traveled daily by van
Street traffic	Traffic volume on streets in the system excluding sidewalk and bike lane traffic	Distance traveled daily on streets by any vehicle divided by daily average travel speed
Offline shopping volume	Volume of offline shopping transactions in the system. Offline shopping is defined as shopping in physical stores excluding 3D printing shops	Number of daily transactions

Online shopping volume	Volume of online shopping transactions in the system excluding transactions of data for 3D printing	Number of daily transactions
3D home printing volume	Volume of 3D home printing transactions in the system	Number of daily prints
3D shop printing volume	Volume of orders in 3D printing shops	Number of daily prints
Sustainability awareness	Sustainability awareness of politics, economy and society in the system	Likert scale where 0 represents no sustainability awareness at all and 5 represents a very high sustainability awareness
Emissions (local)	Extent of produced local emissions (particles & noise) in the system	Amount of local emissions emitted daily
Emissions (global)	Extent of produced global emissions (CO_2) in the system	Amount of global emissions emitted daily
Service quality of offline shopping	Relative service quality of offline shopping containing accessibility, product range, costs and shopping experience	Likert scale where 0 represents no service quality at all and 5 represents a very high service quality
Service quality of online shopping	Relative service quality of online shopping containing accessibility, product range, costs and shopping experience	Likert scale where 0 represents no service quality at all and 5 represents a very high service quality
Service quality of 3D home printing	Relative service quality of 3D home printing containing accessibility, product range, costs and shopping experience	Likert scale where 0 represents no service quality at all and 5 represents a very high service quality
Service quality of 3D shop printing	Relative service quality of 3D shop printing containing accessibility, product range, costs and shopping experience	Likert scale where 0 represents no service quality at all and 5 represents a very high service quality

Table 17 Set of variables for the system

Table 17 not only contains a description of variables but also options for their measurements. The sensitivity model does not require an quantitative measurement of the identified variables. Nevertheless, the determination of measurements is helpful to better understand effects and effect directions in the further course of the sensitivity model. One proposed measurement for accessibility is the accessibility rate. A mathematical equation for this rate according to Hansen (1959) is presented in the following.

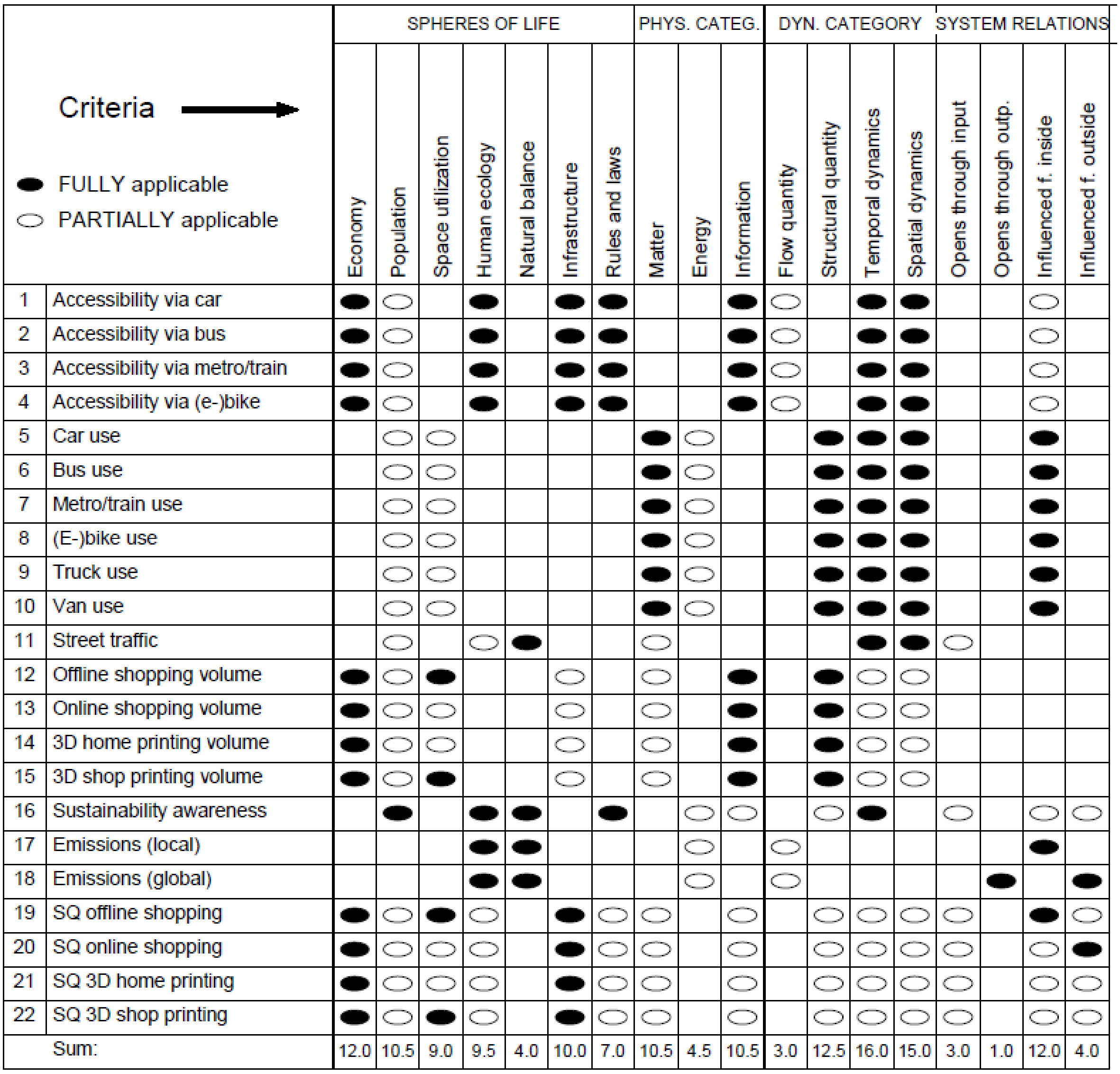
$$A_i = \sum_j D_j f(c_{ij}) \tag{6.13}$$

In Equation 6.13, A_i represents the accessibility from a certain location i. D_j represents the activity destinations at location j and $f(c_{ij})$ represents a function of generalized costs of a trip from location i to all other locations j. In this context, the costs c_{ij} include travel time, costs and comfort.

The set of variables is created in an iterative process using a workshop with experts for consolidation. An initial version of the set of variables is presented in the appendix (Table 23).

6.2.3. Criteria Matrix

According to Vester (2019, p. 218), the criteria matrix should check if the set of variables fulfills



Criteria →

● FULLY applicable
○ PARTIALLY applicable

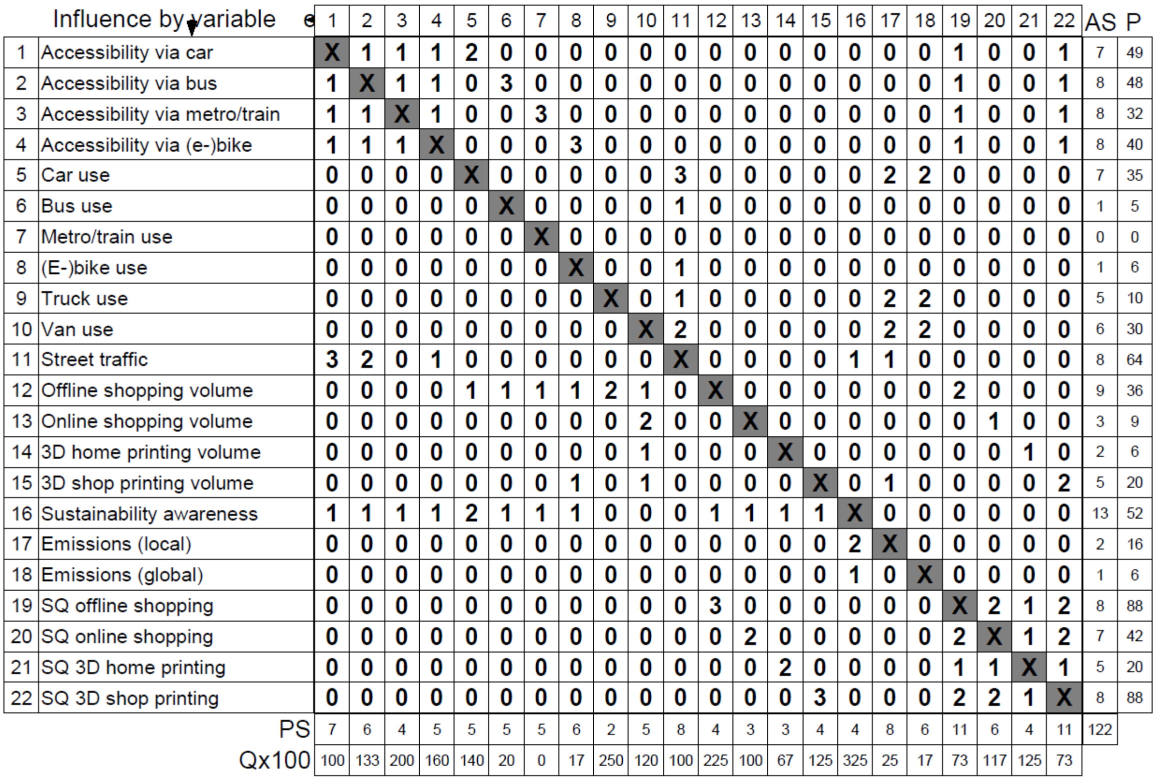
		SPHERES OF LIFE							PHYS. CATEG.			DYN. CATEGORY				SYSTEM RELATIONS			
		Economy	Population	Space utilization	Human ecology	Natural balance	Infrastructure	Rules and laws	Matter	Energy	Information	Flow quantity	Structural quantity	Temporal dynamics	Spatial dynamics	Opens through input	Opens through outp.	Influenced f. inside	Influenced f. outside
1	Accessibility via car	●	○		●		●	●			●	○		●	●			○	
2	Accessibility via bus	●	○		●		●	●			●	○		●	●			○	
3	Accessibility via metro/train	●	○		●		●	●			●	○		●	●			○	
4	Accessibility via (e-)bike	●	○		●		●	●			●	○		●	●			○	
5	Car use		○	○					●	○			●	●	●			●	
6	Bus use		○	○					●	○			●	●	●			●	
7	Metro/train use		○	○					●	○			●	●	●			●	
8	(E-)bike use		○	○					●	○			●	●	●			●	
9	Truck use		○	○					●	○			●	●	●			●	
10	Van use		○	○					●	○			●	●	●			●	
11	Street traffic		○		○	●			○					●	●	○			
12	Offline shopping volume	●	○	●			○		○		●		●	○	○				
13	Online shopping volume	●	○	○			○		○		●		●	○	○				
14	3D home printing volume	●	○	○			○		○		●		●	○	○				
15	3D shop printing volume	●	○	●			○		○		●		●	○	○				
16	Sustainability awareness		●		●	●		●		○	○		○	●		○		○	○
17	Emissions (local)				●	●				○		○						●	
18	Emissions (global)				●	●				○		○					●		●
19	SQ offline shopping	●	○	●	○		●	○	○		○		○	○	○	○		●	○
20	SQ online shopping	●	○	○	○		●	○	○		○		○	○	○	○		○	●
21	SQ 3D home printing	●	○	○	○		●	○	○		○		○	○	○	○		○	○
22	SQ 3D shop printing	●	○	●	○		●	○	○		○		○	○	○	○		○	○
	Sum:	12.0	10.5	9.0	9.5	4.0	10.0	7.0	10.5	4.5	10.5	3.0	12.5	16.0	15.0	3.0	1.0	12.0	4.0

Figure 28 Filled criteria matrix for the set of variables (output of the sensitivity model software)

certain predefined criteria and contains variables from different spheres of life. The criteria matrix of the created set of variables is presented in Figure 28. Variables that are fully applicable to a certain category add one point to the associated sum. Partially applicable variables add half a point. The sums show that every predefined criterion is considered in the set of variables. It has to be noted that there is no lower limit for the sums of the criteria. According to Vester (2019), the criteria matrix is rather intended to be a guide for a balanced set of variables.

6.2.4. Influence Matrix

The influence matrix represents the effects of the system's variables on each other. Thus, the influence matrix is an important basis for further steps in the sensitivity model. In particular, the influence matrix enables the determination of systemic roles as well as the creation of partial scenarios. Figure 29 presents the influence matrix containing effect strengths without effect directions as well as in-degree centrality (indicated as PS) and out-degree centrality (indicated as AS). Furthermore, Figure 29 presents Q- and P-values according to their definitions in subsection 6.1.3. Thus, the influence matrix provides first indications of systemic roles. Selected effects that are non-trivial and were intensively discussed in the expert workshop are further described and explained in the appendix (see Table 24). Thus, the influence matrix becomes transparent.



	Influence by variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	AS	P
1	Accessibility via car	X	1	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	7	49
2	Accessibility via bus	1	X	1	1	0	3	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	8	48
3	Accessibility via metro/train	1	1	X	1	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	8	32
4	Accessibility via (e-)bike	1	1	1	X	0	0	0	3	0	0	0	0	0	0	0	0	0	0	1	0	0	1	8	40
5	Car use	0	0	0	0	X	0	0	0	0	0	3	0	0	0	0	0	2	2	0	0	0	0	7	35
6	Bus use	0	0	0	0	0	X	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	5
7	Metro/train use	0	0	0	0	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	(E-)bike use	0	0	0	0	0	0	0	X	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	6
9	Truck use	0	0	0	0	0	0	0	0	X	0	1	0	0	0	0	0	2	2	0	0	0	0	5	10
10	Van use	0	0	0	0	0	0	0	0	0	X	2	0	0	0	0	0	2	2	0	0	0	0	6	30
11	Street traffic	3	2	0	1	0	0	0	0	0	0	X	0	0	0	0	1	1	0	0	0	0	0	8	64
12	Offline shopping volume	0	0	0	0	1	1	1	1	2	1	0	X	0	0	0	0	0	0	2	0	0	0	9	36
13	Online shopping volume	0	0	0	0	0	0	0	0	0	2	0	0	X	0	0	0	0	0	0	1	0	0	3	9
14	3D home printing volume	0	0	0	0	0	0	0	0	0	1	0	0	0	X	0	0	0	0	0	0	1	0	2	6
15	3D shop printing volume	0	0	0	0	0	0	0	1	0	1	0	0	0	0	X	0	1	0	0	0	0	2	5	20
16	Sustainability awareness	1	1	1	1	2	1	1	1	0	0	0	1	1	1	1	X	0	0	0	0	0	0	13	52
17	Emissions (local)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	X	0	0	0	0	0	2	16
18	Emissions (global)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	X	0	0	0	0	1	6
19	SQ offline shopping	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	X	2	1	2	8	88
20	SQ online shopping	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2	X	1	2	7	42
21	SQ 3D home printing	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1	1	X	1	5	20
22	SQ 3D shop printing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	2	2	1	X	8	88
	PS	7	6	4	5	5	5	5	6	2	5	8	4	3	3	4	4	8	6	11	6	4	11	122	
	Qx100	100	133	200	160	140	20	0	17	250	120	100	225	100	67	125	325	25	17	73	117	125	73		

Figure 29 Influence matrix (output of the sensitivity model software)

As mentioned in subsection 6.1.3, the influence matrix and the set of variables are developed in an iterative process (see Figure 27). The workshops with experts are used to consolidate and modify the initial versions of both the set of variables and the influence matrix. Initial versions of the set of variables and the influence matrix are presented in the appendix (Table 23 and Figure 47) to demonstrate the iterative process of creating and consolidating these results.

6.2.5. Systemic Roles

The determination of systemic roles is essential to understand interrelations in a complex system. For this reason, an advanced analysis of systemic roles is performed by extending the sensitivity model with additional centrality measures (see subsection 6.1.3). Besides degree-centrality (C_{in-D} & C_{out-D}), closeness-centrality (C^*_{Cl} & C^*_{Cr}) and eigenvector-centrality (C_{El} & C_{Er}) of the variables are considered to determine their systemic roles. Table 18 presents the relevant centrality measures of the variables. Figure 30-Figure 32 provide a graphical representation of degree-, closeness-, and eigenvector centrality. Due to a lack of space, variable names are replaced with variable numbers. Thus, the assignment of variables to markers in the graph is ensured. Variable names and variable numbers are documented and assigned in Table 18. In Figure 30, the colors

Nr.	Variable	C_{in-D}	C_{out-D}	P	Q	C^*_{Cl}	C^*_{Cr}	C_{El}	C_{Er}
1	Accessibility via car	7	7	49	1.00	0.41	0.51	0.15	0.30
2	Accessibility via bus	6	8	48	1.33	0.41	0.49	0.13	0.26
3	Accessibility via metro/train	4	8	32	2.00	0.32	0.47	0.08	0.23
4	Accessibility via (e-)bike	5	8	40	1.60	0.41	0.49	0.10	0.26
5	Car use	5	7	35	1.40	0.39	0.37	0.12	0.23
6	Bus use	5	1	5	0.20	0.39	0.34	0.12	0.06
7	Metro/train use	5	0	0	0.00	0.40	0.00	0.10	0.00
8	(E-)bike use	6	1	6	0.17	0.41	0.34	0.15	0.06
9	Truck use	2	5	10	2.50	0.30	0.38	0.08	0.11
10	Van use	5	6	30	1.20	0.37	0.38	0.14	0.17
11	Street traffic	8	8	64	1.00	0.45	0.50	0.16	0.35
12	Offline shopping volume	4	9	36	2.25	0.41	0.48	0.25	0.23
13	Online shopping volume	3	3	9	1.00	0.38	0.36	0.14	0.10
14	3D home printing volume	3	2	6	0.67	0.38	0.36	0.09	0.05
15	3D shop printing volume	4	5	20	1.25	0.41	0.42	0.25	0.15
16	Sustainability awareness	4	13	52	3.25	0.37	0.70	0.11	0.35
17	Emissions(local)	8	2	16	0.25	0.45	0.43	0.18	0.12
18	Emissions(global)	6	1	6	0.17	0.38	0.43	0.11	0.06
19	SQ offline shopping	11	8	88	0.73	0.49	0.40	0.47	0.32
20	SQ online shopping	6	7	42	1.17	0.39	0.37	0.37	0.26
21	SQ 3D home printing	4	5	20	1.25	0.39	0.37	0.23	0.16
22	SQ 3D shop printing	11	8	88	0.73	0.49	0.40	0.47	0.29

Table 18 Centrality measures of variables in the system

of markers represent the value of P which is defined as the product of in-degree centrality (C_{in-D}) and out-degree centrality (C_{out-D}) according to Vester (2019, p. 231). In Figure 31, marker colors represent the sum of left closeness centrality (C^*_{Cl}) and right closeness centrality (C^*_{Cr}). In Figure 32, marker colors represent the sum of left-eigenvector centrality (C_{El}) and right-eigenvector centrality (C_{Er}).

