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Simulation-Based Evaluation Of The Hub-And-Spoke Concept To Support The Centrally Managed Supply Of Urban Factories

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Abstract

The progressive urbanization and increasing decentralization of manufacturing lead to a growing need for the integration of manufacturing plants into urban areas. As a result, industrially induced traffic volumes and emissions are increasing in these areas. Therefore, it is important to manage urban logistics as effective as possible to reduce costs and environmental impacts. A promising approach to support the effective supply of urban factories can be seen in a centrally managed supply. Especially the hub-and-spoke concept is known to solve the problem of the last mile, e.g. within the parcel-industry. That is why most past research activities about hub-and-spoke concepts focus on deliveries to individuals or deliveries in the retail sector while only considering parcel deliveries. However, differing from the parcel industry the supply of urban factories requires especially just in time and just in sequence deliveries. Therefore, new approaches are required which help to analyse if and how a centrally managed supply of urban factories can support the reduction of traffic volumes and with this costs and environmental impacts. In this contribution we conduct a feasibility study on the effectiveness of a centrally managed supply of urban factories using a simulation approach. Based on the analysis of possible stakeholders and different hub concepts, we take a closer look on the application of the hub-and-spoke concept for urban logistics and provide a simulation based evaluation realized with the software Simulation of Urban Mobility (SUMO).

Keywords

Urban Factories; Logistics; Simulation-based evaluation; Emissions; Traffic Volume

1. Introduction

In the year 2018, more than half of the world´s population lived in urban areas, while forecasts predict further growth [1]. Because of that, urban factories are facing new challenges. In principle, there are two kinds of urban factories: On the one hand, there are factories, which originally were build outside of the city and, because of the urbanization, are now producing right next to residential areas. On the other hand, there are those factories, which are planned and build right in the city to use potentials of urban areas because of new production technologies and business models. [2] A decisive factor for the acceptance for both kinds of urban factories is the design of effective logistics flows within the city, which can help reducing the traffic volume and meeting emission limits. German cities frequently struggle with high pollutant emissions resulting from high traffic volume. Therefore, new approaches are needed to lower the traffic volume, especially the one resulting from industry-related logistics. One approach, which tackles the challenge of the “last mile” within the logistics of the parcel industry, is the hub-and-spoke concept [3–5]. In this approach, a centrally managed node (= hub) functions as a decoupling element between the decentrally organized flow of goods to the city boundaries and the centrally organized deliveries within the city. Even though the hub-and-spoke concept promises a high potential, it has not been evaluated thoroughly in the context of industry-related deliveries. Furthermore, production specific characteristics, e.g. just in time deliveries, have to be considered. That is why this work focusses on conceptualizing the centrally managed supply of urban factories and aims to conduct a feasibility study using a simulation-based approach. To this end, the paper is structured as follows: Section 2 shows the relevant state of research as a basis for the introduction of the methodology in section 3. Section 4 then illustrates the development process of the simulation-based approach, which is exemplarily applied in a case study in section 5. Finally, section 6 concludes this work and gives an outlook.

