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E-Grocery in Terms of Sustainability – Simulating the Environmental Impact of Grocery Shopping for an Urban Area in Hanover

Wie nachhaltig ist der Online-Lebensmittelhandel? Eine Simulationsstudie zu den ökologischen Auswirkungen von Lebensmitteleinkäufen am Beispiel eines Stadtteils in Hannover

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Abstract: This study proposes a simulation model for modelling, assessing and quantifying travel distances caused by stationary grocery shopping activities as well as e-grocery deliveries. By means of a sophisticated emission calculation algorithm, the simulated travel values are converted into relevant emission output factors in order to assess the individual impact of e-grocery deliveries compared to individual shopping trips by private consumers in different scenarios. While e-grocery does not yield an emission saving potential with low penetration rates of up to 20 %, up to 53 % of the total emission outputs can be cut when home deliveries are employed for all bulk-shopping activities.

1 Introduction

Cities are running out of space. The growing population as well as the increasing importance of internet-/mail-order business and the urbanisation trend put a major strain on the infrastructure of metropolitan areas in Germany. High traffic volumes caused by commercial as well as private traffic do not just result in perseverative congestions and extended travel times, they also lead to high vehicle emission outputs. While commercial traffic in cities is dominated by last-mile deliveries, besides of commuting activities and leisure trips, a high share of private traffic emissions in Germany result from shopping actions (Sima et al. 2012). In 2017, 17.5 % of the entire traffic volume from motorised private transport in Germany originated from shopping trips, whereby the major proportion of these trips belonged to the supply of grocery and foodstuffs (BMVI 2017).

Due to shifting consumer patterns and the impact of the digitalisation, the food retail industry has experienced a major transformation within the last decade. While first approaches to online food retailing, in short e-grocery, already became evident in the 1990s, especially nowadays the popularity of e-grocery in Germany is constantly increasing, indicated by a total turnover increase of 127 % in online food retailing between 2012 and 2016 (Saskia et al. 2016). Particularly in urban areas, where last mile logistics, traffic volumes andpollution have become major points of concern, an increased utilisation rate of e-grocery might aid in reducing traffic loads and consequently emission outputs, as tours by delivery vehicles can substitute shopping trips of consumers (Mkansi et al. 2018).

Resulting from the fact that e-grocery usage as well as shopping trip proportions are behaviour-dependent variables and hence are not completely adaptable to a real-world setting, a parametrizable simulation model can offer valuable clues about the environmental impacts of stationary grocery shopping vs. online grocery deliveries in terms of emission outputs. Hence, the aim of this paper is to provide a simulation framework that is capable of comparing both concepts, whereby e-grocery will be examined in terms of delivering from a food fulfilment centre, as this currently is the prevailing and most profitable business model for online grocery providers in Germany (Dippold 2018). By developing and employing a sophisticated simulation model for analysing the individual emissions caused within the context of e-grocery and stationary food retailing, all relevant details (e.g., kilometrage) and dynamic structures like behavioural influences (e.g., mode of transport choices) within the respective system can be reproduced and quantified. While the model proposed in this paper focuses on *Hannover Mitte*, an urban district in the centre of the city of Hanover, Germany, the simulation approach can also be adapted for other metropolitan areas and therefore provides an uniform approach to assess the environmental value of e-grocery in different peculiarities.

2 Related work

Recently, Hardi and Wagner (2019) have published a study on the CO_2 emissions caused by grocery deliveries as well as private shopping activities for a city district of Munich, Germany. By means of a modelling approach based on real-world geo-data and Monte Carlo simulation, taking into account randomly selected target households, delivery probabilities and individual routing methods, break-even points for energy consumption and CO_2 emissions, based on vehicle distances and individual energy consumptions factors, are identified and analysed. The results show that e-grocery has a significant potential to reduce emissions compared to individual shopping trips in the focused district. However, the calculation is static and does not take into account individual shopping behaviours, such as supermarket choice depending on shopping type and chained trips. Moreover, delivery time windows are not investigated, further limiting the practical relevance.

Other contributions to the specified research area include studies from Coley et al. (2009), who have made an empirical analysis of contrasting food distribution systems in terms of carbon emission outputs resulting from local farm shopping as well as a large-scale vegetable box system. Van Loon et al. (2015) have created an LCA model in order to quantify the environmental impact of different e-fulfilment methods with regards to fast-moving consumer goods. Moreover, approaches to solve different routing problems in urban areas have been proposed by Blas et al. (2017) and Mayer et al. (2018), whereas Rabe et al. (2018) provide insights into the use of discrete event simulation in supply chain context.