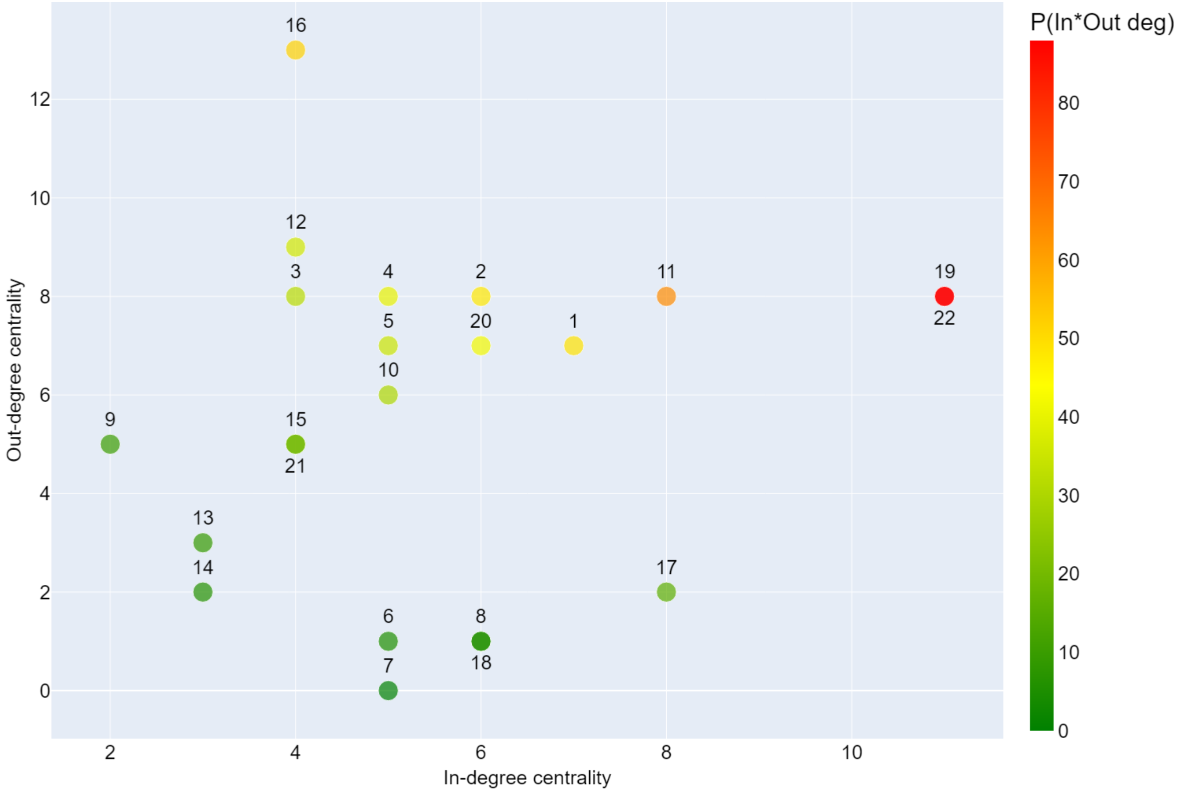


Figure 30 Degree centrality

Table 18 and Figure 30-Figure 32 show, that some variables have a higher centrality than others. Four variables stand out due to a relatively high in-degree centrality. These variables are *local emissions (17)*, *street traffic (11)*, *service quality offline shopping (19)* and *service quality 3D shop printing (22)*. According to the classical interpretation of the sensitivity model, these variables are passive and strongly influenced by the other variables in the system. According to Vester (2019, p. 228), small changes in the system are enough to strongly influence variables with a relatively high in-degree centrality. Vice versa, small changes in variables with a relatively high out-degree centrality are enough to strongly influence other variables (Vester 2019, p. 228). Figure 30 shows, that the variable *sustainability awareness (16)* stands out due to a relatively high out-degree centrality. This fact indicates, that an increased sustainability awareness in politics, economy and society may have strong effects on the whole system of urban mobility and logistics. Besides sustainability awareness, there are other variables with a relatively high out-degree centrality such as the *accessibility of different means of transport*, *offline shopping volume (12)*, *street traffic (11)*, *service quality offline shopping (19)* and *service quality 3D shop printing (22)*. The last two can be considered as critical variables because they combine a relatively high in-degree centrality with a relatively high out-degree centrality. This means that already small

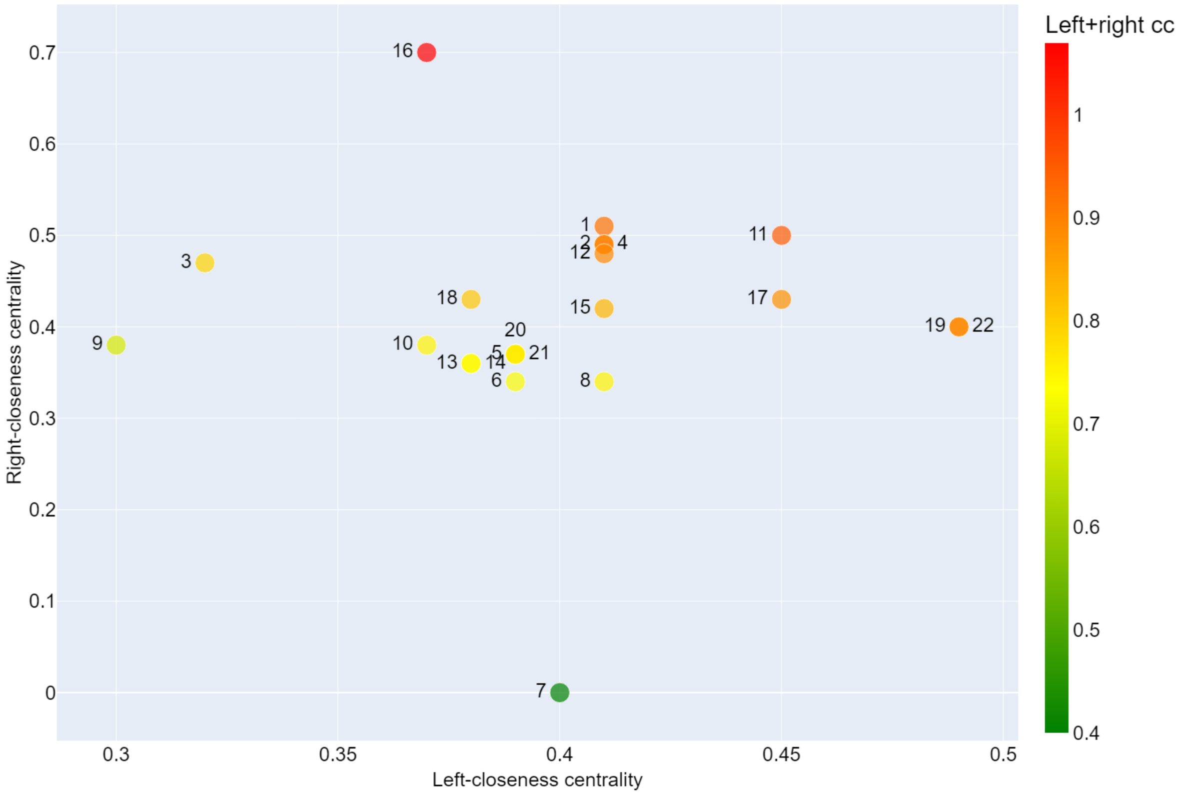


Figure 31 Closeness centrality

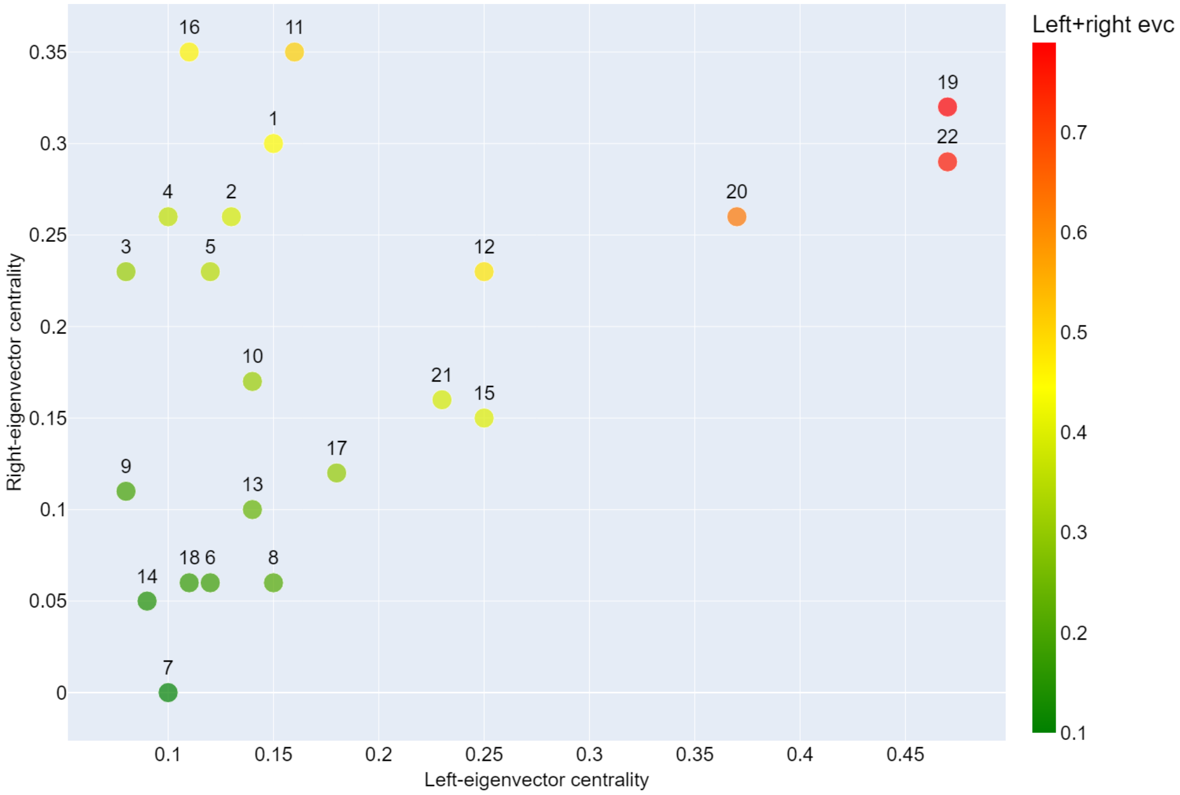


Figure 32 Eigenvector centrality

changes in these variables can trigger strong effects in the system. On the other hand, these variables are strongly influenced by already small changes in other variables in the system. Furthermore, *service quality offline shopping (19)* and *service quality 3D shop printing (22)* have the highest values of P.

As described in subsection 6.1.3, closeness centrality is based on the average shortest path distances. Therefore, closeness centrality can be interpreted as the immediacy with which variables affect or are affected by the system. In this context, variables with high left closeness centrality are likely to be affected more directly by changes within the system. Vice versa, variables with high right closeness centrality are likely to immediately influence other variables in the system. Figure 31 represents the closeness centrality of variables and has similarities to Figure 30. The variables *street traffic (11)*, *service quality offline shopping (19)* and *service quality 3D shop printing (22)* have a relatively high left closeness centrality. This means, that these variables are directly influenced by changes within the system. The analysis reveals that the variable *local emissions (17)* has a similar left closeness centrality to *street traffic (11)*. Thus, changes within the system are likely to have immediate effects on local emissions. The variable *sustainability awareness (16)* stands out due to the highest right-closeness centrality. This fact indicates that changes in sustainability awareness are likely to impact the system with high immediacy. On the other hand, the variable *sustainability awareness (16)* has a relatively small left-closeness centrality. This means that changes in the urban system need a relatively long time to influence sustainability awareness in politics, economy and society. Sustainability awareness is likely to be affected indirectly by intermediate variables.

According to subsection 6.1.3, the eigenvector is an important centrality measure to determine the activity or passivity of a variable. In contrast to in-degree centrality and out-degree centrality, eigenvector centrality also considers indirect effects which are transmitted via intermediate variables. Figure 32 supports the assumption that the variables *service quality offline shopping (19)* and *service quality 3D shop printing (22)* are most influenced by other variables in the system. The variables do not only have the highest in-degree centrality but also the highest left-eigenvector centrality. Thus, the variables *service quality offline shopping (19)* and *service quality 3D shop printing (22)* are strongly influenced both directly and indirectly via intermediate variables. In addition, *service quality offline shopping (19)* and *service quality 3D shop printing (22)* have a relatively high right-eigenvector centrality. This means, that the variables are very active and influence the other variables in the system both directly and indirectly. The analysis of right-eigenvector centrality shows that *service quality offline shopping (19)* and *service quality 3D shop printing (22)* are almost on the same level as *sustainability awareness (16)*. Another variable that stands out due to a relatively high right-eigenvector centrality is *street traffic (11)*. Overall street traffic has the second highest right-eigenvector centrality. In addition, street traffic has a medium out-degree centrality compared with the other variables in the system. The combination of these two centrality measures indicates that the direct effects of street traffic on the system are limited. However, indirect effects of the variable on the other variables in the system are relatively high. Thus, street traffic can be considered a very active variable although it only has a medium out-degree centrality. According to the analysis of out-degree centrality, the variable *offline shopping volume (12)* seems to be relatively active due to many direct effects on other variables. However, the variable only has a medium right-eigenvector centrality. Thus, the variable *offline shopping volume (12)* may not be as active as first suspected. Figure 30-Figure 32 provide a good overview of all further variables.

The goal of the system analysis is the evaluation of impacts of 3DP and distributed AM on the system of urban mobility and logistics. The analysis of systemic roles shows that especially the variable *service quality 3D shop printing (22)* is active and may have a leverage effect to initiate system changes. Thus, increasing the service quality of 3D printing shops might be beneficial if distributed AM is intended to be implemented in urban areas.

6.2.6. Effect System

As described in subsection 6.1.2, the effect system extends the influence matrix by considering effect directions. Furthermore, the effect system provides a graphical representation of effects between variables in the system. The effects and interrelations are displayed as a network. Figure 33 presents the effect system for the system of urban mobility and logistics. According to Vester (2019), parallel effects are represented by solid arrows and opposite effects are repre-

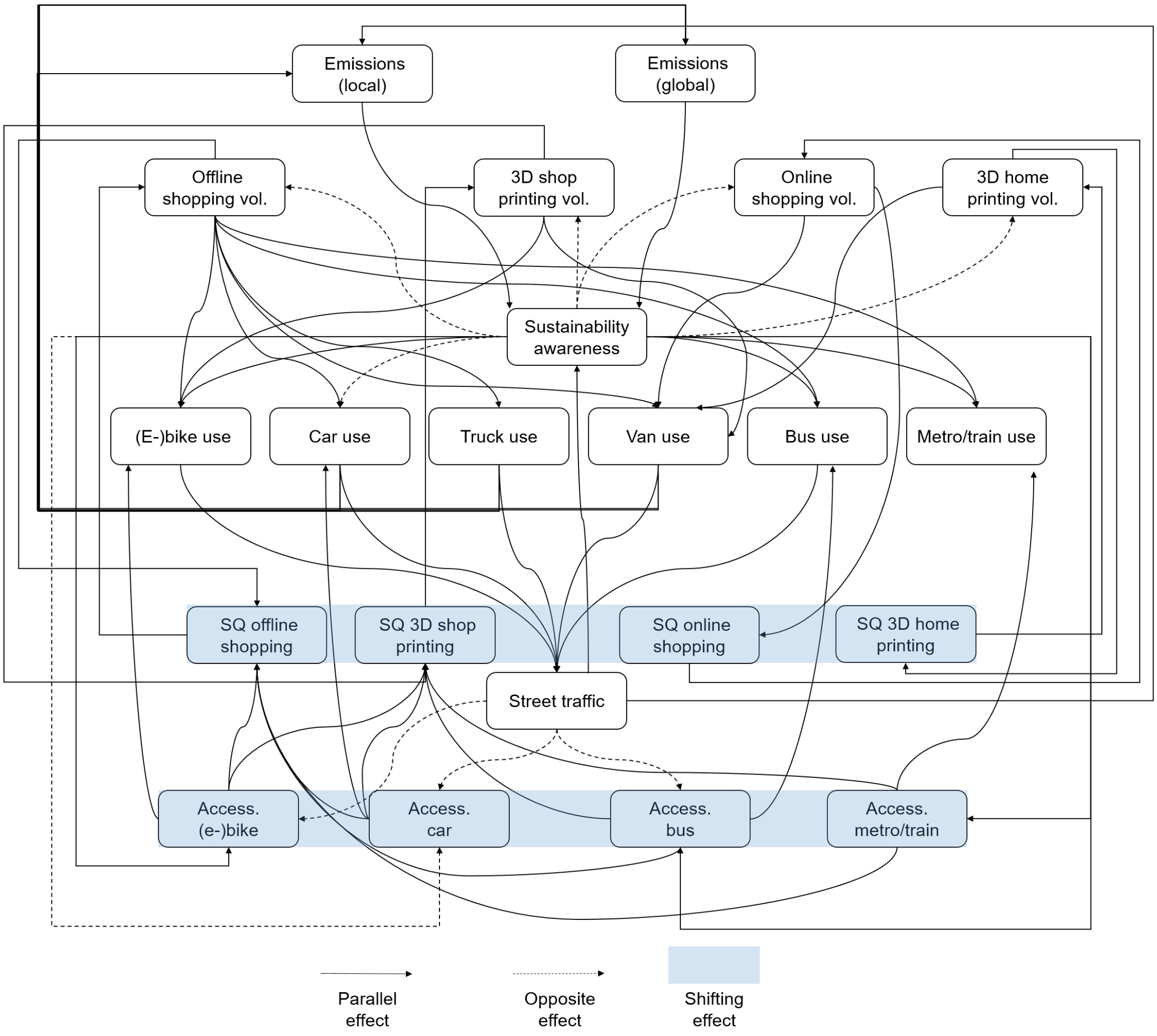


Figure 33 Effect system

sented by dotted arrows (see subsection 6.1.2).

Figure 33 extends the classical effect system notation, which is provided in Vester's sensitivity model software by introducing a blue box. Such a blue box contains variables that are subject to reciprocal shifting effects. In detail, every variable in a blue box has opposite effects on every other variable in the box. Furthermore, every variable is affected by the other variables in the box through opposite effects. As a result, the blue box represents shifting effects. The representation of such effects as boxes instead of individual links enables a clear arrangement and display of both variables and links in the effect system.

Shifting effects between variables containing accessibility are intuitive since accessibilities of means of transport are defined as relative accessibilities (see Table 17). This means that the accessibility of one mean of transport depends on the other accessibilities. If the accessibility via car decreases, other means of transport become more attractive and thus the relative accessibility of the other means of transport increases. The definition of accessibilities as relative measures enables the modeling of shifting effects between means of transport within the system.

The variables containing service qualities of shopping options are also subject to shifting effects and are therefore displayed in a blue box. Similar to accessibilities, service qualities are also defined as relative measures depending on the service quality of all other shopping options (see Table 17). If the service quality of offline shopping decreases, other shopping options become more attractive and their relative service quality increases.

The partial scenarios provide a more detailed view on certain patterns and components of the effect system. These scenarios are presented in the next subsection to provide deeper insights into the examined system.

6.2.7. Partial Scenarios

According to Vester (2019, p. 250), the analysis of partial scenarios should be used to better understand the system's cybernetics. In this context, the most interesting parts of a created effect system can be modeled as a partial scenario to answer concrete questions.

Since cars predominantly determine street traffic in cities, it is interesting to understand the mechanisms of car traffic in the system of urban mobility and logistics. The first partial scenario examines this mechanism.