2. State of research

The importance of sustainable inner-city logistics has been emphasized by a wide variety of researchers, e.g. [6,7]. In literature, different approaches are proposed which aim at achieving a city-compatible and economical supply of goods while also considering the ecological needs of the environment. For example, Bernsmann and Vashtag [6] consider the creation of incentives instead of driving bans for freight traffic as an adequate approach and propose, among other things, electric mobility, night deliveries and small logistical locations in the heart of the city as possible solutions. Russo and Comi [8] investigate the relationships between city characteristics and the possible reduction of pollutant emissions and present a tool that can be used to identify promising measures to reduce pollutant emissions in a given city. Hesse [9] recommends traditional forms of planning as well as cooperation between companies or between municipal planning and companies as building blocks for a city logistics concept. Moreover, the use of various instruments is examined to determine ecological or urban quality standards for freight transport in new planning projects. Furthermore, an important and complex task is finding the best long-term location for a facility, which is why Kik et al. [10] introduce the Regional Facility Location and Development Planning Problem (RFLDP) and present a model that supports a company´s process of selecting a facility location. Gevaers et al. [11] use best practices and case studies to describe new concepts for solving inner-city delivery problems of the last mile. In addition to the delivery of mail to individuals, the transport of goods to companies and factories is also considered and technological innovations are highlighted. Göpfert [12] addresses numerous logistics visions and successful strategies for companies. The latest topics in future research for logistics, such as autonomous data-driven logistics, sustainable supply chains in the sense of the last mile and flexibility in complex supply networks, are dealt with. Besides the topic of the last mile, the necessity of data-driven approaches is also being examined in various papers: Ehmke offers a quantification of the value of dynamic and time-dependent information for improved route guidance in city logistics and connects different areas of traffic data acquisition with data mining and research techniques [13]. Furthermore, Montoya et al. [14] provide a quantitative assessment of the effects of collaborative approaches and mathematical models for optimizing inner-city freight traffic. There is also preliminary work for the simulation of transport orders for which free card and traffic data were used [15–17]. Taniguchi et al. [18] present recent trends and innovations in modelling city logistics with a focus on emissions, health care problems and logistics modelling for mega cities. Particularly for parcel deliveries the hub-and-spoke concept has been investigated and proven to be suitable to minimize the driven distance and time used for deliveries [19–22]. However, so far, little is known about its application to industry-related deliveries since there are no studies about the hub-and-spoke concept that consider production specific requirements, e.g. just in time deliveries. That is why this paper aims at filling exactly that research gap by investigating if a hub-and-spoke concept has any benefits in regards to driven distance and pollutant emissions in the context of urban factories.

3. Methodology

Based on the afore mentioned research gap an integrated approach for the evaluation of hub-and-spoke concepts for industry-related deliveries is proposed and exemplarily applied. The following research question is addressed: "How can the industry-related traffic volumes and the resulting pollutant emissions in cities be reduced using a hub-and-spoke concept?" The air pollution not only depends on emission-free drive concepts, but also on traffic disruption, e.g. congestions. Therefore the traffic management is very important to plan the traffic as effective as possible [23,24]. To do that, new forms of regulation for transportation planning processes and a broader database are needed [25]. The planning processes have to be aligned with each other, which is why a centrally managed organization makes sense. Accordingly, it can be hypothesized that a centrally managed supply of urban factories by using the hub-and-spoke concept may also reduce the traffic volume and resulting pollutant emissions. To prove this hypothesis, a simulation-based feasibility study is conducted. Therefore, first requirements for this concept are investigated by using a stakeholder-analysis based on a literature review. Afterwards the simulation approach is developed. It is based on the investigated requirements and considers the selection of different delivery car types that are usable in inner cities, just in time deliveries, a methodology to consolidate deliveries and different average speed of individual car traffic in inner cities dependent on the daytime. Finally, the simulation is used in a case study in the city of Hamburg. For the simulation the Software SUMO is used, which is a microscopic, free access traffic simulation that enables loading open source card data into it [26]. The simulation approach is closely linked to the development of the requirements of the stakeholders and a holistic evaluation system as well as the conception of distribution centres, means of transport planning and fleet combination. In this way, a comprehensive evaluation of sustainable inner-city logistics concepts can be guaranteed. The approach further offers potential for scenario-based analysis and redesign of inner-city logistics concepts.

4. Development of the simulation study

As a foundation of the simulation-based approach, a stakeholder analysis is implemented (see Figure 1).

