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ENVIRONMENTAL SUSTAINABILITY AS FOOD FOR THOUGHT! SIMULATION-BASED ASSESSMENT OF FULFILLMENT STRATEGIES IN THE E-GROCERY SECTOR

Marvin Auf der Landwehr
Maik Trott
Christoph von Viebahn

Hochschule Hannover
Faculty IV – Business and Informatics
Ricklinger Stadtweg 120
Hannover, 30459, GERMANY

ABSTRACT

Environmental sustainability is among the key concerns of our time. Especially the traffic and transportation sector entails a high degree of negative consequences on sustainability metrics such as CO_2 emissions, increasing the need for innovative concepts to cope with the requirements of our modern society, while at the same time decreasing environmental pollution. A potential solution in this regard are grocery deliveries (e-grocery), which can achieve economies of scale by bundling orders. Within the last two decades, multiple e-grocery concepts have evolved in operational practice, which we assess by means of a comprehensive simulation study to guide future systematic investigation on (simulation-based) sustainability research. The concrete results of our study indicate that grocery deliveries by courier, express, and parcel organizations can outperform fulfillment strategies based on insourcing by up to 50 % in terms of mileages as well as 39 % and 66 % regarding CO_2 and PM2.5 emissions.

1 INTRODUCTION

"In the middle of every difficulty lies opportunity". This statement from the famous physician Albert Einstein seems to be at the core of the issues and challenges currently faced by our modern society. The global COVID-19 pandemic and the associated preventive measures have resulted in severe societal and economic restrictions as well as an enormous surge of the digital transformation in many business sectors (Grashuis et al. 2020). Especially the grocery retail industry, which featured comparably low online growth rates over the last two decades compared to the general e-commerce sector, has recently experienced major increases in demand and popularity (Dannenberg et al. 2020; Saphores and Xu 2021). To cope with the new demand structures and to ensure a high degree of operational efficiency, both pure online players as well as stationary retailers experiment with various commercialization, logistics and service concepts that can entail significant implications on the environment (Naidoo and Gasparatos 2018). Road traffic resulting from private transport activities contributes a major share of emissions to particulate matter (PM) and carbon dioxide (CO_2) concentrations, both in urban as well as rural surroundings (Pant and Harrison 2013; Zhang et al. 2019). Due to its potential to reduce private traffic loads by avoiding or minimizing private errands and shopping trips by substituting customer trips with delivery tours (Mkansi et al. 2018), the online grocery concept has been subject to multiple studies within recent years (Martín et al. 2019). Several attempts have been made to evaluate the environmental impact of the grocery home delivery notion within different contexts (e.g., Hardi and Wagner 2019; Auf der Landwehr et al. 2020) and degrees of consideration (e.g., Van Loon et al. 2015; Fikar et al. 2018; Trott et al. 2020), proving its potential expedience, depending on various influencing factors such as utilization rates, consumer shopping behavior, and structural environment. However, taking into account the diversity of e-grocery business and operation models

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(e.g., Hübner et al. 2016; von Viebahn et al. 2020), current research approaches lack a holistic comparison of common fulfillment archetypes in terms of environmental consequences, which is required to ensure valid propositions and provide reliable recommendations for digitalizing the grocery industry.

Taking into account an international perspective on e-grocery fulfillment, depending on the given context, market, and capabilities as well as objectives of the retailer, supply and delivery strategies exhibit a huge degree of variance. In order to improve the operational process efficiency on the order processing side, several organizations rely on dedicated distribution centers as fulfillment points for e-grocery operations (Hübner et al. 2016). Alternatively, e-retailers can opt to operate home-delivery activities by picking and processing orders within supermarket outlets (SO) or tackle the e-grocery segment by offering click & collect services (Agatz et al. 2008). Moreover, different strategies with third-party governance of various fulfillment elements such as inventories or deliveries have been established and are primarily viable for pure online grocery players such as Instacart in the USA or Picnic in Germany and the Netherlands (Hübner et al. 2019). In the former case, orders are directly shipped from the producer to the final customers, which is a concept known as dropshipping, while in the latter case, delivery duties are transferred to logistics service providers (LSP) such as CEP companies (von Viebahn et al. 2020). To assess the environmental value of various fulfillment strategies within a uniform and comparable setting, we propose a simulation approach to model both mileages as well as CO_2 and PM emissions accruing due to the logistical peculiarities of supply and order fulfillment operations. Thereby, we focus on the six e-grocery fulfillment archetypes developed by von Viebahn et al. (2020), to analyze e-grocery fulfillment on a holistic basis. To collect insights on relevant process flows and gather realistic input parameters required to conduct reliable simulation experiments, we closely cooperate with several industry partners in the e-grocery sector. The aim of this paper is the identification of CO_2- and PM-emission-related implications of different e-grocery fulfillment archetypes in four representative city districts of the city of Hanover in Germany.