Additionally, a large amount of less recent publications on the environmental impacts of home delivery concepts is available (e.g. Hopkinson and James 2001; Weijers 2001). Regarding computer simulation approaches, several studies on assessing delivery concepts in comparison to stationary retail have been conducted (Cairns 1996; Palmer 2001; Punakivi et al. 2001; Punakivi and Saranen 2001). Here, different modelling approaches in various international contexts have been employed to simulate the routes taken by households when executing shopping actions, consecutively enabling the comparison of total distances.

While the results of all these studies indicate that home deliveries may well result in lower emission outputs, most of them are outdated and hence do not reflect current state-of-the-art methods as well as data inputs, diluting the overall validity, significance and transferability to the real-world system. Furthermore, all models lack complexity in terms of dynamic interdependencies resulting from individual behavioural influences, parameter variation possibilities to reflect different scenario settings and additional emission outputs - like NOx and NH_3 emissions. The utilised modelling and simulation approaches are case-dependent and hence cannot be transferred to different contexts and cities, implicitly illustrating the value of a uniform, parametrisable simulation model.

3 Approach

In order to provide a simulation framework for quantifying distances in terms of kilometre outputs caused by e-grocery as well as stationary retail shopping activities and consequently assess and compare the environmental impact, a multi-stage process is required. While the definition of the examination area, the determination of the research scope as well as the choice of an appropriate simulation software and the selection of an adequate research approach are crucial as general research framework, the simulation model, the simulation results and the emissions model are the main elements of this publication and provide valuable insights into the environmental impact of different grocery shopping concepts.

First, using the java-based multipurpose software AnyLogic, an agent-based simulation model is built to reflect the individual, commercial and combined kilometrage caused by both concepts in the district *Mitte* in Hanover, Germany. Subsequently, an emission model based on emissions factors of the European Environment Agency (European Environment Agency 2016) is developed to transfer kilometrage outputs from the simulation model into several comparable emission output values, namely CO, CO_2, N_2O, NH_3 and NOx. This approach allows for a more dynamic, flexible and thorough comparison, as kilometre outputs from the simulation model can always be complemented or adapted in order to reflect behavioural and technological scenarios that exceed the scope of consideration of the simulation. Both, the simulation as well as the emission model are supported and backed up by means of information and data acquired during an in-depth literature review. Figure 1 supplies a synopsis on the overall multi-stage research approach.

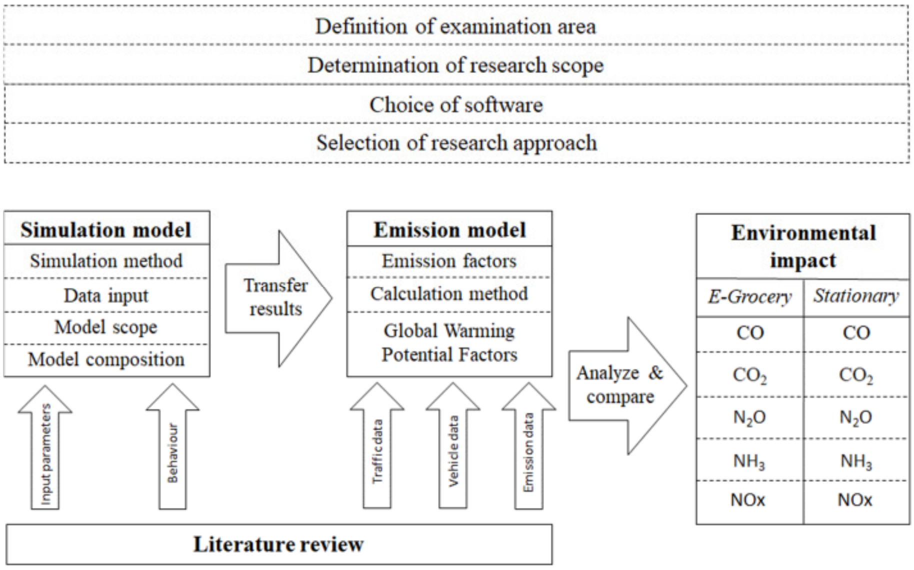

Figure 1: *Multi-stage research approach*

4 Simulation Model

In line with the complexity of the given problem and the need to replicate interdependencies between customers, supermarkets, delivery conditions and behavioural influences regarding shopping activities, an agent-based simulation model can effectively reproduce the real-world system in the given examination area. In contrast to microsimulation, it enables two-direction interactions and can also simulate interactions between individuals in the system, which is crucial when it comes to reflecting behavioural scenarios (Heppenstall et al. 2012). The technology applied is discrete event simulation employing a time-advancing mechanism, where the operation of our simulation system is represented as the progress of events and in which all relevant entities are modelled as particular active objects (Wagner and Nardin, 2018). In this context, events are integrated by an event list and include process as well as decisions elements outlined in Figure 3.