Partial Scenario 1: Car Transport

Partial scenario 1 represents a simple scenario with only three variables to understand the basic mechanisms of car traffic in urban environments. Figure 34 represents the first partial scenario. The presented scenario is simple and consists of only one negative feedback loop leading to stabilizing feedback. Stabilizing feedback loops are indicated with a $-$. Figure 34 indicates that an increase in car use leads to increasing street traffic in the system. However, increased street traffic reduces accessibility via car due to congestion, longer travel times, and reduced travel comfort. The reduced accessibility via car leads to stabilizing feedback due to decreasing car use in the system. Vice versa, reduced street traffic may induce traffic in the further course by increasing the accessibility via car and car use. The concept of induced traffic is well known in

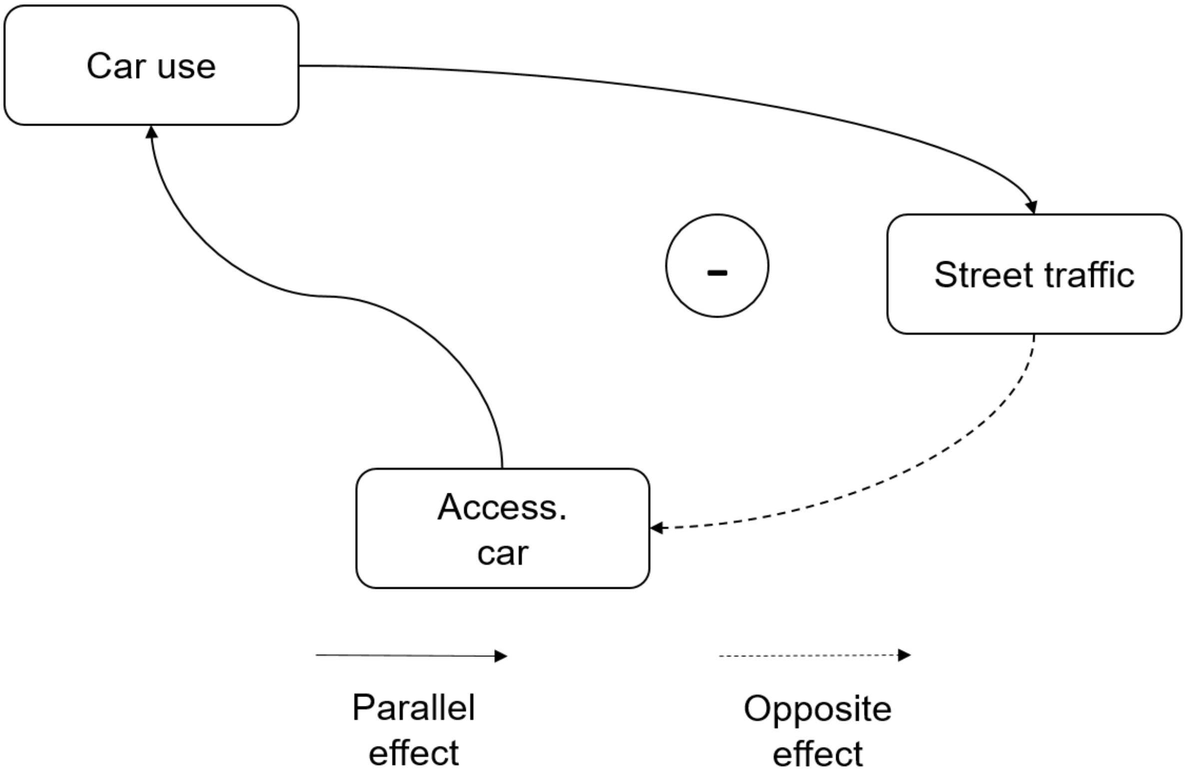


Figure 34 Partial scenario 1

the scientific literature and described by Goodwin (1996) among others. This mechanism plays a central role in the investigated system from a cybernetic point of view. The described feedback loop appears in other partial scenarios and is referred to as the stabilizing feedback loop of street traffic.

The identified stabilizing feedback loop indicates that interventions in the partial scenario are likely to have no sustainable effects. Thus, increasing accessibility via car by building new roads may induce more car traffic.

Partial Scenario 2: Passenger Transport

Partial scenario 2 extends the first scenario by including other means of passenger transport. Figure 35 represents the partial scenario of passenger transport. The analysis of partial scenario 2 in the sensitivity model software shows that it contains 18 negative (stabilizing) and 24 positive (reinforcing) feedback loops. In particular, the accessibilities are part of many reinforcing feedback loops. As mentioned, the blue box represents shifting effects between all contained variables. These shifting effects create reinforcing feedback loops. Thus, policies affecting accessibility are likely to trigger shifting effects between means of transport within the system. In this process, street traffic buffers these shifting effects towards car use, bus use, and (e-)bike use as presented in partial scenario 1 and Figure 34. The accessibility via metro/train is not affected by street traffic. Thus, policies that increase the accessibility via metro/train may imply sustainable behavioral changes in the considered system towards increased metro and train use.

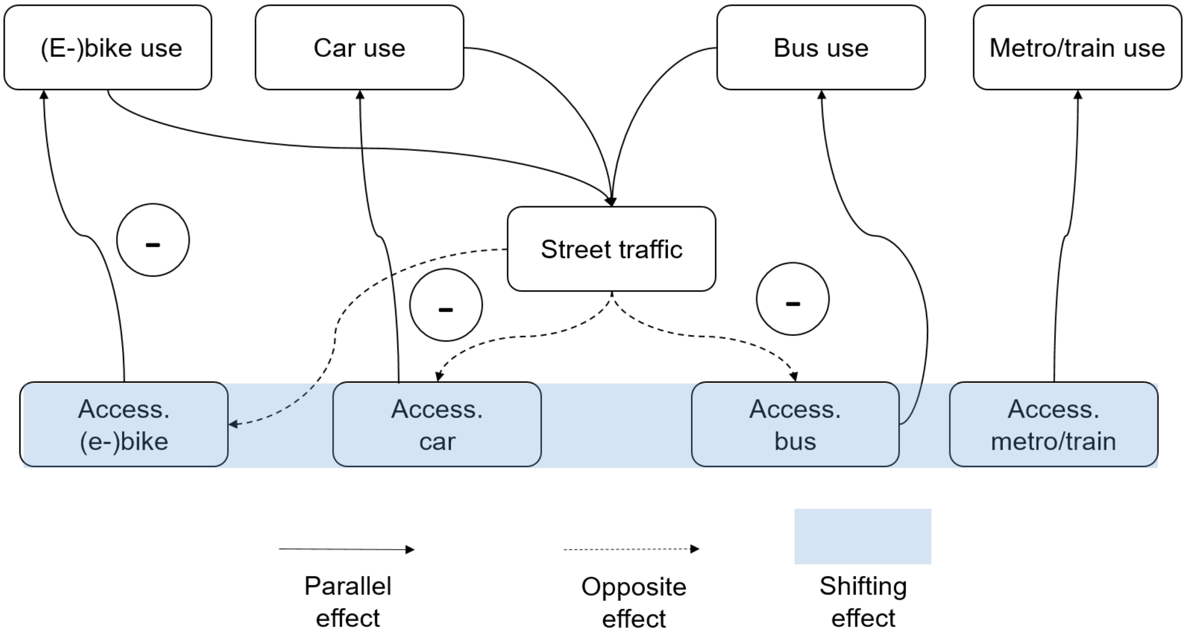


Figure 35 Partial scenario 2

Partial Scenario 3: Offline Shopping and Car Transport

Partial scenario 3 examines the interrelations between classical offline shopping and car trans-

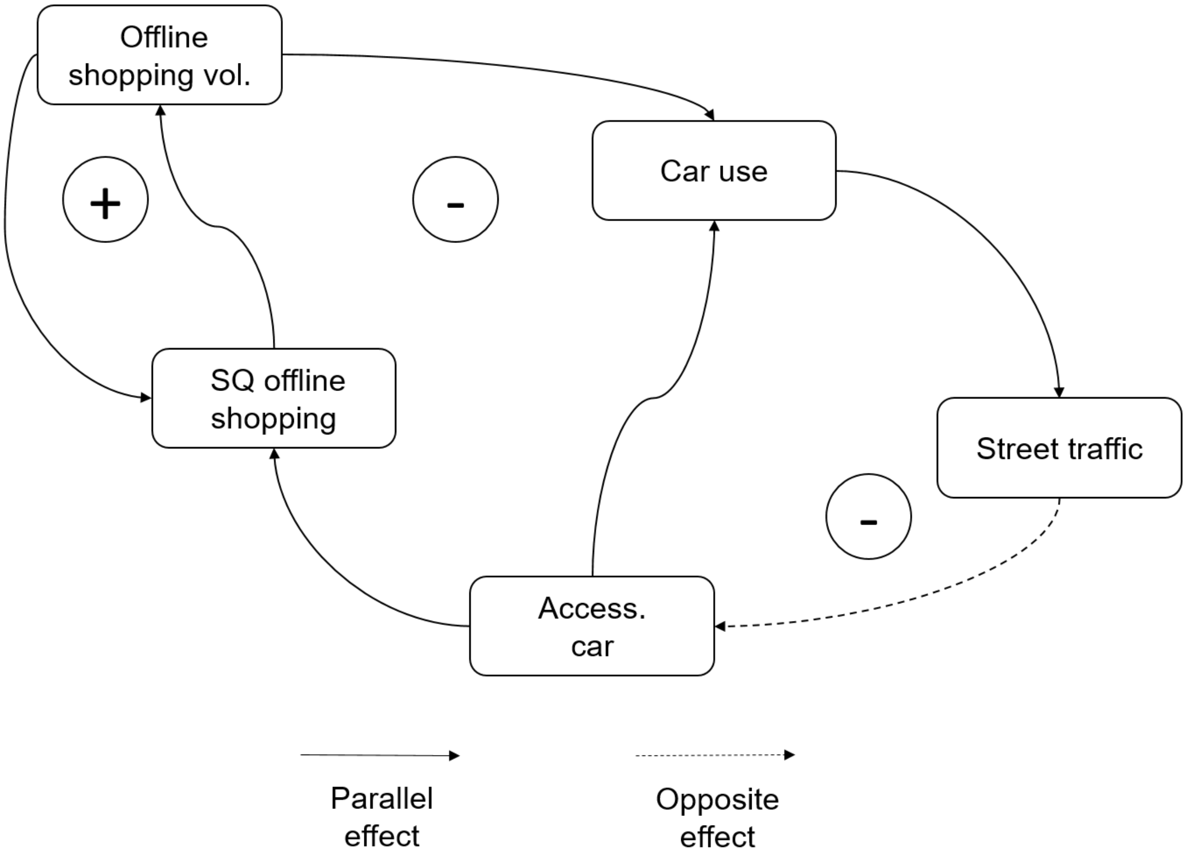


Figure 36 Partial scenario 3

port. Explicitly, only car transport is considered to reach offline shopping facilities in this scenario. Figure 36 represents partial scenario 3.

The presented scenario consists of two negative (stabilizing) feedback loops and one positive (reinforcing) feedback loop and thus constitutes a cybernetic element in the whole effect system. The first negative feedback loop is already described in partial scenario 1 and Figure 34. The stabilizing feedback loop of street traffic controls street traffic and limits a reinforcing increase in car use and traffic. Figure 36 presents a bigger feedback loop by considering offline shopping in the system. An increase in service quality of offline shopping leads to an increase in offline shopping volume. Such an increase induces car use and subsequently increases street traffic. Increased street traffic decreases accessibility via car. Accessibility is an important part of offline shopping service quality. Thus, a decrease in accessibility via car reduces the service quality of offline shopping, closing the stabilizing feedback loop.

Figure 36 shows that the described stabilizing feedback loop limits a reinforcing increase in service quality of offline shopping. This limitation makes other shopping options attractive and may lead to shifting effects, which are considered in the following partial scenario. Due to a high level of street traffic, people could refuse to visit shops in the city and turn to online shopping or local 3D printing of products.

Partial Scenario 4: Shopping Behavior and Shopping Transport in General

Partial scenario 4 focuses on shopping behavior and related transport in the system. Figure 36 represents this scenario. The fourth partial scenario contains 11 negative (stabilizing) and 17 positive (reinforcing) feedback loops. The feedback loops only occur between the relative service qualities of shopping options themselves and between service qualities and shopping volumes. Interventions in these variables may trigger feedback loops and changes in the system. Through these shifting effects, changes in shopping behavior and volumes can be achieved. The other variables in partial scenario 4 are not part of any feedback loops. Thus, they have a limited cybernetic function in the scenario. Instead, they serve as an indicator for changes triggered by the feedback loops of the service quality variables. Figure 37 indicates that shifting effects between service qualities increase one specific type of shopping volume while the others are partly substituted and thus decreased. Changes towards increased offline shopping increase individual car use, truck use, and van use because the shops have to be supplied and customers need to get to the shops. Changes towards increased 3D shop printing volume, online shopping volume, or 3D home printing volume only increase van use in the system model. This fact indicates that shifting effects towards less offline shopping volume can reduce car- and truck use while increasing van use. Both means of transport contribute to street traffic. However, one van can serve many customers. Therefore, shifting from individual car use to van use may reduce street traffic. It has to be noted that the primary effect system, presented in Figure 33, and partial scenario 4, presented in Figure 37, assume a dense infrastructure of 3D printing shops with high proximity to customers in the urban system. Furthermore, it is assumed that 3D printing shops do not support car use due to high proximity to customers and potential parking restrictions. For these reasons, 3D shop printing induces active means of transport such as walking or cycling instead of car use in the

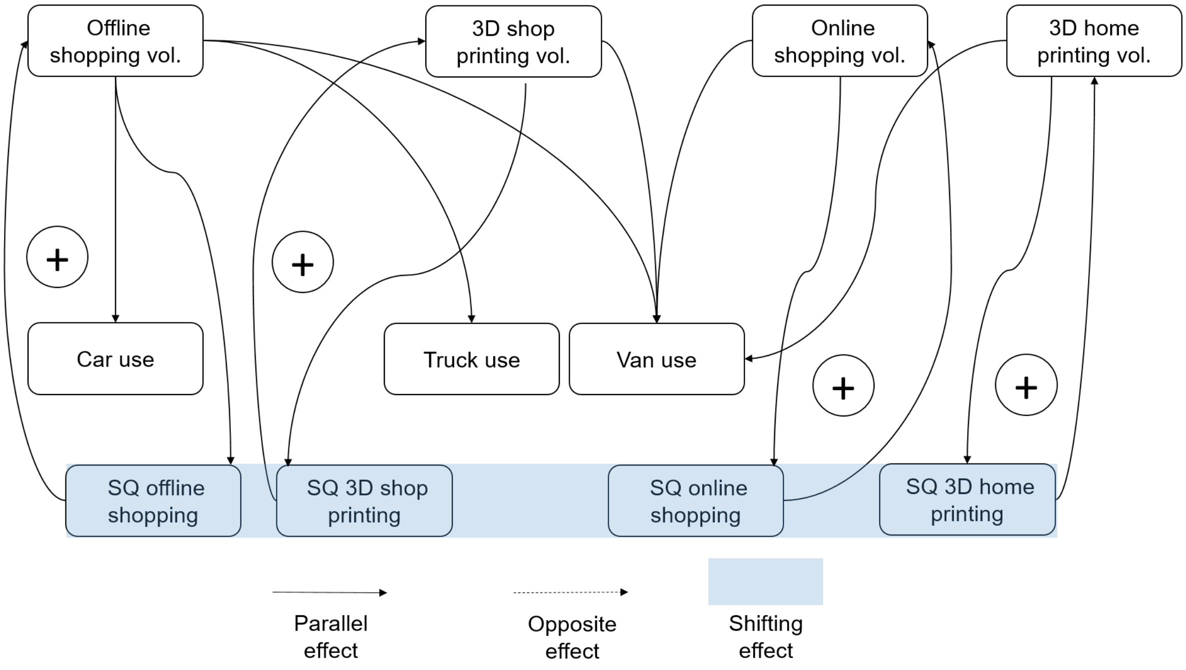


Figure 37 Partial scenario 4

primary effect system and partial scenario 4.

If there is a sparse infrastructure of 3D printing shops with fewer facilities, longer distances to customers, and no parking restrictions, the effects on the used means of transport are different. Partial scenario 5 is created to analyze the differences between 3D shop printing in a dense and sparse infrastructure scenario.

The mentioned shifting effects are enhanced by the reinforcing feedback loops between service qualities and volumes of the different shopping options indicated by a +. These feedback loops may occur because the increased service quality of a certain shopping option increases the related customer demand. Due to such an increase in demand, providers can increase their capacities and service quality which induces even more customer demand closing the reinforcing feedback loop.

In conclusion, shifting effects between service qualities lead to changes in shopping behavior. Shifting effects towards more 3D shop printing, online shopping, and 3D home printing is likely to reduce car use, especially if 3D printing shops provide more proximity to customers. The positive feedback loops between service qualities and shopping volumes reinforce these shifting effects. Thus, distributed AM can substitute certain parts of traditional shopping activities. The transport effects of such substitution are further examined in scenario 5.

Partial Scenario 5: 3D Shop Printing in Different Infrastructure Scenarios

Partial scenario 5 introduces new variables that are not part of the original effect system and reallocates the means of transport to motorized and non-motorized transport use. According to Vester (2019, p. 250), this is appropriate to examine specific patterns of the system in detail.