The remainder of this paper is structured as follows: First, we elaborate on the research background and provide a synopsis on online grocery business models as well as e-grocery simulation approaches to position and motivate our study (Section 2). Subsequently, we outline our research design in terms of methodology, model specifications, parameters, and conceptual simulation scenarios (Section 3), before we present our simulation results and findings (Section 4). Ultimately, we conclude with a discussion on the implications of our study and derive an agenda for future research on e-grocery simulation (Section 5).

2 RESEARCH BACKGROUND

2.1 Online-Grocery Business and Fulfillment Models

First approaches to online-grocery retailing have already been implemented in the early 2000s (Agatz et al. 2008). Since then, players such as Walmart in the USA, Tesco in the United Kingdom, and Rewe in Germany have developed and utilized various business models to improve their operational efficiency, deliver additional customer value and gain a competitive advantage in the market (von Viebahn et al. 2020). Due to its extensive impact on the supply and demand side, order fulfillment logistics is at the core of each online-grocery business model, both, in terms of operational efficiency as well as value proposition (Martín et al. 2019). To classify and structure existing as well as future e-grocery fulfillment models, Hübner et al. (2016) have developed a framework consisting of two major dimensions, namely backend fulfillment and last-mile delivery. This framework has been extended by von Viebahn et al. (2020), who developed an e-grocery fulfillment taxonomy and identified six common fulfillment archetypes to guide future research and support systematic investigation in this field of business. Omni-channel retailers, which are characterized by the presence of an online as well as offline grocery sales channel, may opt to utilize existing infrastructural assets for the provision of e-grocery services (Hübner et al. 2016). In this case, online orders are picked in SOs and either shipped by means of attended home deliveries or collected by the customer, which is also referred to as click & collect (Scott and Scott 2008). Alternatively, organizations can employ decentralized dedicated distribution centers, so called food fulfillment centers (FFC), as main order fulfillment point. FFCs are exclusively operated for online channels and feature a moderate to high degree of automatization to support the efficiency of backend operations such as picking and packing (Hays et al. 2005). Deliveries are conducted by means of light commercial vehicles (LCV) such as vans and the order reception process has to be attended by the customer (von Viebahn et al. 2020). Due to their size, FFCs are generally located in industrial areas or city outskirts, resulting in additional costs on the last mile (compared to store fulfillment), caused by the increased distances between point of fulfillment and consumers (Hübner et al. 2016). Another logistics model for fulfilling online grocery orders is the integration of offline and online activities in a central warehouse (CW). The intended advantage of this approach is the simplification of supply processes for the online channel (Wollenburg et al. 2018). In this model, medium duty trucks (MDT) deliver groceries to urban transshipment points (spokes) in close proximity to the area that is to be served, where they are transferred to LCVs and shipped to the final customers (Hübner et al. 2019). While the outlined concepts generally vary in terms of backend activities and fulfillment point, last-mile deliveries are mainly similar and require an attended order reception (except for the click & collect model). An alternative reception approach can be pursued through unattended parcel deliveries. Here, orders are either assigned to manufacturers or wholesalers, who use third-party LSPs for delivery processes on the penultimate as well as last mile (dropshipping), or handed over to LSPs from CW facilities of an e-retailer, who then becomes responsible for deliveries on the last mile (Janjevic and Winkenbach 2020). Each of the proposed models offers distinct benefits for retail organizations, which are synopsized in Table 1. While store deliveries suffer from inefficient picking procedures, FFC fulfillment strategies impair additional costs on the last mile. Hence, e-grocers need to consider the individual tradeoffs resulting from different strategies before selecting an appropriate model (Scott and Scott 2008).