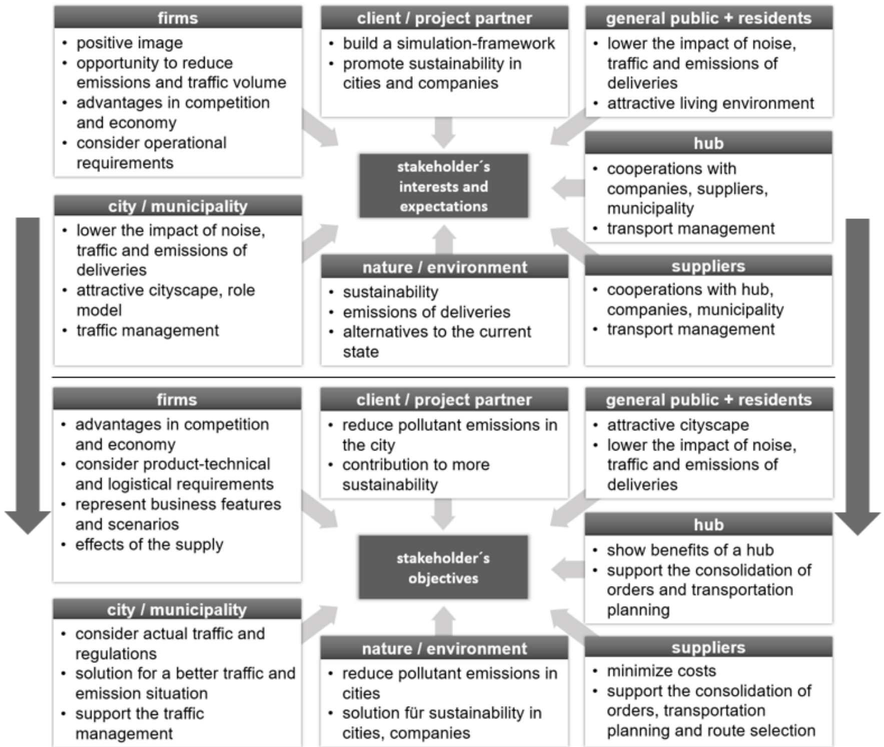

Figure 1: Stakeholder´s interests and expectations (on top), stakeholder´s objectives (bottom), derived based on [27,28]

The stakeholder analysis is based on a qualitative literature review and the approach described by [27,28]. It serves the derivation of the interests and expectations of all relevant stakeholders and consequently of their objectives as a basis for the simulation. The stakeholder analysis comprises firms, clients and project partners / clients, general public and residents, the hub itself, suppliers, the city or municipality as well as the nature and environment. Thereby, firms and municipality can be seen as the most important stakeholders in regards to the implementation of a simulation-based evaluation of the hub-and-spoke concept, since those are the possible end users of the simulation and the subsequent evaluation.

Based on the stakeholder objectives, which are derived from the stakeholder´s interests and expectations, the technical and organizational requirements of a hub, the requirements on the formation of transport orders for industry-related delivery as well as the requirements for the simulation study are formulated as illustrated in Figure 2. The technical and organizational requirements of a hub are derived from the stakeholder objectives and serve as a basis for the formation of transport orders for industry-related delivery, which should consider the shown requirements. Also based on the findings of the stakeholder-analysis, it is possible to generate the requirements for the simulation study that are shown as well.

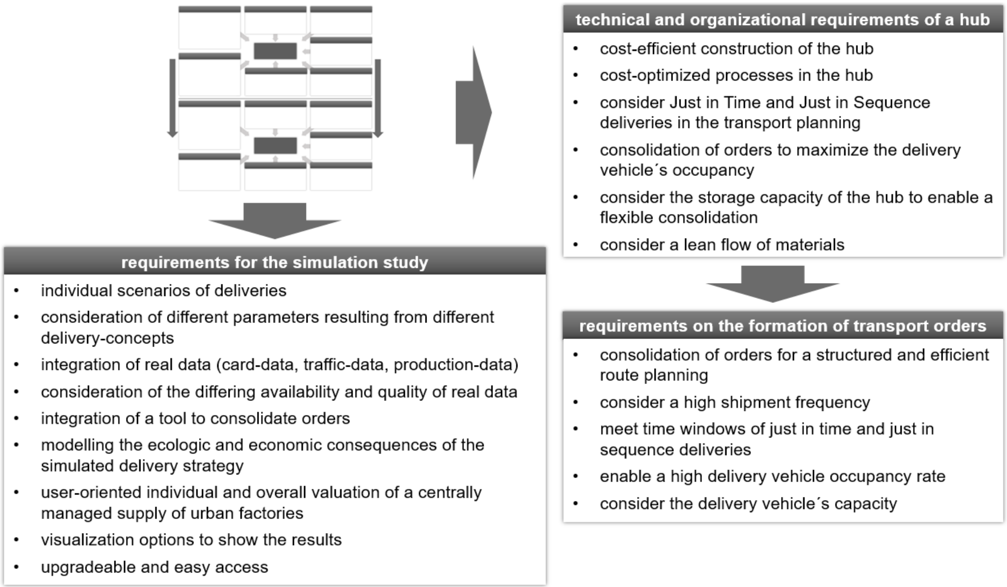

Figure 2: Requirements for the simulation study, technical and organizational requirements of a hub and requirements on the formation of transport orders