The new variable *motorized transport use* is defined to include all individual means of motorized

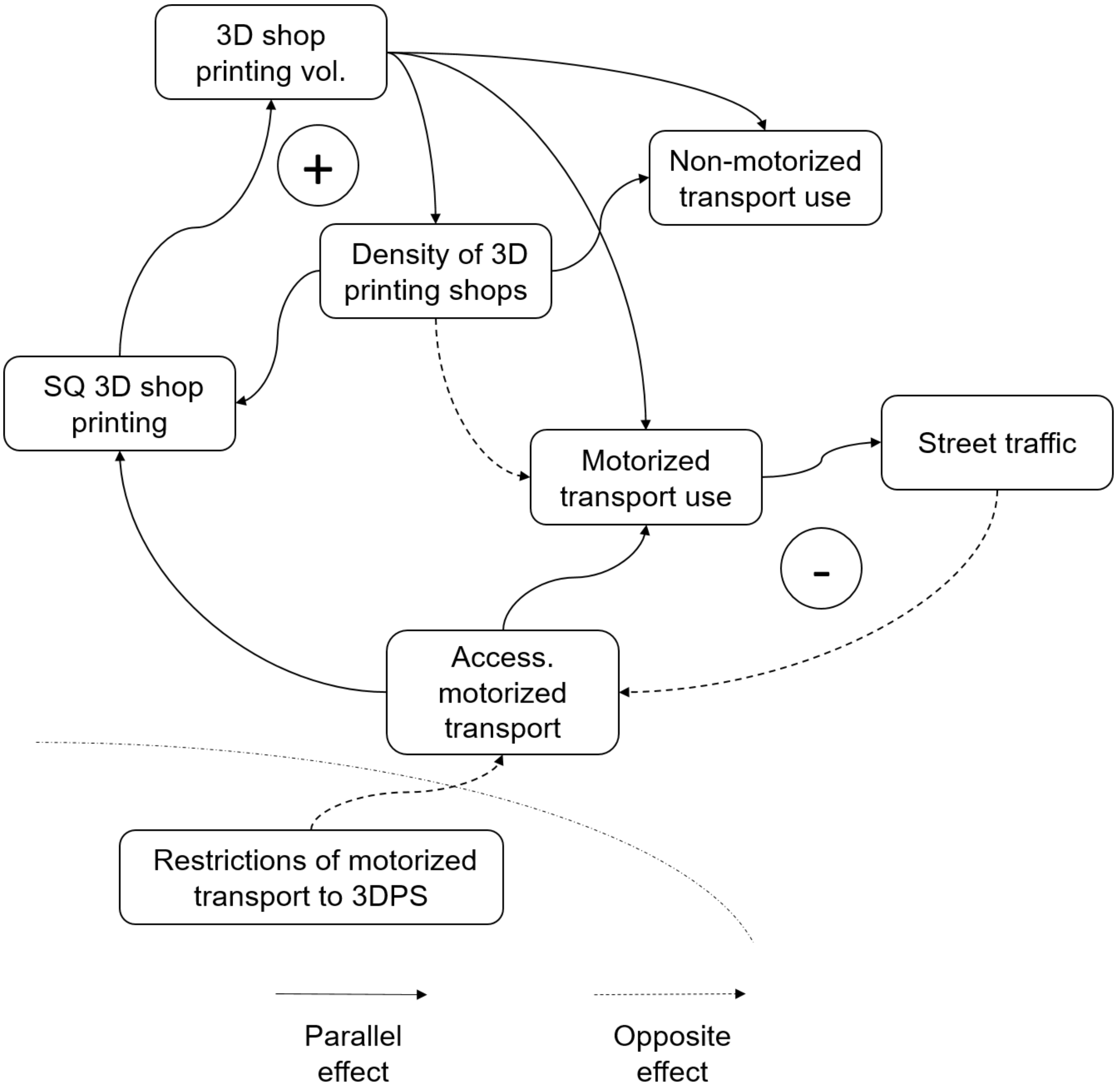


Figure 38 Partial scenario 5

transport except e-bikes. Per definition, this new variable includes car use, bus use, metro/train use, van use and truck use. The accessibilities of motorized means of transport are summarized in the new variable *accessibility via motorized transport*. The new variable *non-motorized transport use* is defined to include the use of all non-motorized means of transport. In particular, this new variable includes cycling and walking.

Furthermore, the infrastructure density of 3D printing shops in an urban area is considered by introducing the new variable *density of 3D printing shops*, which indicates the proximity of customers to their closest 3D printing shop. In addition, *restrictions of street transport to 3D printing shops* are considered as a potential policy by introducing a new variable within partial scenario 5. One example restriction is the introduction of car parking bans at 3D printing shops.

According to the sensitivity model software analysis, partial scenario 5 contains two negative (stabilizing) feedback loops and two positive (reinforcing) feedback loops. Two feedback loops marked in Figure 38 are short and easy to identify. The first one is the stabilizing feedback loop controlling street traffic. This feedback loop is already described in partial scenario 1. The second short feedback loop is reinforcing and contains the variables *service quality 3D shop printing*, *3D shop printing volume*, and *density of 3D printing shops*. Increased service quality of 3D printing shops leads to increased 3D shop printing volume. Due to increased customers and orders, 3D printing shops become profitable. Thus, the number and density of 3D printing shops in urban areas will likely increase. Higher proximity to customers due to an increased density of 3D printing shops increases the service quality of 3D printing shops. Thus, the feedback loop is closed. Vice versa, a decrease in service quality of 3D printing shops can trigger the opposite feedback effects. Figure 38 reveals that the density of 3D printing shops influences the use of means of transport. If density increases, proximity from customers to 3D printing shops increases, and customers are more likely to use non-motorized transport, such as walking or cycling on bike paths, to get to the shops and pick up their orders. If density decreases, customers are more likely to use motorized transport, such as cars, to reach 3D printing shops to pick up their produced orders. In a sparse infrastructure of 3D printing shops, it is also more likely for customers to rely on home delivery. In this case, vans or other means of freight transport might be used for home delivery and thus increase street traffic.

The analysis of partial scenario 5 in the sensitivity model software reveals another reinforcing feedback loop, which is more complex and difficult to identify. This loop contains the variables *street traffic*, *accessibility via motorized transport*, *service quality 3D shop printing*, *3D shop printing volume*, *density of 3D printing shops* and *motorized transport use*. Increased service quality of 3D shop printing increases the volume of 3D shop printing. Thus, the density of 3D printing shops in an urban area increases due to increased order volume. A dense infrastructure of 3D printing shops with high proximity to customers may reduce the use of motorized transport for shopping because 3D printing shops are located within a shorter distance and thus can be reached by walking or cycling. A decrease in motorized transport use reduces street traffic and thus increases accessibility via street transport. As the last step, closing the feedback loop, increased accessibility via street transport increases the service quality of 3D shop printing.

The described feedback loop may reinforce the contained variables. It has to be noted that this big feedback loop is connected to the stabilizing feedback loop of street traffic (see partial scenario 1). This connection inhibits the presented reinforcing effects on motorized transport and street traffic. Thus, policies increasing the service quality of 3D shop printing can reinforce the volume of 3D shop printing and non-motorized transport use for shopping. However, shopping traffic is only one component of street traffic in general. Street traffic is subject to a strong stabilizing feedback loop which either induces or prevents more traffic.

Partial scenario 5 considers restricting street transport to 3D printing shops as a policy. As already mentioned, parking bans could be one measure to restrict car transport in particular. Figure 38 indicates that restrictions serve as an external input to the scenario. Such restrictions decrease the accessibility via motorized transport. This aspect reduces the service quality of 3D shop printing and might trigger the reinforcing feedback loop, which steadily decreases the volume of 3D shop printing, the density of 3D printing shops, and thus the service quality of 3D printing shops. Such effects pose problems if 3D printing shops are intended to be implemented. For this reason, restrictions on street transport to 3D printing shops should be regarded with caution, especially at the beginning of implementing a 3D printing shop infrastructure in a city. Instead, the reinforcing feedback loop should be exploited to increase the density of 3D printing shops constantly. Thus, motorized transport to and from 3D printing shops is automatically reduced due to cybernetic mechanisms within the system. Restrictions can be successfully used if the infrastructure of 3D printing shops is already implemented and other policies are used in parallel to compensate for the lost service quality of 3D printing shops. Thus, 3D printing shops and non-motorized transport to and from these shops can be promoted simultaneously.

Furthermore, Figure 38 indicates a potential rebound effect within the examined system. On the one hand, a reinforcing increase in 3D shop printing service quality, 3D shop printing volume, and density of 3D printing shops lead to decreased motorized transport use for shopping due to increased proximity to customers who are enabled to walk or cycle. On the other hand, the reinforcing feedback loop increases motorized transport use because vans have to be utilized to serve 3D printing shops with required printing materials.

Partial Scenario 6: Potential Rebound Effects due to Increased Shopping Offer

Partial scenario 4 and partial scenario 5 show the substitution potential of distributed AM in shopping behavior and shopping transport. However, distributed AM, represented by 3D printing shops and 3D home printing, combines a new technology and a new concept in logistics. This combination represents a entirely new shopping option, complementing traditional shopping opportunities. Thus, the increased shopping offer can lead to undesired rebound effects under certain circumstances. Partial scenario 6 examines these potential rebound effects and is displayed in Figure 39. The scenario is quite similar to partial scenario 4 but additionally includes the central variable *sustainability awareness*. If sustainability awareness of politics, the economy, and society decreases and shopping budgets are not yet exhausted, the shopping volume of all shopping options, including 3D shop and 3D home printing, might increase due to increased unsustainable consumption. In this case, the new concept of distributed AM leads to complementing shopping activities instead of substitution. Thus, the overall shopping volume in the system is increased, and shopping transport in different forms is induced. This rebound effect is enhanced by the positive feedback loops between service qualities of shopping options and their related shopping volumes. The described rebound effect might induce additional shopping transport, emissions, and traffic and should therefore be avoided.

The variable *sustainability awareness* is a lever for controlling and limiting the described rebound effect. If sustainability awareness of politics, the economy, and society can be raised, the overall shopping volumes will decrease due to more sustainable consumption. Thus, distributed AM can substitute different shopping activities, and street transport for shopping can be reduced in particular. The evaluation of systemic roles in subsection 6.2.5 shows that the variable *sustainability awareness* is very suitable for policies and thus might trigger changes in the system towards more sustainable consumption and less shopping transport. For this reason, policies to strengthen sustainability awareness in the system are not only desirable but necessary.

In conclusion, distributed AM in 3D printing shops or at home might substitute other shopping activities, which cause more individual motorized street transport and traffic. If sustainability aware-

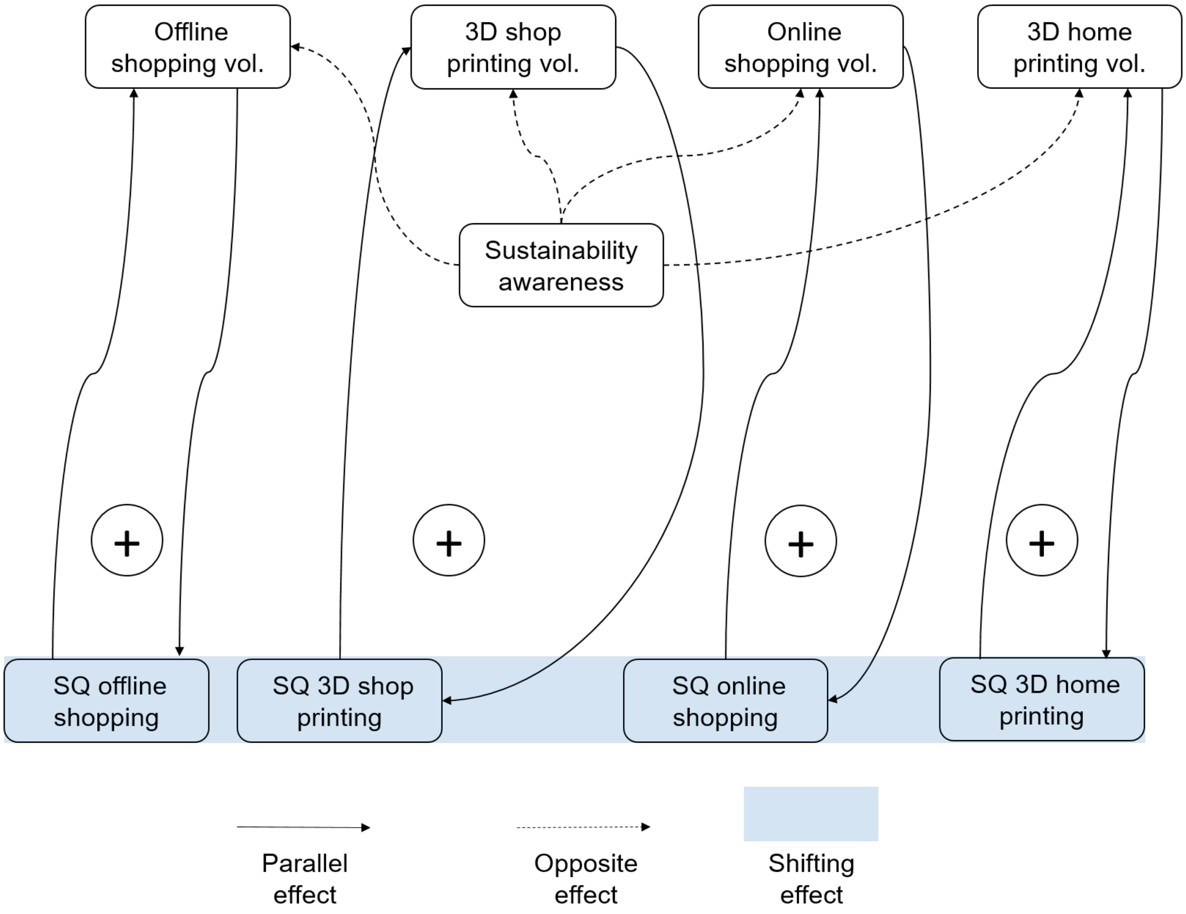


Figure 39 Partial scenario 6

ness is not pronounced and budgets are not exhausted in the system, 3D shop printing could also complement the existing shopping activities instead of substituting them. Thus, traffic caused by 3D shop printing might add to the traffic caused by the existing shopping options (offline and online shopping). The primary effect system presented in Figure 33 indicates that sustainability awareness in politics, economy, and society should be raised to prevent such a rebound effect.

6.2.8. System Evaluation

The different steps of the adjusted sensitivity model provide essential insights into the system of urban mobility and logistics. Furthermore, the results of these steps contribute to estimating the impacts of distributed AM on the system as well as triggered interactions.

Some components of the investigated system have a buffering character, while others are reinforcing and may trigger changes within the system. Shifting effects between the accessibility via means of transport affect the mobility behavior of people and the extent of use. Changes in mobility behavior can be achieved through policies that influence accessibility via means of transport. The analysis of systemic roles shows that all accessibility variables have a relatively high out-degree centrality. In addition, especially the variable *accessibility via car* has a relatively high right-eigenvector centrality. Thus, the accessibility variables play an active role in the system, which means that interventions in these variables have the potential to trigger changes in the system. Policies to promote public transport can be successful if the accessibility, which consists of travel time, travel costs, and travel comfort, is increased sustainably. However, the system model shows that mobility behavior is subject to the stabilizing feedback loop of street traffic. Thus, policies reducing street traffic imply increased accessibility via means of transport on streets, such as cars. This increase is likely to induce new street traffic. The stabilizing feedback loop shows that street traffic is difficult to control in the long term.

Shopping behavior and related shopping trips are also subject to the stabilizing feedback loop of street traffic since accessibility influences the service quality of different types of shopping. Nevertheless, shifting effects between service quality and shopping options can still be exploited to influence shopping behavior, especially towards shopping options more independent of individual motorized transport, such as online shopping, 3D home printing, or 3D shop printing. These shopping options tend to generate less individual street traffic compared with classical offline shopping due to the increased independence from individual car use. According to the analysis of systemic roles, the variables *service quality offline shopping* and *service quality 3D shop printing* are likely to trigger changes in the system. Both variables have a relatively high right-eigenvector centrality. Furthermore, both variables have the highest in-degree centrality and left-eigenvector centrality. According to Vester (2019, p. 235), such variables, which are active and reactive simultaneously, can be considered critical in the system. Critical variables can serve as catalysts to trigger changes in the system. Thus, interventions in the variables *service quality offline shopping* and *service quality 3D shop printing* can be used as levers.

The created system model aims to estimate the potential impacts of distributed AM on the system of urban mobility and logistics. Partial scenario 5 and Figure 38 indicate that introducing local 3D printing shops in urban areas may promote active means of non-motorized transport such as walking or cycling on bike lanes for shopping activities. Thus, street traffic for shopping can be decreased. This potential effect is supported by a reinforcing feedback loop, which can increase the density of 3D printing shops. It has to be noted that shopping traffic is only one component of street traffic as a whole. Thus, reductions in street traffic for shopping might induce new traffic through the stabilizing feedback loop of street traffic.

Printing ordered products at home or in local 3D printing shops represents additional shopping options complementing traditional online and offline shopping. This increased offer might lead to rebound effects in shopping volume and traffic. The created effect system shows that increasing sustainability awareness in politics, the economy, and society is necessary to prevent such rebound effects in the system. According to the analysis of systemic roles, the variable *sustainability awareness* has the highest out-degree centrality, right-closeness centrality, and right-eigenvector centrality. Thus, *sustainability awareness* is the most active variable in the whole system and predestined for interventions. Strengthening sustainability awareness in politics, economy, and society decreases shopping volumes and car use.

In conclusion, the introduction of distributed AM represented by 3D shop printing or 3D home printing in urban areas is likely to change people's shopping behavior in the system. If a dense infrastructure and high service quality of 3D printing shops are present, customers are motivated to use active means of transport such as walking or cycling to get to the shops and pick up their produced orders. Thus, car use for traditional offline shopping and van use for home delivery can be partly substituted. Furthermore, a dense infrastructure of 3D printing shops enables non-motorized home delivery causing less street traffic. However, the introduction of distributed AM in urban logistics alone does not solve the problem of urban street traffic since shopping traffic is only one component of urban traffic as a whole.

6.3. Critical Discussion

A system modeling approach is used to evaluate the impacts of distributed AM, represented by 3D printing shops and 3D home printing, on the system of urban mobility and urban logistics (see section 6.1). A modified version of the sensitivity model by Vester (2019) is used to model the investigated system. As described in subsection 6.1.3, the modified sensitivity model enables comprehensible modeling and analysis of complex systems. Furthermore, it enables the participation of stakeholders and experts. However, the modified sensitivity model has some downsides that must be critically discussed.

The modified sensitivity model is a qualitative approach. Thus, the predictive power of quantitative results is limited. Instead, the modified sensitivity model helps to get a deeper understanding of cybernetic mechanisms within a complex system. Generating a set of variables depends on subjective decisions, which decrease the transparency and reproducibility of the results. The first workshop is conducted to increase the objectivity in creating a set of variables and include experts' knowledge. Thus, it is ensured that the selected variables adequately represent the investigated system. The influence matrix also depends on subjective decisions to determine effect strengths between variables. The second expert workshop is conducted to consolidate the influence matrix and to reduce subjectivity. The knowledge of experts is used to revise the initial influence matrix. In addition, research of existing literature dealing with certain relationships between variables is used to support the determination of effect strengths. Although two workshops are conducted to include experts, and scientific literature is reviewed, a certain degree of subjectivity does exist in the results.

The modified sensitivity model does not perform simulations of partial scenarios, which are intended in the classical sensitivity model process according to Vester (2019). The reason for this is the lack of precise input data as described in subsection 6.1.3.

The results of the modified sensitivity model should not be interpreted as a precise quantitative prediction of future changes in variables. The results instead provide deep insights into the cybernetic mechanisms of the system. Furthermore, the modified sensitivity model identifies variables that can be used for adjusting and leveraging changes in the system toward more sustainable urban freight and passenger transport.

Part III

Concluding Discussion and Recommendations

7. **Conclusions**

This last chapter is intended to conclude the dissertation and to provide an outlook on future developments and research. First, the results of the dissertation are summarized. Then, a concluding critical discussion of this dissertation is presented. Since 3D printing shops play an essential role in distributed AM, recommendations for implementing these shops are proposed. Last, the need for further research is identified.

7.1. Summary

The aim of this dissertation is to answer the three defined research questions.

- RQ1 (To what extent can shipments in B2C logistics be substituted using distributed additive manufacturing near the customer?)
- RQ2 (How do home delivery distances in urban areas change due to distributed additive manufacturing represented by 3D printing shops in cities?)
- RQ3 (What effects does distributed additive manufacturing have on the system of urban mobility and logistics?)