Table 1: Online-grocery fulfillment models and characteristics.

Model	Main characteristics	Operational benefits	Customer value-added	Competitive advantage
Store fulfillment *(e.g.,Scott and Scott 2008; Hübner et al. 2016)*	• Order handling in store outlets • Attended delivery or Click & collect	• Delivery flexibility • Avoidance of slack • Low investment requirements • Low delivery costs	• Short lead times • In-store returns	• Logistical performance
FFC fulfillment *(e.g., Trott et al. 2020; von Viebahn et al. 2020)*	• Order handling in dedicated fulfillment centers • Attended delivery	• Efficient picking and packing • Optimized scaling and planning • Low inventory costs	• Large product portfolio • Little stock-outs • High product quality	• Product quality
Integrated fulfillment *(e.g.,Wollenburg et al. 2018; Hübner et al. 2019)*	• Order handling in superordinate central warehouses • Attended delivery	• Efficient picking and packing • Optimized scaling and planning • Low inventory costs	• Large product portfolio • Little stock-outs • High product quality	• Product quality
Third-party fulfillment *(e.g., Hays et al. 2005; Janjevic and Winkenbach 2020)*	• Order handling by third parties or in central warehouses • Unattended delivery	• Fast set-up • Few changes to existing systems required • Minor inventory costs • Minor investment needs	• Little stock-outs • Unattended reception • Extensive delivery area	• Costs

2.2 E-grocery Simulation Approaches

As a result of the sophisticated characteristics and requirements of e-grocery fulfillment, manifold studies have addressed the need to assess and improve strategic decision making as well as operational planning with the aid of simulation methodologies (e.g., Punakivi and Saranen 2001; Cagliano et al. 2014). Tadei et al. (2016) conducted a simulation study to evaluate the ecological and economic advantages of local online grocery supplies, outlining distinct efficiency gains by integrating local supply operations with innovative ICT solutions. Moreover, Pan et al. (2017) proposed a new approach to utilize customer-centric data for optimizing home-delivery activities within the grocery context based on simulated absence probabilities.

Similarly, the impact of various demand variables such as order volumes, customer utility, and absence probability on delivery service quality was investigated by Waitz et al. (2018), who employed an agent-based simulation model to support decision-making based on profitability and efficiency metrics. In terms of sustainability, the life cycle assessment model of Van Loon et al. (2015) indicates that shopping behavior, fulfillment strategy, and basket value are the main drivers of low-emission e-grocery operations. Correspondingly, Koç et al. (2016) conducted research on the combined implications of depot location, fleet composition, and routing procedures on emission outputs caused by urban grocery logistics, while Durand and Gonzalez-Feliu (2012) conducted a simulation optimization experiment, indicating that a hybrid fulfillment model combining home deliveries and reception points (unattended reception) could be most beneficial in terms of operational efficiency and environmental impact. Other studies on the (simulated) environmental impact of e-grocery fulfillment include publications of Kämäräinen et al. (2001), Siikavirta et al. (2002), Hardi and Wagner (2019) and Auf der Landwehr et al. (2020). A comprehensive overview about e-grocery research in general can be found in Martín et al. (2019), while Trott and al. (2020) elaborate on simulation-related e-grocery studies. However, despite of the growing relevance of e-grocery, to the best of our knowledge, existing research has not yet dealt with a holistic and comparative assessment of different fulfillment strategies, analyzing supply chain operations as well as penultimate and last-mile deliveries.

3 METHODOLOGY

3.1 Research Design and Conceptual Scenarios

As outlined in Figure 1, we have employed a multi-layer research design, consisting of three major phases. During the first stage, the general framework for the simulation study was determined. Based on the insights presented in Section 2, six conceptual fulfillment scenarios were derived (see Section 3.2).