To reduce computing time, enable multiple simulation runs as well as experiments and increase the degree of generalisability and transferability, the scope of the model is restricted to the city district *Mitte* in Hanover. With 1.604 households, the simulation covers about 22 % of the entire population (7.230 private households) in *Mitte* (Landeshauptstadt Hannover 2018). Overall, the simulation model provides outputs in terms of kilometres covered. In line with the main investigation objective, this approach allows for reliably quantifying simulation results to flexibly transfer them into emission factors and consequently assess the individual environmental impact (Rabe et al. 2017). For producing reliable, reproducible and meaningful results, a parametrisable simulation model is required. In this context, specific parameters with regard to shopping as well as driving behaviour and e-grocery utilisation can significantly influence the simulation results and hence need to be adapted according to the respective environment and usage scenario. By means of a behaviour model, e-grocery utilisation can be specified, which aids in reflecting more probable scenarios. For example, due to given constraints like minimum order values, e-grocery will presumably be used more often for bulk instead of small purchases. Other output-relevant input parameters within the model as well as reference values for the examination area are shown in Table 1.

Parameter	Stationary retail	E-grocery	Ref. value
Shopping frequency	X	X	0,51
Car possession rate*	X		0,56
Share of bulk purchases*	X		0,42
E-grocery utilisation rate*		X	0,05
Multiple shop selection	X		Yes
Delivery fleet		X	5 vehicles
Capacity per vehicle		X	18 orders
Loading time per order		X	2 min
Parking time		X	5 min
Unloading time per order		X	10 min
Average driving speed	X	X	25 / 30 km/h

**relevancy of the parameter depends on respective behaviour model*

Table 1: *Input parameters and values for the simulation model*

Regarding the composition of the simulation model, in total nine agent types have been defined to reflect both shopping concepts. The behaviour of an agent is controlled via state charts that define the complex decision-making processes within the given environment. Figure 2 provides an overview about the class diagram for stationary retail and e-grocery. All listed classes represent agent types specified with the stereotype “agent”. The agent type “Main” includes the visualisation of the simulation by providing a GIS map, while the “Household” agent type represents the households and “Grocery” all super- and hypermarkets in the city district *Mitte*. At runtime, only one instance of the agent type “Main” exists. At the same time, 1 to *n* agents of the type “Household” and “Grocery” can be instantiated and used within the “Main” agent. The agent type “Car” is assigned to the agent type “Household” with multiplicity 1 and is responsible for the actual journey from household to supermarket. The agent type “Purchase” represents a data type and is assigned to the “Household” with multiplicity 0..*n*, representing a household’s choice to make none up to several purchases. In contrast, the e-grocery class diagram contains six agent types. For the simulation runtime, always one instance of the agent type “Main” is given, which is responsible for displaying the agent types “Household” and “DCenter” (Distribution Center). At runtime, 1..*n*, agents of the type “Household” and one agent of the type “DCenter” can be instantiated. The “DCenter” agent receives orders from the population “Households”, which are represented by the agent type “Order”. The “DCenter” aggregates all incoming “Order” agents to a “Shipment” agent. Subsequently, the agent “Shipment” is handed over to the “Vehicle”, who delivers the orders.