For each research question, a method is developed to answer it. The first research question is answered using a printability potential estimation approach, which combines a technological evaluation and a market potential estimation. The classical potential analysis, which examines technical product printability, uses a developed criteria catalog to classify products as printable or not printable. The market-based potential analysis uses a structured estimation method to estimate the extent to which classical shipments in B2C e-commerce can be substituted with distributed AM near the customer. This estimation is based on shipment volumes of product segments in e-commerce. The estimation results show that approximately 6% of shipments in e-commerce could be substituted with distributed AM of the ordered product near the customer. This result only applies to the current state of the art in AM and the selected assumptions.
The second research question examines changes in home delivery fulfillment traffic and distances resulting from distributed AM represented by 3D printing shops in Munich. A simulation approach is developed to answer this research question. This simulation approach optimizes delivery tours of vans to compare delivery distances in different infrastructure scenarios of 3D printing shops. The simulation results indicate that the implementation of distributed AM represented by 3D printing shops in urban logistics leads to an increase in home delivery distances of vans at low substitution rates. At substitution rates of approximately 40%, the total delivery distances of vans start to decrease compared to the status quo scenario where home delivery is only performed from CEP depots. Furthermore, comparing different infrastructure scenarios indicates that a dense infrastructure scenario of 3D printing shops performs better than a sparse infrastructure scenario when it comes to decreasing home delivery distances and, thus, home delivery fulfillment traf-

fic. Distributed AM in urban logistics offers another advantage in addition to reducing delivery distances of vans at high substitution rates. As visualized in Figure 22, local production in 3D printing shops and home delivery from these locations reduces long approaches from CEP depots located outside the city center. Thus, 3D printing shops are an enabler of more sustainable means of freight transport, which are only designed for short delivery distances, especially on the last mile. Examples of such freight transport are presented in Figure 10. 3D printing shops can enable the last mile home delivery using cargo bikes, delivery robots, or drones. These options require less space on streets and can relieve street traffic. 3D printing shops can also enable self-pick-up for customers, substituting home delivery. In conclusion, enabling different means of freight transport is a greater lever for reducing street traffic than simply substituting classical van delivery tours from CEP depots with van delivery tours from 3D printing shops. It is unlikely to reach the required substitution rates for reducing home delivery fulfillment traffic using vans in the near future. Thus, van delivery distances are likely to increase due to the introduction of 3D printing shops, given today's technological capabilities and limited customer demand. Nevertheless, 3D printing shops are likely to emerge in our future cities. For this reason, 3D printing shops must be designed to avoid inducing new street traffic and make urban logistics and home delivery more sustainable. Recommendations for the design and implementation of 3D printing shops in cities are provided in section 7.4.

The third research question examines the potential impacts of distributed AM on the system of urban mobility and logistics. The sensitivity model by Vester (2019) is modified and applied to answer this research question. The results, which experts consolidate in workshops, reveal the cybernetic mechanisms in the investigated system. In opposite to the simulation approach, the modified sensitivity model does not only consider the impacts of distributed AM on home delivery fulfillment traffic. Instead, it examines the potential impacts of distributed AM represented by 3D printing shops and 3D home printing on the whole system of urban mobility and logistics. The system evaluation indicates that distributed AM enables the new shopping options 3D shop printing and 3D home printing. An increase in service quality of these new options can trigger behavioral changes in shopping. This also includes changes in shopping transport and traffic. In conclusion, shopping traffic is only one component of overall street traffic. Therefore, a sustainable reduction in street traffic due to distributed AM is difficult to achieve.

The simulation approach and the modified sensitivity model provide answers to the research questions and represent new methodological approaches that can be adapted and used in further research. In particular, the sensitivity model of Vester (2019) is extended using a detailed analysis of systemic roles and network analysis measures.

7.2. Connection of the Results

Figure 1 presents the interrelations of problems, needs of stakeholders, and the solution approach of distributed AM in urban logistics to derive the research questions of this dissertation. The figure contains certain unknown effects of the solution approach on the needs and problems. The conducted research studies are intended to examine some of these unknown effects. Figure 40 presents the new version of the heuristic effect system introduced in Figure 1 and includes the

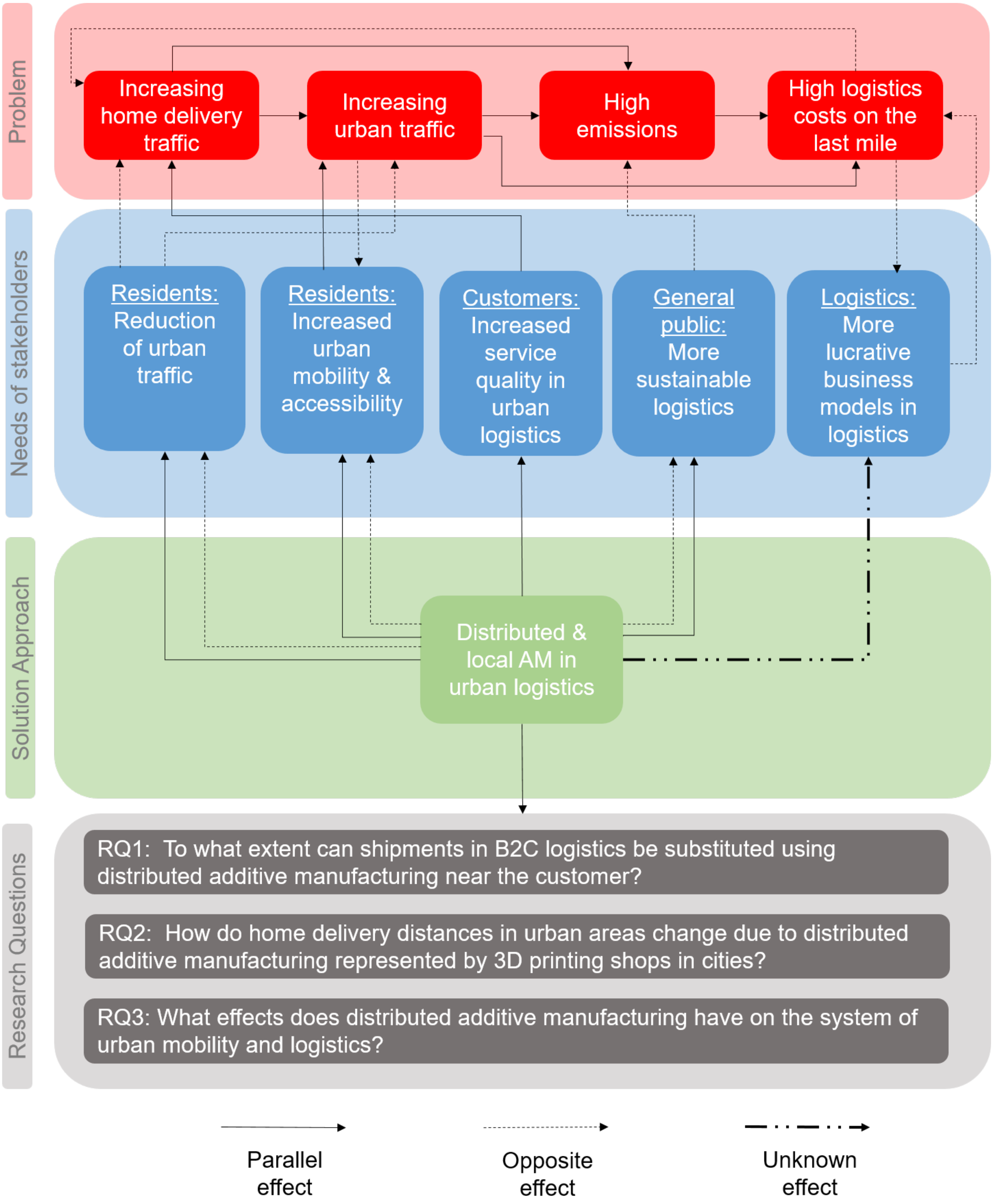


Figure 40 Connection of the results

findings of this dissertation. One central need of residents in urban systems is reducing urban traffic, especially on streets. Urban freight transport and urban logistics are important components influencing urban traffic. Therefore, this dissertation examines the effects of distributed AM on urban traffic by simulating home delivery fulfillment traffic and using a systems modeling approach for the example of Munich. The results are not trivial and depend on certain assumptions. Thus, the effects of distributed AM on urban traffic must be considered in a differentiated manner. Figure 40 indicates that distributed AM in urban logistics may reduce or increase urban traffic under different circumstances. The simulation approach in chapter 5 assumes that distributed AM is performed in 3D printing shops. Ordered products are printed near the customer in these shops. Furthermore, the approach assumes that orders are delivered to the customer using traditional delivery vans. Under these circumstances, home delivery fulfillment traffic in Munich increases if substitution rates are not high enough. At substitution rates of approximately 40%, home delivery fulfillment traffic of vans starts to decrease compared with the status quo given a dense infrastructure of 3D printing shops. The results of the first research study indicate that substitution rates of approximately 6% can be achieved with today's technology. Thus, the required substitution rate to reduce home delivery fulfillment traffic of vans can not be achieved today. Technological developments in the future might increase possible substitution rates. However, a dense infrastructure of 3D printing shops increases proximity to customers and enables the use of more sustainable means of freight transport, such as cargo bikes or self-pick-up by customers who use active means of transport to get to the shops. Home delivery traffic of vans can be reduced if this potential is retrieved. In conclusion, the third research study indicates that freight transport is only one component of urban traffic. For this reason, the traffic reduction potential of distributed AM in urban logistics is limited.

Another need of residents in urban systems is mobility and accessibility. The effects of distributed AM on urban mobility and accessibility are highly connected to the effects on urban traffic. An increase in urban traffic can lead to congestion and an increase in travel time, costs, and comfort. Thus, urban accessibility of people is decreased. Vice versa, a decrease in urban traffic may increase urban accessibility. Since the effects of distributed AM on urban traffic may be parallel or opposite, the effects on urban mobility and accessibility also depend on the assumptions as well as on the design, the implementation, and the adoption of distributed AM in urban areas. Nevertheless, a dense infrastructure of local 3D printing shops increases the accessibility of residents because additional shopping opportunities are in close range. Since accessibility can be defined according to Geurs & van Wee (2004, p.128) as "the extent to which land-use and transport systems enable individuals to reach activities or destinations by means of a transport mode", 3D printing shops can contribute to mixed-use areas, and other concepts such as the 15-minute city according to Moreno et al. (2021) providing a high degree of accessibility.

The implementation of distributed AM increases the service quality of urban logistics because the concept represents a new shopping option for local customers and has the potential for improving last-mile logistics. If the capacities of 3D printing shops are sufficient and technological capabilities exist, orders from customers can be processed and produced immediately. Furthermore, local production near the customer reduces delivery distances on a big scale. Both aspects shorten the supply chain and may reduce delivery times. Thus, the service quality of last-mile logistics can be improved. Furthermore, 3D printing can produce completely new and complex shapes, which is impossible with conventional manufacturing technologies. Thus, entirely new and optimized products can be offered to customers. In addition, customers can print products at home if they have an appropriate 3D printer. In particular, 3D printing of spare parts is useful for customers because it can be used to lengthen product life cycles and thus avoid repurchases of broken products.

Sustainability in logistics is an upcoming demand of the general public. Distributed AM in urban logistics can contribute to this demand. Similar to urban traffic, mobility, and accessibility, the effects are not trivial and depend on the design, implementation, and adoption of distributed AM in cities. If 3D printing shops are used to substitute traditional shopping activities, and a dense infrastructure of these shops is provided, home delivery fulfillment traffic of vans can be reduced. Thus, CO_2-, particle-, and noise emissions can be reduced. These effects contribute to life quality in cities and sustainable last-mile logistics. Nevertheless, the results of chapter 5 and chapter 6 indicate that distributed AM could also decrease sustainability in logistics if the design and implementation of the new concept are not adequately planned.

The lucrativeness of distributed AM is not explicitly investigated in this dissertation. Thus, the contribution of distributed AM to the lucrativeness of business models in urban logistics is still an unknown effect that has to be examined in further research. In particular, further research should investigate how 3D printing shops must be designed to guarantee cost efficiency and profitability.

In conclusion, the results of all research studies are highly connected to each other. The results of the first study provide an estimation of realistic substitution rates. These rates are considered in the simulations and the system modeling approach. The results of the second research study quantify the impacts of distributed AM on urban home delivery fulfillment traffic of vans, for the example of Munich. The system model in the third research study picks up these results and generalizes them by examining the effect of distributed AM on the system of urban mobility and logistics.

7.3. Concluding Critical Discussion

The methodological approaches and results of the three research studies are already critically discussed in section 4.3, section 5.3, and section 6.3. This section is intended to summarize, link, and conclude the critical discussions.

All research studies in this dissertation examine the concept of distributed AM in urban logistics, which is not yet widely implemented today. Thus, future developments and scenarios are examined. This dissertation predicts the potential impacts of distributed AM in urban areas. These predictions cannot be verified at present.

The first research study estimates the extent to which shipments in B2C logistics can be substituted using distributed AM near the customer. This research study's results must be considered a rough estimation since products are aggregated into product segments. Subsequently, the printability of these product segments is estimated using a non-exhaustive criteria catalog. Furthermore, the first research study relies on outdated e-commerce data because current data is not available. For these reasons, the results of the first research study only represent a rough estimation that is used as an indicator for today's technological capabilities of AM/3DP and as input for the other research studies.

The second research study simulates home delivery fulfillment traffic in Munich and compares delivery distances in different infrastructure scenarios of 3D printing shops. This simulation approach relies on many assumptions. It is assumed that distributed AM is explicitly performed in 3D printing shops and that orders are explicitly delivered to customers using delivery vans from the 3D printing shops. Furthermore, only home delivery fulfillment traffic is considered. The material supply of 3D printing shops and returned deliveries are out of scope. Printing capacities, printing times in 3D printing, and the lucrativeness of the shops are assumed to be appropriate. Thus, the results are limited to the assumptions. Since the simulations are performed on the street network of Munich, the second research study should be considered a case study. Thus, the results can not automatically be generalized to other urban environments. However, the results provide first insights into the effects of distributed AM in 3D printing shops on urban home delivery fulfillment traffic and serve to generate hypotheses.

The third research study applies a system model to predict and generalize the effects of distributed AM on urban mobility and logistics. The modified sensitivity model presented in Figure 27 represents a qualitative model. Therefore, the model is not capable of making exact quantitative predictions. Instead, the modified sensitivity model helps to understand the cybernetic mechanisms of the examined system and identify potential policies to successfully implement distributed AM into urban logistics to avoid undesired rebound effects in the system.

In conclusion, this dissertation cannot precisely predict or generalize the effects of distributed AM on urban traffic or mobility. Instead, this dissertation represents a first attempt to quantify the impacts of distributed AM on home delivery fulfillment traffic in a specific case study for Munich under certain assumptions. In addition, this dissertation examines the potential impacts of distributed AM in cities from a systems perspective. A system modeling approach is applied, combining urban passenger and freight transport. Passenger and freight transport are usually examined separately in the existing literature. Thus, this dissertation provides a scientific contribution by combining both aspects in one system model. Furthermore, this dissertation provides a methodological contribution. The system modeling approach applies the sensitivity model of Vester (2019). This sensitivity model is extended by considering centrality measures from graph theory and network analysis to determine systemic roles. This extended method is a scientific contribution and can be used in future research to analyze complex systems. This dissertation should serve as a foundation for further research concerning the impacts of distributed AM on cities.

7.4. Recommendations for the Implementation of Distributed AM in Urban Areas

Distributed AM is starting to emerge in cities. People often use their 3D printers to produce specific products, such as spare parts at home, but 3D printing shops are also occasionally tested. It is questionable whether 3D home printing can be further expanded on a large scale, as it requires the technical skills of customers and private investments in 3D printing technologies. For these reasons, it is more likely that distributed AM will be performed as a service in 3D printing shops in the future.

Distributed AM in 3D printing shops is a new shopping option and may positively affect home delivery fulfillment traffic under certain conditions. However, the simulation results show that home delivery distances and traffic of vans increase at low substitution rates, especially when a 3D printing shop infrastructure is sparse and not yet fully implemented. To still benefit from the potential of 3D printing shops in urban logistics, the concept, infrastructure, and design of these shops should be well planned. For this reason, recommendations for urban planers and operators/owners of 3D printing shops are presented in the following.

Recommendations for Urban Planners

The second research study examines the potential to use 3D printing shops for local production near the customer in urban logistics. The results indicate that urban home delivery fulfillment traffic of vans is likely to increase if the extent of substitution of home delivery from CEP depots with home delivery from 3D printing shops is not high enough. If these substitution rates are appropriate and proximity of 3D printing shops to customers is provided, urban home delivery fulfillment traffic of vans can be reduced. It is questionable if current AM technologies can provide the required substitution rates to decrease urban home delivery fulfillment traffic of vans. Nevertheless, technological developments in the near future may enable the production of a large number of orders and the required substitution rates. Urban planners and logistics companies should be aware of these temporal dynamics if they implement 3D printing shops in urban logistics. They should expect urban home delivery fulfillment traffic of vans to increase at the beginning of implementing local 3D printing shops. However, technological developments in AM and increasing the production capacities and infrastructure of 3D printing shops can reduce traffic in the future.

The results in Table 15 suggest that distributed AM in a dense infrastructure of 3D printing shops leads to shorter home delivery distances of vans than in a sparse infrastructure. Therefore, a dense infrastructure should be aimed for when distributed AM is implemented in cities and urban areas. Such a dense infrastructure offers high proximity to potential customers and enables further benefits. In particular, a dense infrastructure of 3D printing shops enables the use of sustainable means of freight transport, which are designed for short delivery distances, such as cargo bikes, delivery drones, or delivery robots (see Figure 10). These means of transport require less space on streets for delivery compared to traditional delivery vans and can therefore reduce street traffic. For this reason, it is recommended to consider the infrastructure for such sustainable means of freight transport in the design process of 3D printing shops. One practical example of an appropriate infrastructure is the provision of loading zones and paths for cargo bikes.

In addition, a dense infrastructure of 3D printing shops enables customers to pick up the ordered and manufactured products themselves. Thus, 3D printing shops can contribute to mixed-use areas combining residence, shopping, and other important activities in close range. The versatility of 3D printing offers accessibility to many products within walking distance when 3D printing shops are located in mixed-use areas. Self-pick-up by customers substitutes home delivery on the last mile. This is lucrative for logistics companies since last-mile delivery is usually cost-intensive, least efficient, and most polluting (Gevaers et al. 2014, p. 398). If 3D printing shops are located in close range to customers, they can act as advanced micro-hubs. According to Ballare & Lin (2020, p. 279) and Huang et al. (2020, p. 2), micro-hubs are intended to be located inside the city and supplied from depots outside the city center using vehicles with high capacity to bundle as many deliveries as possible. Micro-hubs have to basic functions of storing and sorting (Ballare & Lin 2020, p. 279). Thus, micro-hubs can temporarily store the delivered parcels in lock boxes.