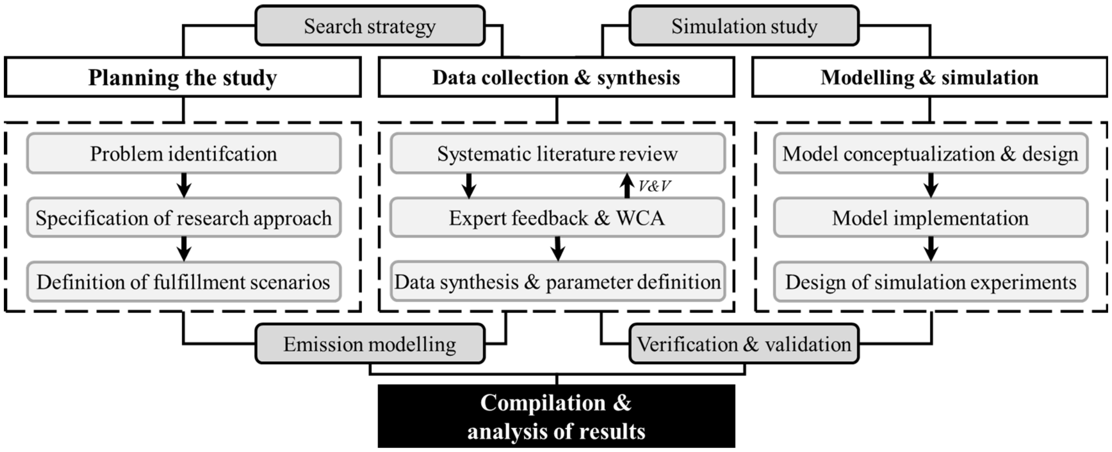


Figure 1: Research design.

Subsequently, we conducted a systematic literature review based on the methodology from Webster and Watson (2002), to collect realistic input parameters for the simulation of the specified fulfillment scenarios. The review was performed in major library catalogues between October 2020 and March 2021 and comprised a total of eight search iterations. Apart from the direct search procedure with keywords related to e-grocery fulfillment, we additionally employed forward and backward search routines, identifying publications quoting pertinent articles from our search results (forward) as well as analyzing relevant citations from the found literature (backward). After reading abstracts and introductions, we excluded publications that did not highlight fulfillment characteristics of e-grocery (non-relevant). Table 2 provides a synopsis on the systematic literature review. To validate and extent the information collected during the review with insights on behavioral consumer patterns and operational peculiarities, we collected expert feedback from a major omni-channel retail organization in Germany. Moreover, we conducted a longitudinal web content analysis (WCA), analyzing various industry reports (e.g., Supermarketnews) about and corporate websites (e.g., Tesco) of the e-retailers that acted as classification objects for the fulfillment archetypes of von Viebahn et al. (2020), which form the basis for our conceptual scenarios.

Table 2: Systematic literature review.

Database	*Search Term*	*Search Fields*	*Hits*	*Relevant*	**Total**
Google Scholar	(“e-“ OR “online” OR “electronic”) AND (“grocery” OR “food”) AND (“retailing” OR “fulfillment” OR “delivery”) AND (“simulation” OR “decision support” OR “supply chain” OR “strategy” OR “model” OR “concept”)	Title, Abstract and Keywords	16.254	154	**255**
AIS eLibrary			194	18	
JSTOR			189	12	
IEEExplore			2.356	56	
Taylor & Francis			267	16	
		Backward/Forward search		34/22	

Within the scope of our simulation study, we assessed six scenarios with different logistics elements and sequences (Figure 2). In Scenario 1 and Scenario 6, SOs serve as main fulfillment point. The locations of the outlets have been determined through a gravity analysis, selecting the most focal SOs (based on the real infrastructure of the partner organization) within the area of investigation. In both cases, centralized regional warehouses (RW) are supplied by heavy duty trucks (HDT) from a CW, before orders are shipped to the individual SOs by MDTs. In Scenario 1, online grocery orders are exclusively fulfilled by means of customer collection, whereas in Scenario 6, home-deliveries with LCVs and a 4-hour delivery time window are conducted. In contrast, Scenario 2 features LCV grocery deliveries from a dedicated FFC, which is supplied by a HDT from a RW. Due to the improved backend process efficiency enabled by FFC operations (Hübner et al. 2016), delivery time windows in this scenario are shorter (2-hour). In Scenario 3 and 4, delivery procedures are mainly handled by third-party LSPs, either by transferring the delivery governance from the retailer to the sort facility (SF) of the LSP (Scenario 3) or by dropshipping orders directly from a manufacturer’s site or a wholesaler’s CW via a CEP distribution center (DC) facility (Scenario 4). In both cases, order reception is unattended without time windows. Ultimately, Scenario 5 describes fulfillment models, where the retailer itself remains responsible for the delivery operations and utilizes RWs as point of fulfillment. In this model, groceries are shipped by MDTs to urban spokes, where they are transshipped to LCVs before the final home deliveries take place with moderate delivery time windows.