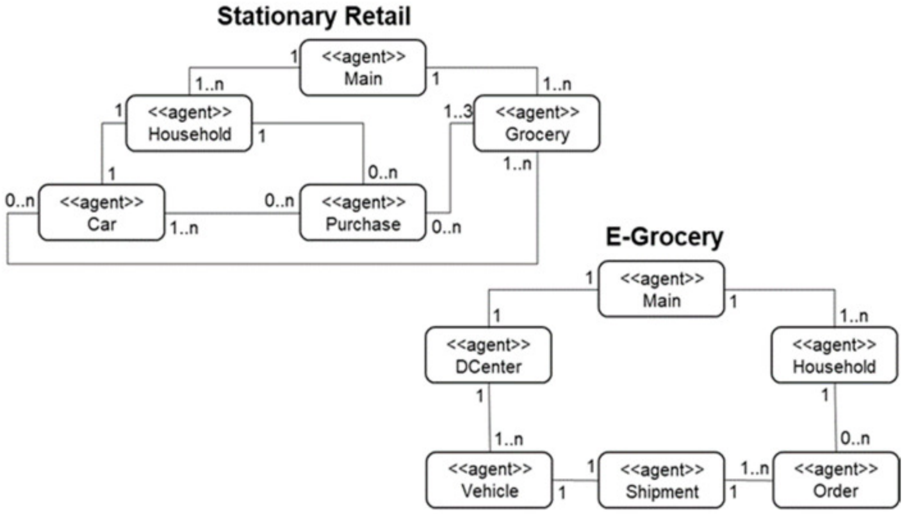

Figure 2: *Overview about agent types and agent relationships*

Regarding the process flow, the simulation model consists of two agent networks responsible for executing the actual shopping activities in e-grocery and stationary retail, as exemplary shown for e-grocery in Figure 3.

When it comes to stationary retail, at first, a behaviour model is implemented and executed in order to set general rules in accordance with the parameters described above. Subsequently, “Household” agents engaging in stationary grocery retail decide if they want to execute a shopping activity (bulk or small purchase) on the simulated day. If that is the case, the model evaluates, based on a primarily specified probability distribution, if the respective “Household” is going to use a car for the shopping activity. If the evaluation returns true, a “Car” agent is created, “Grocery” agents are classified into small and large supermarket and an order list as well as the actual grocery stores within the model are generated. Finally, “Households” select suitable supermarkets depending on their shopping trip type (large supermarkets for bulk purchase and small supermarkets for minor purchases) and drive to the designated destination. For the selection algorithm, mobility and behaviour input parameters from a nationwide study on mobility behaviour in Germany (Nobis and Kuhnimhof 2019) are employed and distributed randomly using a Weibull distribution in order to reflect respective variances in decision-making. If several supermarkets are required to complete a bulk purchase activity, households head for additional supermarkets until no orders are left within their order list.

Concerning e-grocery, orders are created from “Household” agents that have decided to order their grocery items online. These orders are collected within the “D. Center” (Distribution Center) and distributed among the given vehicle fleet. Afterwards, a shipment list is collected and “Vehicles” start to deliver the orders from the list. If a consignee is not at home during the delivery process for this “Household”, specified by a given probability distribution, the “Vehicle” parks at the designated location for a short while and continues with delivering remaining orders. In contrast, if an agent is at home, the parking time is extended in order to reflect the delivery process. In any case, the “Vehicle” agent evaluates if it has any orders left within the shipment list after each delivery attempt. If orders are left, in the next step the agent checks if it has capacities left to complete remaining orders from the list. If the expression returns true, the "Vehicle" proceeds traveling to the next customer and restarts the delivery process. If the expression returns false, the "Vehicle" returns to the "D. Center", where it is refilled before it starts to fulfil the remaining orders from the shipment list. Kilometres and distances for both agent networks are tracked and transferred into statistical diagrams as soon as a driving activity is executed. Both stationary retail shopping activities and e-grocery deliveries within the given agent networks complement each other, providing a complete overview about total distances resulting from various e-grocery utilisation rates and shopping behaviours.