Smaller delivery vehicles can pick up the stored parcels and deliver them to the customers, or they can pick up their parcels at the micro-hub. Thus, the concepts of micro-hubs and 3D printing shops are quite similar. However, 3D printing shops provide an additional advantage and can be denoted as advanced micro-hubs. Instead of parcels, 3D printing shops only need to store printing materials. With these materials, 3D printing shops can manufacture any ordered product. Thus, 3D printing shops are more versatile and have a more efficient storage concept than traditional micro-hubs. Combining 3D printing shops with traditional micro-hubs and post offices is recommended. Thus, the delivery of parcels and printing materials from outer depots to the hub and from the hub to the customer can be bundled. Furthermore, a combination of a 3D printing shop, micro-hub, and post office represents a central location with accessibility to many services.
As already mentioned, a dense infrastructure of 3D printing shops enables self-pick-up, which is lucrative for logistics companies but can also have some undesired effects on transport. Self-pick-up replaces home delivery transport with individual transport of customers to the 3D printing shop. If customers use cars to get to 3D printing shops, this can increase street traffic and cause additional congestion as well as emissions. Therefore, it is recommended to design 3D printing shops so that individual transport by car is prevented. One measure to prevent individual car transport is to provide high proximity from 3D printing shops to customers' residences. A dense infrastructure of 3D printing shops contributes to such proximity and, therefore, decreases delivery distances of vans and promotes active means of transport compared to a sparse infrastructure scenario. Furthermore, individual car transport can be prevented by reducing the accessibility to 3D printing shops by car. Parking bans near 3D printing shops could serve to achieve such an accessibility reduction. However, the evaluation of partial scenarios indicates that restrictions on individual motorized transport to 3D printing shops reduce service quality and can subsequently trigger a reinforcing feedback loop decreasing the density of 3D printing shops (see subsection 6.2.7). For this reason, it is recommended to first support the implementation of a dense infrastructure of 3D printing shops by improving the service quality of these shops. When such an infrastructure is implemented, parking bans can restrict individual car transport to 3D printing shops. The decrease in service quality by restricting car transport should be compensated with other measures. Car transport to 3D printing shops can also be prevented by increasing accessibility via other means of transport. The modified sensitivity model suggests that such an increase may trigger shifting effects and behavioral changes regarding individual transport. Locating 3D printing shops near metro stations or bus stops is recommended to increase accessibility via these means of transport. Furthermore, it is recommended to provide an appropriate biking infrastructure around 3D printing shops to promote self-pick-up by customers using bikes.

If car restrictions are not enforceable and 3D printing shops can only be implemented in areas where cars are predominantly used, it is recommended to locate these 3D printing shops at big hubs, which are regularly approached by cars, such as supermarkets or shopping malls. Thus, customers can couple their car trips, and less additional car use is induced.

The developed system model in chapter 6 suggests that even if the implementation of 3D printing shops is perfectly planned, rebound effects might occur. 3D printing shops represent an additional shopping option and thus increase the overall service quality of shopping. Therefore, consumption and related transport demand might be induced. The system model identifies the variable *sustainability awareness* as a lever to limit these rebound effects. Urban planners and politicians, in general, should raise sustainability awareness to control and limit the rebound effect of induced transport demand for shopping activities.

As mentioned earlier, the density of 3D printing shops is important to support sustainable urban logistics, especially on the last mile. Customer acceptance and customer demand are required to enable such a dense infrastructure. The service quality of 3D printing shops is crucial to increase acceptance and generate demand. Therefore, recommendations for operators and owners of 3D printing shops are also provided to increase the service quality of 3D printing shops. The most important recommendations for urban planners are summarized in the following:

- Be aware of the temporal dynamics involved in the implementation of a 3D printing shop infrastructure.
- Promote a dense infrastructure of 3D printing shops with high customer proximity to enable home delivery by sustainable means of freight transport and self-pick-up.
- Promote self-pick up by public transport, bike or walking instead of by car.
- Combine 3D printing shops with micro-hubs and post offices to bundle deliveries.
- Locate 3D printing shops near big hubs, which are regularly approached such as supermarkets or shopping malls, to allow customers to bundle shopping trips.
- Use dense infrastructure of 3D printing shops to ensure high accessibility, service quality and sufficient production capacity.
- Raise sustainability awareness of politics, economy and society to prevent rebound effects.

Recommendations for Operators and Owners of 3D printing Shops

As mentioned, the service quality of 3D printing shops is crucial to increase customer acceptance and generate customer demand. Therefore, recommendations for operators and owners of 3D printing shops are provided in the following to increase the service quality of 3D printing shops.

First, the offer of printable products should be as high as possible to meet the demand and requirements of as many customers as possible. A wide range of 3D printing technologies provides versatility in production due to various manufacturing principles and printing materials. For 3D printing shops, investing not only in one specific AM technology is recommended. Instead, owning a farm of different machines and technologies is recommended. Thus, different customer requirements can be met. Furthermore, more 3D printers increase the capacity of 3D printing shops. Thus, more customers can be served, and lead times can be reduced. Sufficient production capacity of 3D printing shops can also be ensured through a dense infrastructure which implies a large number of shops in a considered area. In such a dense infrastructure, one 3D printing shop has to cover a smaller area than one 3D printing shop in a sparse infrastructure. Thus, a 3D printing shop serves fewer customers and is more likely to meet the demand. These aspects are decisive in increasing the service quality of 3D printing shops.

Another pivotal aspect of service quality is costs. These costs of products in 3D printing shops should be at least comparable to other shopping options. Thus, shifting effects in shopping behavior can be triggered. Furthermore, shopping comfort is another important component of service quality. For this reason, it is recommended to offer 3D printing as a service in 3D printing shops. Unlike 3D home printing, customers should not have to print their orders themselves. Instead, hiring a technical operator with expertise in additive manufacturing is recommended. Thus, product quality and customer comfort are ensured. In addition, shopping comfort and experience can be increased if 3D printing shops are coupled with social activities in mixed-use areas. Figure 10 shows how such a combination may look like. This concept combines a 3D printing shop with a coffee shop. Customers can have a drink and socialize with others while waiting for the ordered products to be printed and prepared. It is recommended to couple 3D printing shops with locations for social activities. This increases comfort and contributes to the revitalization of social life in city centers threatened by online shopping and the Covid 19 pandemic.

The service quality of 3D printing shops strongly depends on the availability of digital twins. These digital twins are an essential requirement for the 3D printing of products. Thus, digital twins should be provided to customers. In addition, 3D printing shops should provide 3D scanning services to create digital twins of already existing products (see Figure 10).

Today, sustainability is an important factor that determines customers' shopping behavior and thus contributes to the service quality of 3D printing shops. Sustainability in distributed AM has different dimensions. This dissertation focuses on delivery distances on the urban scale. However, local AM has the potential to substitute delivery distances on the global scale, which has the potential to reduce global emissions. 3D printing shops are recommended to promote locale production and their sustainability concept. 3D printing provides the processing of a wide range of recycled printing materials. Thus, 3D printing shops are recommended to offer such recycled materials to their customers. Furthermore, 3D printing enables the inexpensive and uncomplicated production of spare parts in small batch sizes. Thus, 3D printing shops should promote the production of spare parts, enabling the extension of product life cycles. In particular, broken components of products could be reverse-engineered using 3D scanning and subsequently reproduced using 3D printing. Thus, 3D printing shops can prevent new shopping activities for broken products and contribute to the transformation from a consumer society to a repair society.

The most important recommendations for operators and owners of 3D printing shops are summarized in the following:

- Increase service quality of 3D printing shops by offering a wide range of AM technologies.
- Offer 3D printing as a service.
- Design 3D printing shops as social meeting points to increase the shopping experience.
- Provide digital twins.
- Support 3D printing of spare parts to prevent new purchases of complex product systems.
- Make use of the sustainability potentials of distributed AM.

7.5. Scientific Contribution

This dissertation contributes to science by quantifying the transport reduction potential of distributed AM, which has only been abstractly mentioned in previous research. In addition, this dissertation examines the potential impacts of distributed AM in cities from a systems perspective. A system modeling approach is applied, combining urban passenger and freight transport. Passenger and freight transport are usually examined separately in the existing literature. Thus, this dissertation provides a scientific contribution by combining both aspects in one system model. Furthermore, this dissertation provides a methodological contribution. The system modeling approach applies the sensitivity model of Vester (2019). This sensitivity model is extended by considering centrality measures from graph theory and network analysis to determine systemic roles. This extended method is a scientific contribution and can be used in future research to analyze complex systems.

8. Need for Further Research

The need for further research results from the limitations discussed in section 4.3, section 5.3, section 6.3, and section 7.3 . As mentioned in section 4.3, the printability potential estimation is based on outdated shipment data. For this reason, there is a need to collect data on today's shipment volumes of different product segments in e-commerce. In further research, this generated dataset should be used to adjust the estimation of product printability and shipment substitution potential. Furthermore, it should be examined how existing products, classified as not printable, can be re-designed for additive manufacturing. Such a re-design supports distributed AM and opens up new possibilities in urban logistics.

As mentioned in section 5.3, the simulations of home delivery traffic are only conducted on the postal code level due to limited computing power. In the future, increased computing power should be used to simulate more scenarios, more postal code areas, and more extensive areas. Thus, changes in van delivery distances can be estimated more precisely. Furthermore, the developed methodological approach for simulation changes in home delivery traffic due to local production in 3D printing shops should be applied to other cities. This can generate more general results in urban logistics. Furthermore, comparing different cities helps to understand the infrastructure required to implement 3D printing shops sustainably. The simulations conducted in this dissertation only consider vans for home delivery. Instead of only simulating van delivery in urban areas, further research should consider alternative means of freight transport to evaluate changes in home delivery fulfillment traffic. Furthermore, future research should simulate not only home delivery but also individual shopping transport.

The modified sensitivity model qualitatively examines the impacts of 3D printing shops on the system of urban mobility and logistics. Further research could quantitatively evaluate specific components of this system using simulations or a system dynamics approach if required data is available. In addition, further research should examine how 3D printing shops have to be designed to enable alternative freight transport, such as cargo bike delivery, drone delivery, or robot delivery. 3D printing shops can be implemented not only in cities but also in rural areas. For this reason, further research should also investigate the impacts of distributed AM in rural areas. 3D printing shops in rural areas could have an excellent potential for reducing individual shopping traffic since customers in these areas usually have to travel long distances to different shops compared to customers in densely populated urban areas.

The results of this dissertation show that a dense infrastructure of 3D printing shops reduces delivery distances compared to a sparse infrastructure and enables self-pick-up. To implement such a dense infrastructure, 3D printing shops must be lucrative. Therefore, future research should examine the business model of 3D printing shops and how these shops can contribute to saving or earning money in the logistics sector.

Digital twins of products are the basis of distributed AM. Therefore, future research should examine how and in which format digital twins can be saved to provide all relevant information for 3D printing. Furthermore, digital platforms should be designed to exchange these digital twins and to increase accessibility to the production data. In this context, digital rights management has to be

examined. Further research should investigate how additive manufacturing can be used without violating usage or trademark rights.
Specific research questions for further research that can be derived from the investigations and limitations in this dissertation are presented in the following:

- What infrastructure and capacities of 3D printing shops are required to satisfy different customer demands?
- What is the maximum lead time of distributed AM to ensure service quality for customers?
- What business models of distributed AM are lucrative?
- How do digital twins have to be designed and shared to enable distributed AM?
- How can digital twins be used and shared without violating copyrights?
- How is distributed AM adopted by customers?

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9. Appendix

Depot	Latitude	Longitude
DHL Zustellbasis Neuhausen-Nymphenburg (Muenchen City)	48.1449743	11.5239338
DHL Zustellbasis Muenchen Riesenfeld MechZB	48.1890461	11.5608444
DHL Zustellbasis in Muenchen Neuaubing MechZB	48.1380309	11.42086987
DHL Zustellbasis in Ottobrunn	48.07192335	11.64826159
DHL Zustellbasis in Unterschleissheim	48.2635544	11.5938509
DHL Zustellbasis am Neubruch MechZB	48.19325073	11.49571807
DHL Paketzentrum Aschheim	48.16499372	11.73562397
DHL Germering	48.14018264	11.36843261
DPD in Neufahrn (Depot 180)	48.31332545	11.64853814
DPD in Geretsried (Depot 182)	47.88760945	11.43630931
GLS in Erding / Muenchen (Depot 80)	48.30983055	11.88029411
GLS in Geretsried (Depot 81)	47.89005375	11.43368831
Hermes Verteilzentrum Muenchen-Nord	48.50999075	11.57593018
UPS Depot Garching	48.2531505	11.6109962
UPS Depot Muenchen Ost / Kirchheim	48.15616005	11.76397635
UPS Depot Allershausen	48.4298092	11.573378
UPS Depot Wolfratshausen	47.9066738	11.4266271

Table 19 Coordinates of CEP depots

Postal Code Area/Printing Shop ID	Latitude	Longitude
80804	48.17040045	11.57843975
81929	48.1486495	11.6503175
81925	48.16254112	11.62388987
80992	48.17756441	11.51682332
80999	48.18917403	11.45666294
80993	48.18558628	11.52244149
81671	48.12124159	11.61719758
81371	48.11684628	11.54723497
80807	48.18303232	11.57614405
80995	48.2070636	11.53115756
81825	48.11882412	11.65874808
81545	48.08965104	11.56116934
80939	48.20239533	11.60633669
80797	48.16345269	11.56075191

81541	48.11992977	11.58358498
80799	48.15244811	11.57519387
80798	48.15528065	11.56587552
81735	48.10827091	11.64229295
81739	48.08564198	11.65095559
80636	48.15290386	11.54295952
80538	48.14054206	11.58960145
80796	48.16241968	11.57012772
81669	48.12425327	11.59580628
81827	48.11109719	11.6934043
81247	48.16648882	11.47079542
81737	48.10019503	11.64068964
80935	48.2013659	11.5525048
80337	48.12748972	11.55830334
80336	48.1347241	11.55583897
81243	48.14804042	11.43667286
81547	48.10383396	11.57637136
81543	48.11472447	11.56999586
80687	48.1407747	11.50900701
81241	48.14320711	11.46206035
80801	48.15868726	11.57941914
80686	48.1326786	11.50876637
80689	48.13023553	11.48989091
80639	48.15153266	11.51201417
81379	48.09907977	11.530587
81479	48.07848236	11.52325851
80638	48.16317158	11.5163929
81245	48.15871247	11.4463816
80331	48.13539508	11.57197825
81369	48.11165515	11.53230841
80634	48.15037368	11.53079009
80997	48.18248282	11.48604821
81249	48.1510343	11.41391673
81377	48.11208004	11.50144167
81373	48.12153174	11.53394921
80805	48.17462731	11.59739119
81375	48.11947685	11.48688978
80809	48.18324252	11.56136114
81673	48.12824011	11.63085111
81549	48.10170613	11.59912524
80333	48.1490029	11.56433822
81476	48.09236218	11.495491

81679	48.14836523	11.60865668
80469	48.12819867	11.57175546
81667	48.13051118	11.59868917
80937	48.20557798	11.57281017
81829	48.13094841	11.69003681
80339	48.13586861	11.53841204
81677	48.14015158	11.61645661
80803	48.16408448	11.57958719
80802	48.16215033	11.58893457
81475	48.08806355	11.48060318
81477	48.08408296	11.50866593
80335	48.15005435	11.55362174
80933	48.216601	11.55700795
81539	48.1108763	11.58733054
81675	48.13672995	11.60425812
80637	48.16197441	11.53785973
81927	48.16142304	11.63863748
80539	48.14873454	11.58314012
82031	48.04236844	11.53156312
85635	48.0207073	11.71854387
82061	48.09189496	11.46326828
85579	48.07554514	11.6640447
85540	48.10879851	11.72554985

Table 20 Coordinates of 3D printing shops in scenario 2

Printing Shop ID	Latitude	Longitude
3DPS1	48.114839	11.561943
3DPS2	48.113568	11.649178
3DPS3	48.13844	11.482072
3DPS4	48.17331	11.563744

Table 21 Coordinates of 3D printing shops in scenario 3

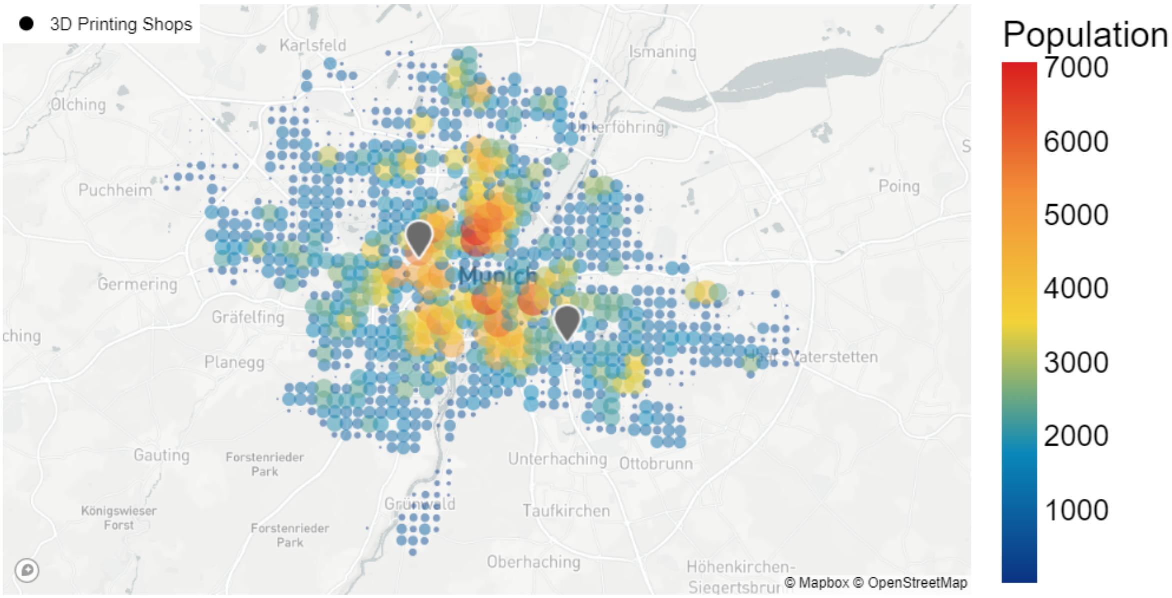


Figure 41 Result of 2-median problem for determining optimized 3D printing shop locations in scenario 3

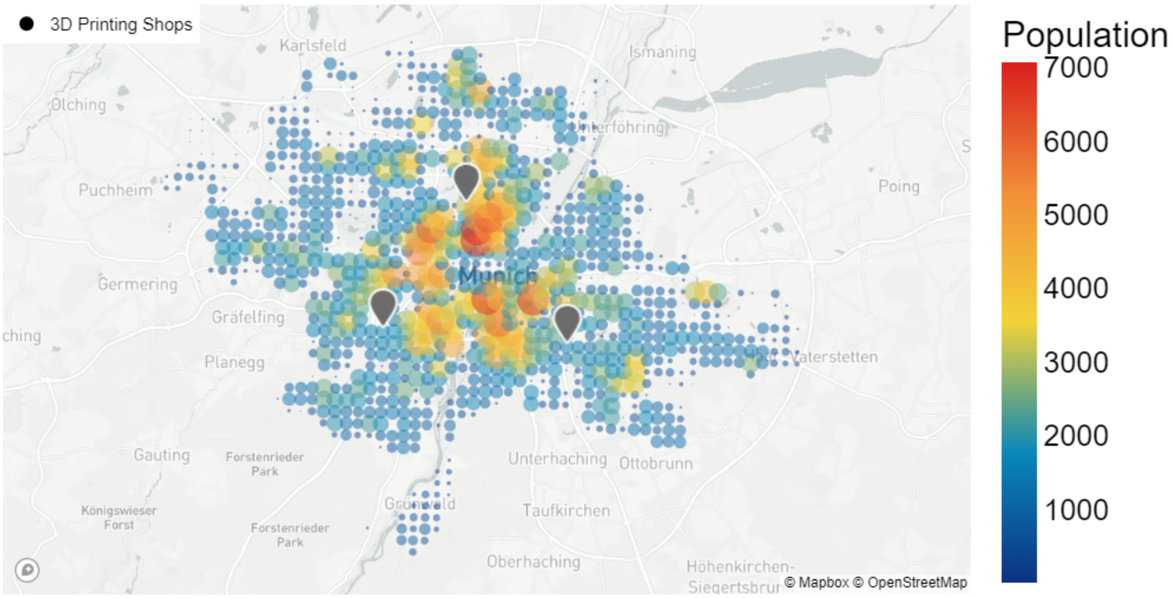


Figure 42 Result of 3-median problem for determining optimized 3D printing shop locations in scenario 3