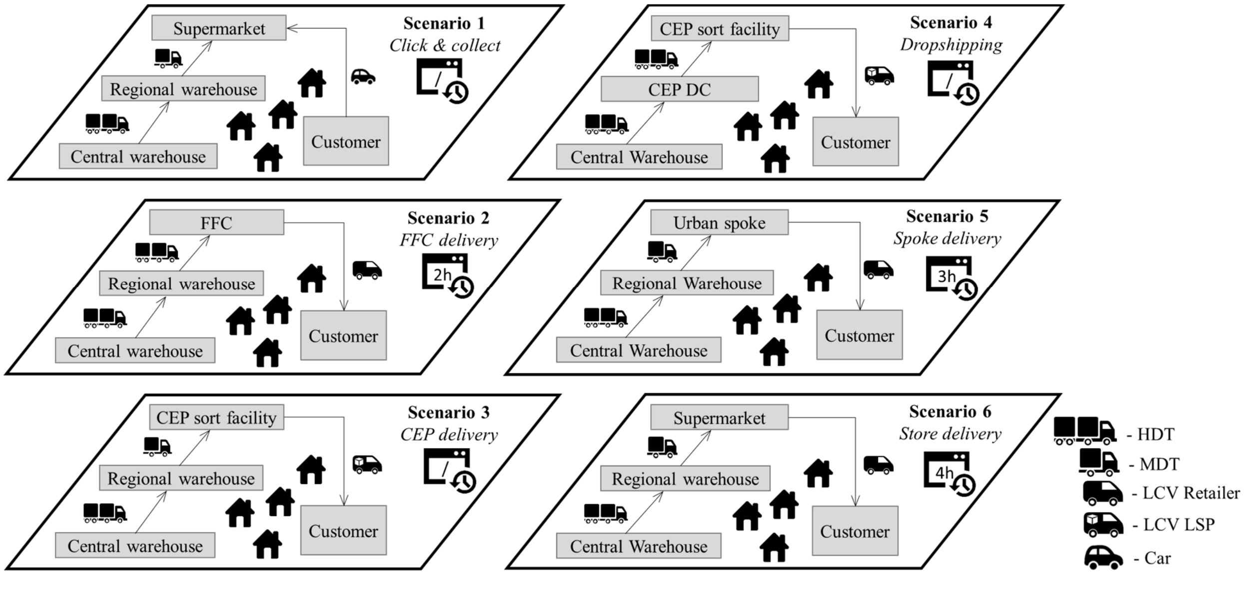


Figure 2: Conceptual fulfillment scenarios including delivery time windows.

3.2 Model Parameters and Key Performance Indicators

The scope of our simulation study is restricted to four representative urban districts (high density core, extended core and mid-size center, (sub-)urban edge and commercial area with service sector orientation) in the city of Hanover, Germany (Krehl and Siedentop 2019), with a total population of 9,400 inhabitants (Landeshauptstadt Hannover 2020). The allocation of vehicle types to supply and delivery activities has been determined in line with common practices in the grocery industry (Hübner et al. 2019). The referenced vehicles are a *Renault Master L2H1 with Kiesling Flat Runner Box Body (class: LCV Retailer; 96 kW / 130 PS; ENERGY dCi 145 engine; Diesel; Euro 6b; 2.29 tons tare weight)*, an *Iveco Daily VI 65C14 with Saxxas Box Body (class: LCV LSP; 100 kW / 136 PS; Iveco 3,0l F1C ; Diesel; Euro 6b; 3.7 tons tare weight)*, a *MAN TGL 7.180 with MAN thermal case (class: MDT; 140 kW / 190 PS; MAN D0834 engine; Diesel; Euro 6; 5.3 tons tare weight)* and a *MAN TGS 41.330 with Krone Profi Liner SDP 27 eLB4-CS (Class: HDT; 264 kW / 360 PS; MAN D2066LF80 engine; Diesel; Euro 6; 15.9 + 6.2 tons tare weight)*. If a delivery vehicle is unable to fulfill an order within a given time window because of time or capacity constraints, additional vehicles are utilized to complete the fulfillment process. In accordance with information from our industry partner, a maximum of 12 LCVs can be utilized from the e-retailer. In contrast, due to their large vehicle fleets, we assume that LSPs are not subject to any restrictions regarding the number of LCVs. Moreover, we assume different vehicle capacities in terms of total orders for LCVs of e-retailers and LCVs of LSPs, because the specific packaging requirements of LSP shipping prevent the delivery of large, bulky items, such as water crates, consequently allowing LSPs to ship more orders in total than e-grocery retailers (Thaller et al. 2019; Figliozzi 2020). To increase the comparability among the fulfillment scenarios, we exclusively focus on the operations of one particular grocery retail chain as well as LSP.