With the knowledge about requirements, the simulation approach can be build. It consists of five different modules: 1) the setup-module, 2) the firm-module, 3) the activity-module, 4) the simulation-module and 5) the visualization-module. The *setup-module* is used to build the environment within the simulation, e.g. streets from real card-data, traffic regulations, speed limits and locations of factories. The card-data can be downloaded from OpenStreetMap (OSM), which is an open system that can be edited and shared by users free of charge. In regards to OSM it has to be taken into account that the data is not suitable to use for use-cases where a high level of detail is needed since specific data is missing sometimes, e.g. broad width or acceleration lanes [29]. Furthermore, a few errors of the integration process of the OSM-data into SUMO are existent: Traffic lights sometimes do not function as they should and the traffic regulations are faulty when there are too many vehicles in the simulation. In addition, there is only data about speed limits, but not about traffic demand. In reality, the average driven speed is lower than the speed limit, especially in the inner city [30]. The actual speed of vehicles is affected by many factors, such as seasonal characteristics, the daytime or weather conditions. This information often gets integrated into a simulation by using induction loop measurements. To counteract the described factors and to make the definition process of the simulation easier, average speeds can be used in dependence of the daytime. Figure 3 shows these average speeds. Hence, the most congested times are between six and eight am and between four and five pm.

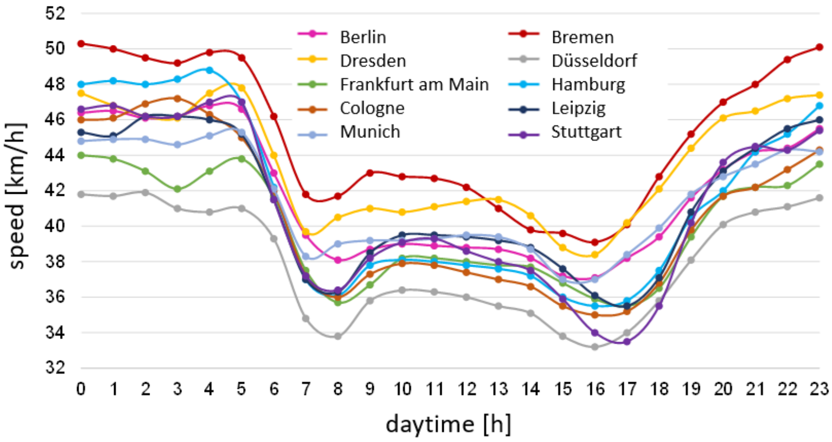

Figure 3: Average speed of individual car traffic in selected german cities (following [31])

The *firm-module* contains data about the simulated firms in an excel sheet, e.g. deliveries per day, weight of the deliveries, number of just in time deliveries. With this data, a python script generates a list of orders. This list is then used in the *activity-module* to generate a file in XML-format, which is used in SUMO to simulate the individual tours. For that, starting points and departure times of the vehicles are generated. If a hub should be considered, other restrictions apply: the time difference between two orders that may get consolidated to one is limited to avoid high stocks within the hub. Furthermore, the total weight of consolidated orders must not exceed the limit of the used delivery vehicle and the total route length as well as the number of stops is limited. While meeting these restrictions the best combination of orders to consolidate is chosen by following this priority:

1. The delivery vehicle should be as small as possible while being as fully laden as possible.
2. The orders that get combined preferably should have the same destination.
3. The occupancy of the delivery vehicle should be as high as possible.
4. The time difference between orders that may get combined should be as small as possible.

In addition, the orders get chronological ordered in a way that the distance is as small as possible while just in time deliveries will always be delivered first and are never combined with another just in time order. Moreover, the driven routes are always ending at the last destination, so the tours are not circular. The *simulation-module* consists of a python-script that starts the configuration-file of SUMO. This enables to change parameters during the running simulation, e.g. changing the average speed of vehicles on the simulated streets. Finally, the *visualization-module* tracks the results of the simulation and converts them into an excel sheet which shows data about departure and arrival times, duration of the tours, length of the routes and the sum of emissions and fuel consumption.

5. Case study: Hamburg

After building the simulation study, it is applied in an exemplary case study onto the city of Hamburg. Therefore, three possible classes of delivery vehicles are considered, which are allowed to drive in inner cities. These are (permissible total weight in brackets): Light duty-vehicles (< 3,5 t), light trucks (≥ 3,5 t and < 7,5 t) and medium-weight trucks (≥ 7,5 t and < 18 t) [32,33]. Figure 4 shows the selected section of Hamburg and the locations of plants and simulated hubs. This section is chosen because it includes a part of the inner city with its bigger access roads, e.g. highways, and therefore deliveries to the hubs are possible and the important main roads of the inner city are mapped. The locations of the plants are partly based on real locations of plants and partly based on the assumption that more firms will move into the city because of the urbanization. The three hubs, which are located near highway exits, represent three of four examined scenarios.