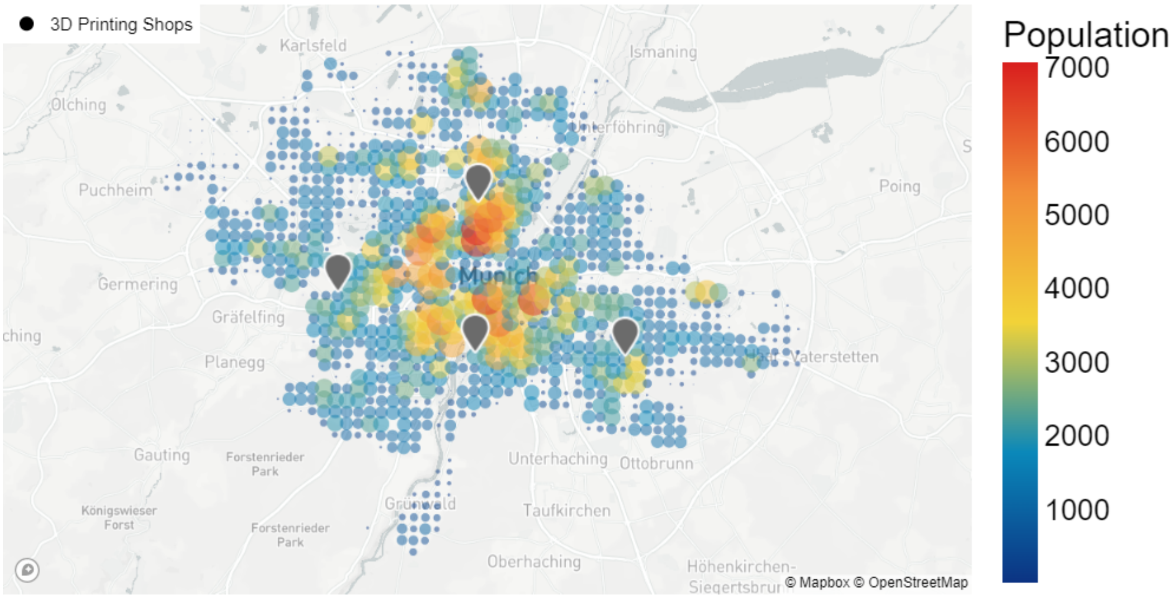


Figure 43 Result of 4-median problem for determining optimized 3D printing shop locations in scenario 3 (chosen variant for scenario 3)

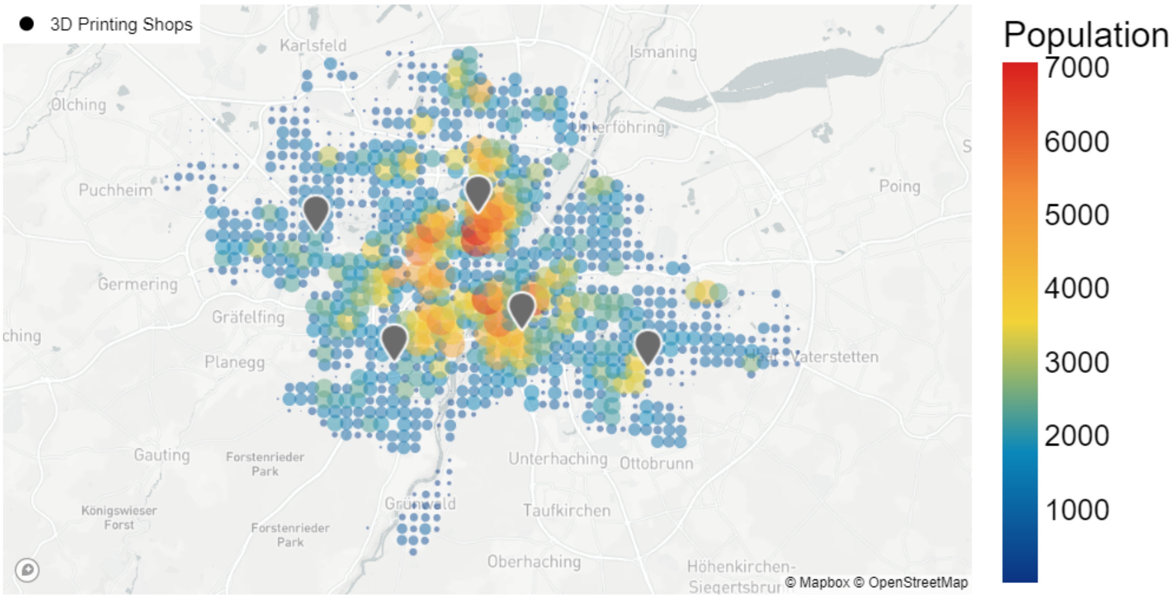


Figure 44 Result of 5-median problem for determining optimized 3D printing shop locations in scenario 3

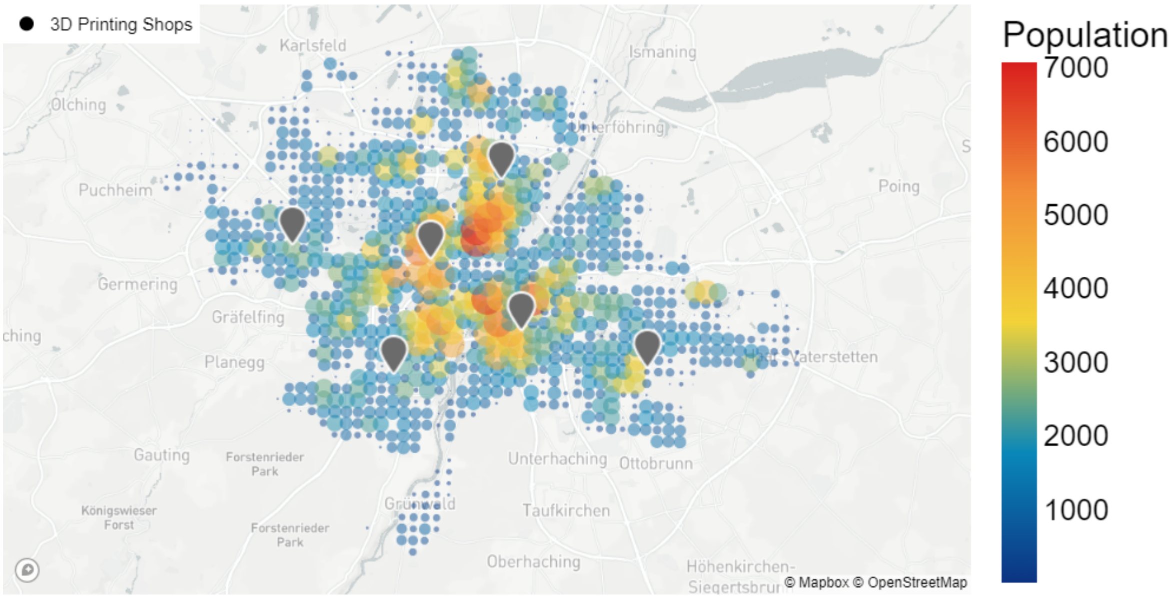


Figure 45 Result of 6-median problem for determining optimized 3D printing shop locations in scenario 3

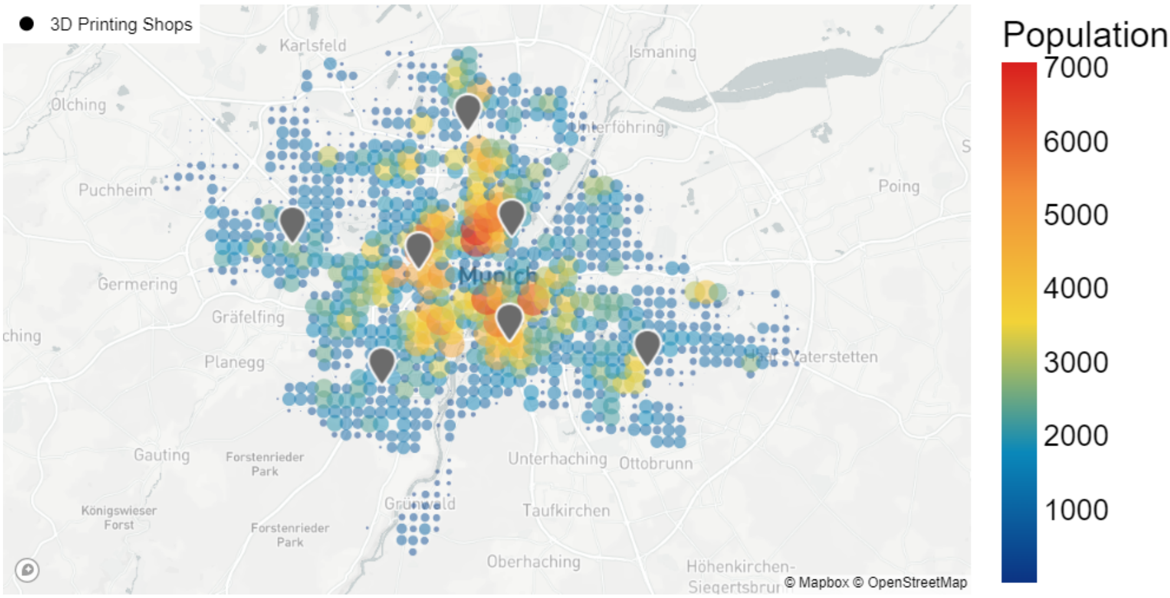


Figure 46 Result of 7-median problem for determining optimized 3D printing shop locations in scenario 3

Postal code area	Scenario	Substitution rate	Region	Costumer rate	Stops	Tours	Tours from 3DPS	Distance	Difference in distance compared to S1
80335	1	0%	inner	0.5	6	348	0	355.22	0.00%
80335	2-1	5%	inner	0.5	7	348	1	367.23	3.38%
80335	2-2	10%	inner	0.5	6	348	1	362.38	2.01%
80335	2-3	20%	inner	0.5	6	348	1	365.24	2.82%
80335	2-4	40%	inner	0.5	6	348	1	354.99	-0.07%
80335	2-5	80%	inner	0.5	7	348	2	333.00	-6.25%
80335	3-1	5%	inner	0.5	7	348	1	373.76	5.22%
80335	3-2	10%	inner	0.5	6	348	1	367.73	3.52%
80335	3-3	20%	inner	0.5	6	348	1	370.42	4.28%
80335	3-4	40%	inner	0.5	6	348	1	364.01	2.47%
80335	3-5	80%	inner	0.5	7	348	2	342.30	-3.64%
80339	1	0%	inner	0.5	6	650	0	402.21	0.00%
80339	2-1	5%	inner	0.5	7	650	1	410.69	2.11%
80339	2-2	10%	inner	0.5	7	650	1	411.61	2.34%
80339	2-3	20%	inner	0.5	7	650	1	409.05	1.70%
80339	2-4	40%	inner	0.5	8	650	2	401.76	-0.11%
80339	2-5	80%	inner	0.5	8	650	3	370.34	-7.92%
80339	3-1	5%	inner	0.5	7	650	1	419.54	4.31%
80339	3-2	10%	inner	0.5	7	650	1	421.71	4.85%
80339	3-3	20%	inner	0.5	7	650	1	430.44	7.02%
80339	3-4	40%	inner	0.5	8	650	2	448.09	11.41%

80339	3-5	80%	inner	0.5	9	650	4	443.44	10.25%
80997	1	0%	outer	0.1	6	473	0	445.45	0.00%
80997	2-1	5%	outer	0.1	7	473	1	464.33	4.24%
80997	2-2	10%	outer	0.1	7	473	1	470.67	5.66%
80997	2-3	20%	outer	0.1	7	473	1	468.18	5.10%
80997	2-4	40%	outer	0.1	8	473	2	459.96	3.26%
80997	2-5	80%	outer	0.1	8	473	3	405.76	-8.91%
80997	3-1	5%	outer	0.1	7	473	1	476.19	6.90%
80997	3-2	10%	outer	0.1	7	473	1	485.29	8.94%
80997	3-3	20%	outer	0.1	7	473	1	480.65	7.90%
80997	3-4	40%	outer	0.1	8	473	2	485.98	9.10%
80997	3-5	80%	outer	0.1	8	473	3	448.87	0.77%
80333	1	0%	inner	0.5	6	485	0	387.71	0.00%
80333	2-1	5%	inner	0.5	7	485	1	397.71	2.58%
80333	2-2	10%	inner	0.5	7	485	1	392.35	1.20%
80333	2-3	20%	inner	0.5	7	485	1	398.63	2.82%
80333	2-4	40%	inner	0.5	7	485	2	389.53	0.47%
80333	2-5	80%	inner	0.5	8	485	3	359.45	-7.29%
80333	3-1	5%	inner	0.5	7	485	1	402.69	3.86%
80333	3-2	10%	inner	0.5	7	485	1	397.70	2.58%
80333	3-3	20%	inner	0.5	7	485	1	400.62	3.33%
80333	3-4	40%	inner	0.5	7	485	2	393.04	1.38%
80333	3-5	80%	inner	0.5	8	485	3	363.29	-6.30%
80331	1	0%	inner	0.5	6	380	0	372.36	0.00%
80331	2-1	5%	inner	0.5	7	380	1	378.46	1.64%
80331	2-2	10%	inner	0.5	7	380	1	376.84	1.20%

80331	2-3	20%	inner	0.5	7	380	1	375.77	0.92%
80331	2-4	40%	inner	0.5	6	380	1	361.09	-3.03%
80331	2-5	80%	inner	0.5	7	380	2	336.36	-9.67%
80331	3-1	5%	inner	0.5	7	380	1	385.45	3.52%
80331	3-2	10%	inner	0.5	7	380	1	383.35	2.95%
80331	3-3	20%	inner	0.5	7	380	1	382.11	2.62%
80331	3-4	40%	inner	0.5	6	380	1	366.45	-1.59%
80331	3-5	80%	inner	0.5	8	380	3	353.00	-5.20%
81929	1	0%	outer	0.1	6	368	0	371.77	0.00%
81929	2-1	5%	outer	0.1	7	368	1	383.15	3.06%
81929	2-2	10%	outer	0.1	7	368	1	386.43	3.94%
81929	2-3	20%	outer	0.1	7	368	1	381.18	2.53%
81929	2-4	40%	outer	0.1	6	368	1	358.64	-3.53%
81929	2-5	80%	outer	0.1	7	368	2	334.01	-10.16%
81929	3-1	5%	outer	0.1	7	368	1	392.57	5.60%
81929	3-2	10%	outer	0.1	7	368	1	394.63	6.15%
81929	3-3	20%	outer	0.1	7	368	1	389.78	4.85%
81929	3-4	40%	outer	0.1	6	368	1	367.82	-1.06%
81929	3-5	80%	outer	0.1	7	368	2	354.58	-4.62%
81475	1	0%	outer	0.1	5	185	0	367.68	0.00%
81475	2-1	5%	outer	0.1	6	185	1	368.87	0.32%
81475	2-2	10%	outer	0.1	6	185	1	377.57	2.69%
81475	2-3	20%	outer	0.1	6	185	1	377.85	2.77%
81475	2-4	40%	outer	0.1	6	185	1	373.05	1.46%
81475	2-5	80%	outer	0.1	6	185	1	357.16	-2.86%
81475	3-1	5%	outer	0.1	6	185	1	380.47	3.48%

81475	3-2	10%	outer	0.1	6	185	1	383.51	4.30%
81475	3-3	20%	outer	0.1	6	185	1	383.19	4.22%
81475	3-4	40%	outer	0.1	6	185	1	380.03	3.36%
81475	3-5	80%	outer	0.1	6	185	1	362.97	-1.28%
80336	1	0%	inner	0.5	6	378	0	352.50	0.00%
80336	2-1	5%	inner	0.5	7	378	1	355.93	0.97%
80336	2-2	10%	inner	0.5	7	378	1	354.28	0.51%
80336	2-3	20%	inner	0.5	6	378	1	347.97	-1.29%
80336	2-4	40%	inner	0.5	6	378	1	344.53	-2.26%
80336	2-5	80%	inner	0.5	7	378	2	317.50	-9.93%
80336	3-1	5%	inner	0.5	7	378	1	361.05	2.42%
80336	3-2	10%	inner	0.5	7	378	1	359.93	2.11%
80336	3-3	20%	inner	0.5	6	378	1	353.83	0.38%
80336	3-4	40%	inner	0.5	6	378	1	351.71	-0.23%
80336	3-5	80%	inner	0.5	7	378	2	333.88	-5.28%
81249	1	0%	outer	0.1	6	428	0	532.63	0.00%
81249	2-1	5%	outer	0.1	7	428	1	550.14	3.29%
81249	2-2	10%	outer	0.1	7	428	1	553.32	3.88%
81249	2-3	20%	outer	0.1	7	428	1	557.89	4.74%
81249	2-4	40%	outer	0.1	8	428	2	545.55	2.43%
81249	2-5	80%	outer	0.1	8	428	3	491.81	-7.67%
81249	3-1	5%	outer	0.1	7	428	1	559.68	5.08%
81249	3-2	10%	outer	0.1	7	428	1	560.79	5.29%
81249	3-3	20%	outer	0.1	7	428	1	566.83	6.42%
81249	3-4	40%	outer	0.1	8	428	2	565.79	6.23%
81249	3-5	80%	outer	0.1	8	428	3	520.94	-2.20%