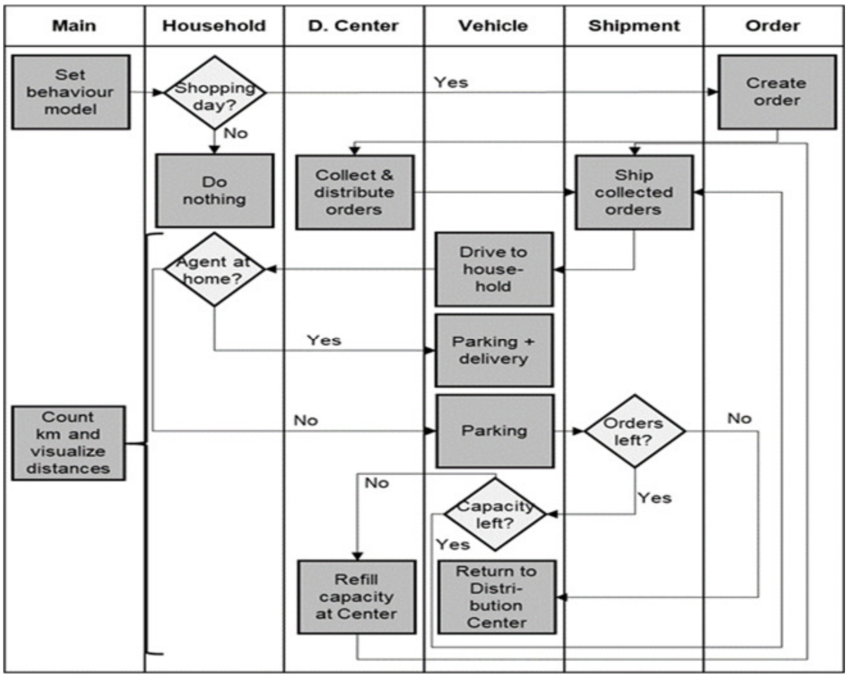

Figure 3: *Process overview about agent network concerning e-grocery*

5 Emission Model

In order to transfer distance values from the simulation model into emissions, a comprehensive emission model is required. By specifying the emission category of the delivery vehicles and the mileage per emission class, emissions can be calculated to a good approximation using the corresponding emission factors (in g / km) of the European Environment Agency (2016). These factors take into account typical values for motorway, highway and urban city trips, driving speeds and distances, etc.. Because the relative effects of the individual scenarios are more important than the absolute accuracy when it comes to a general assessment of a scenario, the model can be seen as simplified reflection of the reality, indicating CO, CO_2, N_2O, NH_3 and NOx emission outputs. The corresponding algorithm for the described method is as follows:

$$E_{ij} = \sum_{k} (N_{j,k} \times M_{j,k} \times EF_{i,j,k} \qquad (1)$$

with $N_{j,k}$ representing the number of vehicles in a nation's fleet of category j and technology k, $M_{j,k}$ illustrating the average annual distance driven per vehicle of category j and technology k in km per vehicle and $EF_{i,j,k}$ being the technology-specific emission factor of pollutant i for vehicle category j. as well as different e-grocery scenarios. While emission tiers are universally valid for the respective vehicle groups, structural data concerning car population are exclusively relevant for Hanover, Germany and need to be adapted when emissions for other cities are calculated (Landeshauptstadt Hannover 2018).

6 Results and conclusion

For the simulation study, parameter reference values as shown in Table 1 have been used. Moreover, the designated food fulfilment centre was placed in the district Langenhagen, in order to reflect the activities of a large grocery supplier operating in Hanover. In total, three potential scenarios have been investigated within the simulation study to represent current and probable future realities:

1. Stationary grocery shopping without any e-grocery activities
2. 5 % e-grocery utilisation rate
3. 20 % e-grocery utilisation rate
4. E-grocery utilization for all consumers engaging in bulk-shopping

With the aim of producing reliable outputs, the results of 1.000 simulation runs with random distribution regarding the given parameters (Monte Carlo approach) have been averaged for each scenario. The referenced transporter is a VW Crafter (Euro 6, 2,0-l-TDI BMT, 75 PS) and the passenger car mix refers to the given mix from Hanover. In order to reflect the entire impacts of a scenario, not just the distances caused by deliveries substituting individual shopping trips, but the total kilometrage of delivery vehicles in e-grocery and private customer vehicles employed for stationary shopping activities are measured. Table 2 shows the results in terms of distances per car and delivery truck as well as total emissions and standard deviation (SD) with 95 % confidence interval based on the given amount of iterations (1.000).

Scn.	Dist. car	Dist. truck	CO	CO_2	N_2O	NH_3	NOx	SD	
0.	2427,5	/	2,108	481,4	0,008	0,049	0,531	103,9	
1.	2320,6	121,9	1,932	482,1	0,008	0,046	0,636	102,1	6,5
2.	1982,5	358,8	1,635	474,6	0,007	0,041	0,837	97,4	16,4
3.	1353,5	542,1	1,063	400,5	0,006	0,028	0,913	73,8	28,1

***Table 2:** Distances (in km), total emission outputs (in kg) and standard deviations for car and truck distances per scenario*

It becomes obvious that e-grocery can indeed aid in reducing emission outputs in Hanover with a specific utilisation rate and behaviour mode. While an e-grocery utilization of 5 % and 20 % results in comparable high emission values, a usage rate equalling the total amount of all consumers engaging in bulk shopping leads to reduced CO, CO_2 and NH_3 emissions (up to 53 %) compared to environmental impacts caused by stationary retail in the research area (scenario 0). NOx emission outputs develop contrariwise to other emission types.

With the proposed simulation framework, environmental influences in terms of emissions can be assessed in an urban context. The model is easily transferable to other cities and models real shopping scenarios dynamically. Additionally, the framework can be used to quantify the individual influence of single parameters and characteristics. While the current simulation model and study offer comprehensive insights into grocery shopping impacts, they do not take into account private consumers engaging in shopping activities in terms of route combinations (e.g., commuting to and from work). Moreover, it can be expected that the location of the fulfilment centre has a major impact on the distance and emission outputs of e-grocery scenarios, which needs to be investigated and quantified by future research.

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