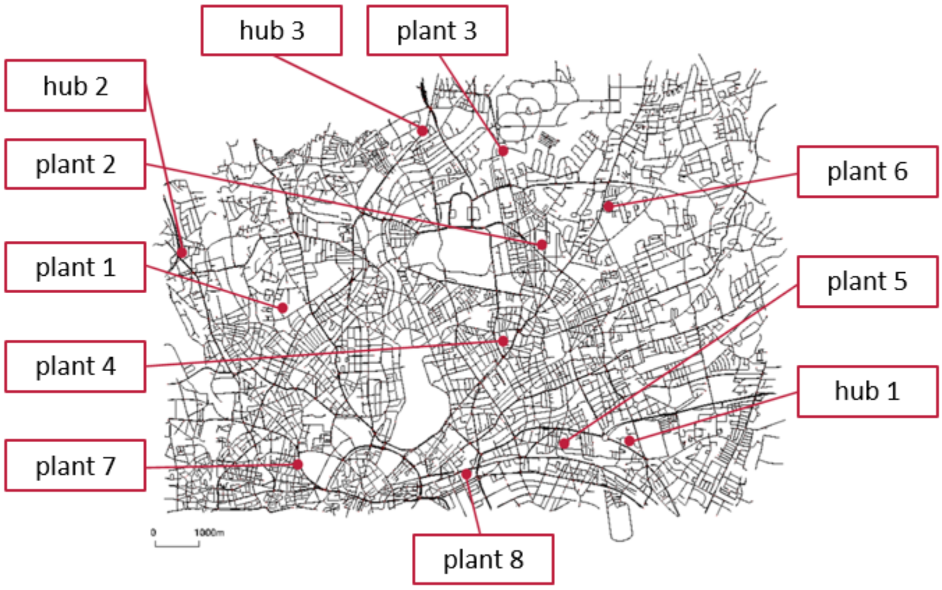

Figure 4: Selected section of Hamburg

These locations enable the decentrally organized supply of the hubs. The other scenario - or base-scenario - includes no hub, which means that the deliveries will start on federal roads and highways around the border of the shown section.

Table 1: Characteristics of plants

Name	Total number of orders simulation´s duration (1 day)	Share of JIT / JIS [%]	Time window JIT / JIS [s]	Minimum weight [t]	Maximum weight [t]
Plant 1	250	20	3600	0.5	9
Plant 2	250	10	3600	0.5	9
Plant 3	124	-	-	0.5	9
Plant 4	118	7	3600	1.2	9
Plant 5	80	-	-	0.5	9
Plant 6	50	-	-	0.5	9
Plant 7	20	-	-	0.5	9
Plant 8	8	-	-	0.5	9

As data for the firm-module, Table 1 serves as input. This information is based on (anonymized) company data. To measure the distance between plants, a preliminary study is conducted in which single delivery cars, whose route is tracked, drive the distances between the shown plants and hubs. The findings are then used in the real simulation to combine orders with a minimum route duration and length. Therefore, the following simplifications are made:

- The generated orders are all between six am and ten pm to avoid a possible ban on night driving.
- The flow of traffic is regulated by the described average speed.
- While consolidating, the volume of goods is not considered, only the weight.
- There is no differentiation between product types so that orders can get combined more freely.

Based on this, the simulation results can be generated. First, Table 2 shows the total number of deliveries and the total sum of driven kilometres. The figures in brackets are the difference to the base-scenario. In Scenario 3, the combination of driven kilometres and total number of deliveries is the lowest, but overall the scenarios that use a hub have a lower number of deliveries and driven kilometres as expected.

Table 2: Comparison of the scenarios

Parameter	Base-scenario	Scenario 1	Scenario 2	Scenario 3
Total number of deliveries (vehicles)	900	557 [-38.11%]	560 [-37.78%]	560 [-37.78%]
Total length of driven tours [km]	7476.63	4385.98 [-41.34%]	5290.99 [-29.23%]	4105.27 [-45.09%]
Average length of a tour [km]	8.31	7.87 [-5.29%]	9.45 [+13.72%]	7.33 [-11.79%]

Table 3 shows that the occupancy of the delivery vehicles is higher while using the hub-and-spoke concept.