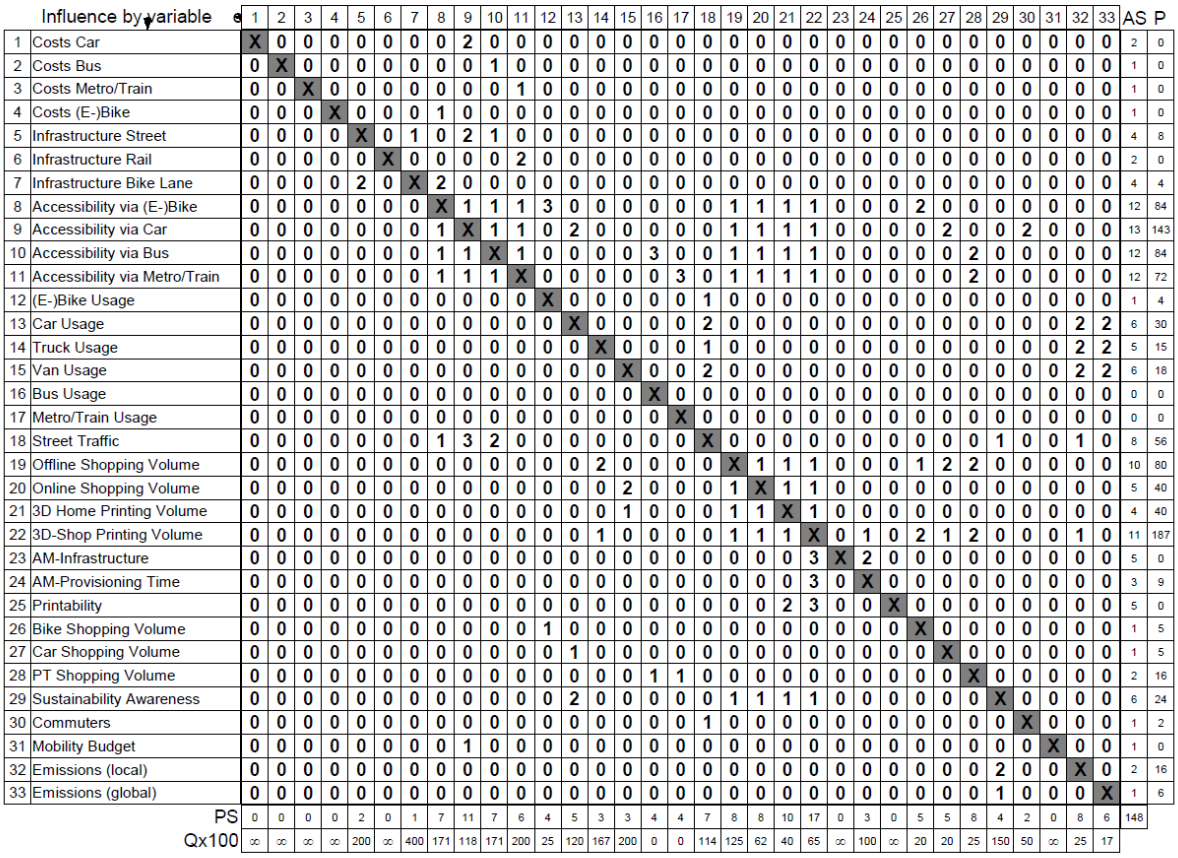
81739	1	0%	outer	0.1	6	414	0	397.21	0.00%
81739	2-1	5%	outer	0.1	7	414	1	408.65	2.88%
81739	2-2	10%	outer	0.1	7	414	1	412.57	3.87%
81739	2-3	20%	outer	0.1	7	414	1	412.40	3.82%
81739	2-4	40%	outer	0.1	7	414	2	403.67	1.63%
81739	2-5	80%	outer	0.1	7	414	2	388.00	-2.32%
81739	3-1	5%	outer	0.1	7	414	1	412.94	3.96%
81739	3-2	10%	outer	0.1	7	414	1	416.50	4.86%
81739	3-3	20%	outer	0.1	7	414	1	412.75	3.91%
81739	3-4	40%	outer	0.1	7	414	2	410.86	3.44%
81739	3-5	80%	outer	0.1	7	414	2	395.42	-0.45%
80337	1	0%	inner	0.5	6	372	0	328.29	0.00%
80337	2-1	5%	inner	0.5	7	372	1	330.42	0.65%
80337	2-2	10%	inner	0.5	7	372	1	327.66	-0.19%
80337	2-3	20%	inner	0.5	6	372	1	322.01	-1.91%
80337	2-4	40%	inner	0.5	6	372	1	317.76	-3.21%
80337	2-5	80%	inner	0.5	7	372	2	306.87	-6.53%
80337	3-1	5%	inner	0.5	7	372	1	335.70	2.26%
80337	3-2	10%	inner	0.5	7	372	1	332.34	1.23%
80337	3-3	20%	inner	0.5	6	372	1	328.62	0.10%
80337	3-4	40%	inner	0.5	6	372	1	332.58	1.31%
80337	3-5	80%	inner	0.5	7	372	2	331.58	1.00%
80939	1	0%	outer	0.1	6	378	0	341.88	0.00%
80939	2-1	5%	outer	0.1	7	378	1	357.34	4.52%
80939	2-2	10%	outer	0.1	7	378	1	359.56	5.17%
80939	2-3	20%	outer	0.1	7	378	1	358.55	4.88%

80939	2-4	40%	outer	0.1	6	378	1	344.63	0.80%
80939	2-5	80%	outer	0.1	7	378	2	318.81	-6.75%
80939	3-1	5%	outer	0.1	7	378	1	364.56	6.63%
80939	3-2	10%	outer	0.1	7	378	1	366.87	7.31%
80939	3-3	20%	outer	0.1	7	378	1	368.76	7.86%
80939	3-4	40%	outer	0.1	7	378	2	362.49	6.03%
80939	3-5	80%	outer	0.1	8	378	3	349.08	2.11%

Table 22 Results of home delivery fulfillment traffic simulations

Variable	Description of variable
Costs Car	Costs of car use in the system
Costs Bus	Costs of bus use in the system
Costs Metro/Train	Costs of metro/train use in the system
Costs (E-)Bikes	Costs of (e-)bike use in the system
Mobility Budget	Budget for mobility
Infrastructure Street	Quality of street infrastructure
Infrastructure Rail	Quality of rail infrastructure
Infrastructure Bike Lane	Quality of bike lane infrastructure
Infrastructure 3D shop printing	Quality of 3D printing shop infrastructure
Accessibility via Car	Accessibility using cars
Accessibility via Bus	Accessibility using the bus
Accessibility via Metro/Train	Accessibility using metro/train
Accessibility via (E-)Bike	Accessibility using (e-)bikes
Accessibility 3D shop printing	Accessibility to the ordered product in the 3D printing shop
Accessibility 3D home printing	Accessibility to the ordered product using 3D home printing
Car use	Extent of car use
Bus use	Extent of bus use
Metro/Train use	Extent of metro/train use
(E-)Bike use	Extent of (e-)bike use
Truck use	Extent of truck use
Van use	Extent of van use
Street Traffic	Extent of traffic on streets in the system
Offline Shopping volume	Volume of offline shopping in the system
Online Shopping volume	Volume of online shopping in system
3D-Shop Printing Volume	Volume of 3D shop printing in the system
3D Home Printing Volume	Volume of 3D home printing in system
Sustainability Awareness	Extent of sustainability awareness from people and companies
Commuters	Amount of commuters
Emissions (local)	Extent of emitted local emissions in the system
Emissions (global)	Extent of emitted global emissions in the system

Table 23 Initial version of the set of variables



	Influence by variable	1	2	3	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	32	33	AS	P
1	Costs Car	X	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
2	Costs Bus	0	X	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
3	Costs Metro/Train	0	0	X	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
4	Costs (E-)Bike	0	0	0	X	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
5	Infrastructure Street	0	0	0	0	X	0	1	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	8
6	Infrastructure Rail	0	0	0	0	0	X	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
7	Infrastructure Bike Lane	0	0	0	0	2	0	X	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	4
8	Accessibility via (E-)Bike	0	0	0	0	0	0	0	X	1	1	1	3	0	0	0	0	0	0	1	1	1	1	0	0	0	2	0	0	0	0	0	0	0	12	84
9	Accessibility via Car	0	0	0	0	0	0	0	1	X	1	1	0	2	0	0	0	0	0	1	1	1	1	0	0	0	0	2	0	0	2	0	0	0	13	143
10	Accessibility via Bus	0	0	0	0	0	0	0	1	1	X	1	0	0	0	0	3	0	0	1	1	1	1	0	0	0	0	0	2	0	0	0	0	0	12	84
11	Accessibility via Metro/Train	0	0	0	0	0	0	0	1	1	1	X	0	0	0	0	0	3	0	1	1	1	1	0	0	0	0	0	2	0	0	0	0	0	12	72
12	(E-)Bike Usage	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	4
13	Car Usage	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	6	30
14	Truck Usage	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	5	15
15	Van Usage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	6	18
16	Bus Usage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	Metro/Train Usage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	Street Traffic	0	0	0	0	0	0	0	1	3	2	0	0	0	0	0	0	0	X	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	8	56
19	Offline Shopping Volume	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	X	1	1	1	0	0	0	1	2	2	0	0	0	0	0	10	80
20	Online Shopping Volume	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	X	1	1	0	0	0	0	0	0	0	0	0	0	0	5	40
21	3D Home Printing Volume	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	X	1	0	0	0	0	0	0	0	0	0	0	0	4	40
22	3D-Shop Printing Volume	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	X	0	1	0	2	1	2	0	0	0	1	0	11	187
23	AM-Infrastructure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	X	2	0	0	0	0	0	0	0	0	0	5	0
24	AM-Provisioning Time	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	X	0	0	0	0	0	0	0	0	0	3	9
25	Printability	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	3	0	0	X	0	0	0	0	0	0	0	0	5	0
26	Bike Shopping Volume	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	0	0	0	0	1	5
27	Car Shopping Volume	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	0	0	0	1	5
28	PT Shopping Volume	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	X	0	0	0	0	0	2	16
29	Sustainability Awareness	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	X	0	0	0	0	6	24
30	Commuters	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	X	0	0	0	1	2
31	Mobility Budget	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	X	0	0	1	0
32	Emissions (local)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	X	0	2	16
33	Emissions (global)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	X	1	6
	PS	0	0	0	0	2	0	1	7	11	7	6	4	5	3	3	4	4	7	8	8	10	17	0	3	0	5	5	8	4	2	0	8	6	148	
	Qx100	∞	∞	∞	∞	200	∞	400	171	118	171	200	25	120	167	200	0	0	114	125	62	40	65	∞	100	∞	20	20	25	150	50	∞	25	17		

Figure 47 Initial influence matrix (output of the sensitivity model software)

Effect of	Effect on	Strength	Explanation of effect strength
Accessibilities	Accessibilities	1	Per own definition, the accessibility of the means of transport in the system are relative factors and thus influence each other. If one accessibility increases, all the other accessibilities are relatively decreased. According to the proposed mathematical definition, these effects of accessibilities on each other have to be lower than proportional (1).
Accessibilities	Offline Shopping Volume & 3D shop printing	1	It is assumed that increasing accessibility via means of transport increases the accessibility of offline shopping destinations and 3D printing shops. The effects are assumed to be lower than proportional (1) because they are split and assigned to different means of transport.
Accessibility via Car	Car Use	2	It is assumed that accessibility via car is the most important reason for car use. Accessibility contains costs, travel speed, and travel comfort. It is also assumed that the elasticity of car use is relatively low compared to other means of transport due to relatively high purchasing costs. That is why the effect is only set to 2 (contrary to the other means of transport, whose accessibilities have an effect strength of 3 on their use).
Car Use	Street Traffic	3	It is assumed that cars make up the majority of traffic participants on the streets. In addition, cars consume much space compared to other means of transport (such as bikes). Therefore, the effect is set to 3
Truck Use	Street Traffic	1	Trucks are mainly used for delivery to shops, stores, and distribution hubs (in contrast to vans, which are responsible for delivery to customers). These shops and stores are often located outside of city centers. Furthermore, the number of trucks in urban areas is relatively small. For these reasons, the effect is set to 1.

Van Use	Street Traffic	2	Vans are mainly responsible for delivery to private customers within the system. Hence, vans are used in city centers. Although the number of vans on urban streets is relatively small compared to the number of cars, it is assumed that vans can generate congestion due to the consumption of urban space while driving and parking (often in the second row) during their delivery activities. For these reasons, the effect is set to 2.
Bus Use	Street Traffic, Emissions (local) and Emissions (global)	0	reflected in street traffic because these changes, first of all, lead to changes in utilization rates of the existing bus routes and not to changes in the number of used buses. Furthermore, the number of buses in urban areas is relatively small compared to the number of cars. For these reasons, the effects on street traffic and emissions are set to 0.
Car Use, Truck Use, and Van Use	Emissions (local)	2	Cars, trucks, and vans emit local emissions (such as particles and noise) especially if they are still using combustion engines. All effects are therefore set to 2.
Car Use, Truck Use, and Van Use	Emissions (global)	2	Cars, trucks, and vans emit global emissions (CO2). All effects are therefore set to 2.
Street Traffic	Accessibility via (E-)Bike	1	Traffic on streets reduces travel speed as well as travel comfort and hence affects accessibility via (e-)bike. The effect is only set to 1 because (e-)bike users still have the opportunity to use bike lanes, which are per definition excluded from classical streets.
Street Traffic	Accessibility via Car	3	Traffic on streets reduces travel speed, travel comfort and also increases costs for car drivers. Hence, accessibility via car is strongly affected. As all three main components of accessibility via car are affected, the effect is set to 3.

Street Traffic	Accessibility via Bus	2	Traffic on streets reduces travel speed as well as travel comfort and hence affects accessibility via bus. Some bus routes in urban areas contain explicit bus lanes which can be used to bypass street traffic. It is assumed that such bus lanes are exceptions. For these reasons, the effect is set to 2.
Street Traffic	Sustainability Awareness	1	It is assumed, that especially increases in street traffic can raise the sustainability awareness of people in the urban system. This effect is estimated to be quite small (1).
Street Traffic	Emissions (local)	1	Congestion leads to an increase in the traffic noise level. As noise emissions are mainly affected by the use of means of transport, this additional effect is set to be quite small (1).
Offline Shopping Volume	Truck Use	2	Changes in offline shopping volume imply changes in truck use because trucks have to be deployed to supply offline shops/stores. This effect is set to be proportional (2).
Offline Shopping Volume	Van Use	1	In contrast to trucks, vans are used less frequently to supply offline shops. Thus, the effect strength is set to 1.
Offline Shopping Volume	(E-)Bike Use	1	Offline shopping requires means of transport to access the shopping destinations. (E-)bikes are one option for reaching these destinations. Therefore, offline shopping volume effects (e-bike) use. The effect strength is set to 1 because offline shopping is only one part of activities, that are accessed via (e-)bike.
Offline Shopping Volume	Car Use	1	Offline shopping requires means of transport to access the shopping destinations. Cars are one option for reaching these destinations. Therefore, offline shopping volume affects car use. The effect strength is set to 1 because offline shopping is only one part of activities, that are accessed via car.

Offline Shopping Volume	Bus Use	1	Offline shopping requires means of transport to access the shopping destinations. The bus is one option for reaching these destinations. Therefore, offline shopping volume affects bus use. The effect strength is set to 1 because offline shopping is only one part of activities, that are accessed via bus.
Offline Shopping Volume	Metro/Train Use	1	Offline shopping requires means of transport to access the shopping destinations. Metro/Train is one option for reaching these destinations. Therefore, offline shopping volume affects metro/train use. The effect strength is set to 1 because offline shopping is only one part of activities, that are accessed via metro/train.
Offline Shopping Volume	Service Quality Offline Shopping	2	An increase in offline shopping volume enables the providers to increase their service quality.
Online Shopping Volume	Truck Use	0	It is assumed, that trucks deliver orders to distribution hubs, which are in most cases located outside the urban system. Therefore, the effect is set to 0.
Online Shopping Volume	Van Use	2	It is assumed, the vans are usually deployed to deliver orders to the private customers within the urban system. Therefore, the effect strength is set to be proportional (2).
3D Home Printing Volume	Van Use	1	3D-home-printing requires printing materials, that are assumed to be delivered directly to private households using vans. It is also assumed, that printing materials only make up a small part of van deliveries (at least in today's situation). Furthermore, printing materials can be delivered efficiently in great quantities (in contrast to finished products, which are typically required in smaller quantities). For these reasons, the effect strength is set to be lower than proportional (1).

3D Shop Printing Volume	Van Use	1	3D-printing shops also have to be supplied with printing materials. Similar to the supply of private households, printing materials can be delivered efficiently in great quantities. This aspect has the potential to save van trips. Therefore, the effect strength is set to be lower than proportional (1).
3D Shop Printing Volume	Service Quality 3D Shop Printing	1	Changes in 3D Shop Printing Volumes lead to changes in capacity utilization of 3D-printing shops. Hence, the provisioning time of 3D-printed products, which is part of the service quality of 3D shop printing, can be affected. Overall the effect is set to be proportional (2).
3D Shop Printing Volume	(E-)Bike Use	1	The concept of 3D-printing shops provides close proximity to private customers. Hence, 3D-printing shops are well accessible via (e-)bike or walking. Trips to 3D-printing shops are only one part of all (e-)bike or walking trips within the system. For these reasons, the effect is set to 1. Note that the effect of 3D Shop Printing Volumes on the use of different means of transport highly depends on the infrastructure and accessibility of 3D-printing shops. Hence, these effects can vary in different scenarios.
3D Shop Printing Volume	Car Use	0	The concept of 3D-printing shops provides close proximity to private customers. Therefore, 3D-printing shops can be easier accessed by foot, via bikes, or public transport than by cars. For this reason, the effect is set to 0. Note that the effect of 3D Shop Printing Volumes on the use of different means of transport highly depends on the infrastructure and accessibility of 3D-printing shops. Hence, these effects can vary in different scenarios.

3D Shop Printing Volume	Emissions (local)	1	3D-printing shops have the potential to shift classical production to decentralized production within urban areas. Such a production implies local emissions such as noise or particles, which are emitted in the 3D-printing process (if no appropriate filtering systems are deployed). Still, the effect is set to be lower than proportional, because there are many other emitters of local emissions (especially in traffic).
Sustainability Awareness	Accessibilities	1	Sustainability awareness in politics can lead to policies increasing or decreasing the accessibility of certain means of transport. However, the effect strengths of such policies are assumed to be limited (1).
Sustainability Awareness	Car Use	2	It is assumed that an increased sustainability awareness of residents leads to decreased car use because a reduction of traffic and emissions is targeted. A decrease in sustainability awareness is expected to dismiss this target. The effect is expected to be proportional (2). The indirect effects on the use of the other means of transport are covered through the shifting effects of/on themselves.
Sustainability Awareness	Shopping and Printing Volumes	1	It is assumed that sustainability awareness affects consumer behavior and thus also shopping and printing volumes. Especially in an affluent society, growing sustainability awareness can lead to cutting consumption. The effect strength is set to be lower than proportional (1) because certain purchases are still necessary for living.
Emissions (local)	Sustainability Awareness	2	Local emissions such as noise or particles are directly perceptible within the system. Therefore, it is assumed that local emissions may affect the sustainability awareness of people. Due to the direct perception, the effect strength is set to 2.

Emissions (global)	Sustainability Awareness	1	Global emissions (such as CO2), which are produced within the considered system, are usually not directly perceptible. Still, it is assumed that global emissions affect sustainability awareness especially due to rising awareness of climate change. The effect strength is set to 1.
Service qualities of offl. shopping, onl. shopping and 3D shop printing	Service qualities of offl. shopping, onl. shopping and 3D shop printing	2	It is defined, that service qualities of different shopping and printing options are relative factors. Thus, shifting effects occur. The effect strength is proportional (2).
Service quality of 3D home printing	Service qualities of offl. shopping, onl. shopping and 3D shop printing	1	The technological capabilities of 3D printing at home are limited. Usually, people do not have the technological capabilities of 3D printing shops at home. Thus, 3D home printing can only partly substitute the other shopping activities. The effect strength is set to be lower than proportional (1).
Service qualities of offl. shopping, onl. shopping and 3D shop printing	Service quality of 3D home printing	1	3D home printing is only suitable for selected products due to technological limitations. Therefore, the relative service quality is only little affected by shifting effects between service qualities (1).

Table 24 Explanation of non-trivial effects and their strengths