Table 3: Selected vehicle types and their occupation

Parameter	Base-scenario	Scenario 1	Scenario 2	Scenario 3
Light duty vehicle				
number [vehicles]	64	26	26	26
occupancy [%]	78.52	94.23	94.23	96.35
Light trucks				
number [vehicles]	329	64	65	66
occupancy [%]	66.16	97.85	97.73	97.66
Medium-weight trucks				
number [vehicles]	507	467	469	468
occupancy [%]	71.01	92.58	92.10	91.39

Table 4 illustrates that the fuel consumption as well as the pollutant emissions are lower in the scenarios that use a hub. To estimate the cost of the driven distance a price of 1.30 Euro per litre diesel is assumed.

Table 4: Summary of the emission results

Parameter	Base-scenario	Scenario 1	Scenario 2	Scenario 3
Fuel consumption [l]	1729.87	1244.44 [-28.06%]	1489.87 [-13.87%]	1179.08 [-31.84%]
Fuel costs [€]	2248.83	1617.77 [-28.06%]	1936.83 [-13.87%]	1532.80 [-31.84%]
CO_2 [kg]	4338.95	3121.38 [-28.06%]	3734.95 [-13.92%]	2957.43 [-31.84%]
CO [kg]	8.81	6.27 [-28.83%]	7.40 [-16.00%]	6.02 [-31.67%]
HC [kg]	2.49	1.76 [-29.32%]	2.04 [-18.07%]	1.71 [-31.33%]
NO_x [kg]	41.23	29.47 [-28.52%]	35.08 [-14.92%]	28.05 [-31.97]
PM_x [kg]	1.01	0.69 [-31.68%]	0.81 [-19.80%]	0.66 [-34.65%]

The shown pollutant emissions are based on the emission classes, which are integrated into SUMO. These are derived from the handbook of emission factors of road traffic ("Handbuch für Emissionsfaktoren des

Straßenverkehrs" – HBEFA) while only direct emissions are considered [34]. The light duty vehicles are in the emission class HBEFA2/P_14_5, the light trucks in HBEFA2//HDV_12_2 and the medium-weight trucks in HBEFA2//HDV_12_12. The figures in the brackets are the difference to the base-scenario. When comparing Table 2 to Table 4 it is apparent that the emissions are not reduced to the same degree as the total driven kilometres are. This derives from the higher percentual amount of bigger vehicles in the scenarios that use a hub (see Table 3). In addition, all just in time deliveries in the simulation met their time windows while using a hub.

All in all the results of the case study show that the hub-and-spoke concept can reduce the total number of tours that take place in the inner city. Depending on the location of the hub, the reduction is up to 38%. Furthermore, the total driven distance can be reduced by 29% to 45%. The occupancy of the delivery vehicle can be improved from 66% to 78% in the base-scenario to 91% to 98% depending on the vehicle class and the location of the hub. In addition, the pollutant emissions of CO_2 are reduced by 14% to 32%. These results indicate that the hub-and-spoke concept in the context of urban production can lead to a higher quality of life by reducing traffic volume and pollutant emissions.

6. Conclusion and outlook

The progressive urbanization and increasing decentralization of manufacturing lead to a growing need for the integration of manufacturing plants into urban areas. As a result, industrially induced traffic volumes and emissions are increasing in these areas. Therefore, it is important to manage urban logistics as effective as possible to reduce costs and environmental impacts. This paper investigates the potential of the hub-and-spoke concept in the context of urban production by providing an integrated evaluation methodology and applying it to exemplarily compare different scenarios in a simulation of a selected area of Hamburg. The results show that there seems to be a high potential in regards to a possible reduction of pollutant emissions and traffic volume. For this, future work is necessary which should include a specific setup, e.g. specific firms and a city that offers real time traffic data. In addition, the related costs of hub-and-spoke concepts need to be investigated in more detail. Furthermore, the specific firm data could show restrictions and limitations of the concept to industrial practice, which then can get investigated further (e.g. storage capacities in the hub). Beyond that, new forms of mobility should get examined, e.g. load bicycles or electrical trucks.

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Biography

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