Trip distances are calculated with a bidirectional A* point-to-point algorithm based on an OpenStreetMap network and validated with geographic data for the simulated city districts. Moreover, shipment frequencies from CW to RW as well as RW to the individual fulfillment point (FFC, SO, or spoke) have been pre-determined, whereas shipping frequencies between point of fulfillment and customer (last mile) dynamically depend on the purchase behavior of consumers at simulation runtime. The online shopping frequency is modelled as black box with fixed shares, whereby the individual household agents engaging in e-grocery are stochastically altered with each simulation run (Monte Carlo approach). A synopsis on the model input parameters used for our simulation study is provided in Table 3.

To convert the simulated mileages into fine dust (PM2.5) emissions, we employed $EP_{i,j} = \sum_k (N_{j,k} \times M_{j,k} \times EF_{j,k})$, with Nj,k being the number of vehicles in a given fleet of category j and technology k, Mj,k representing the average distance driven per vehicle of category j and technology k and EF,j,k depicting the technology-specific emission factor for PM2.5 per vehicle of category j and technology k. The individual values on the emissions factor per vehicle category and technology have been derived from Ntziachristos and Samaras (2019). Vehicle categories include passenger cars, LCVs Retailer, LCVs LSP, MDTs, and HDTs, while technologies range from Euro 1 to 6. Regarding private traffic employed to collect grocery orders in Scenario 1, we distribute vehicle types across the simulation population in accordance with structural data on vehicle registrations (Landeshauptstadt Hannover 2019). CO2 emissions are calculated by the fuel consumption FCCALC of a vehicle of category j and technology k, combusting fuel m and the ratios of hydrogen to carbon (rH:C) and oxygen to carbon (rO:C) in the fuel (Ntziachristos and Samaras 2019):

$$E^{CALC}_{CO_2,k,m} = 44.011 \times \frac{FC^{CALC}_{k,m}}{12.011+1.008 r_{H:C.m}+16.000 r_{O:C,m}}. \tag{2}$$

3.3 Agent-based and Discrete Time Simulation Model

To develop the model for our simulation study, we used the multimethod software AnyLogic (Version 8.7.3). Our model combines agent-based modelling properties with a discrete-event simulation technique, whereby the synchronous time advancing mechanism is triggered by sequential behavioral state changes of agents and the resulting interactions in the specified agent networks. Behavioral rules for individual agents were modelled by state charts, defining the logical system flows, interdependencies, and interactions based on the modeled state. This procedure allows for effectively modeling and representing the autonomous and heterogeneous behaviors of individual system entities (e.g., consumers), while taking into account collective interdependencies and emerging reciprocations (Gómez-Cruz et al. 2017). Each virtual simulation run equals one day. To account for probabilistic system parameters such as vehicle capacities and demand fluctuations, we employed a Monte Carlo approach with 66,000 simulation runs. Figure 3 provides an overview of the conceptual simulation model and its system entities and network connections.

In accordance with the simulation scenarios outlined in section 3.2, we model different, scenario-based supply chain and fulfillment operations based on the exemplary case of a major e-grocery retailer in Germany. The scope is limited to a total of 1,410 households that have been distributed randomly across the area of investigation. As we assume unlimited and unrestricted supplies, sourcing activities are modelled as black box. Depending on the given scenario, HDTs supply the retailer's RW or forward order quantities to a CEP distribution center, where they are buffered and collected. Daily supply frequencies, which describe the exchange of goods between the warehouse and the fulfillment points governed by the e-retailer, and daily delivery frequencies, which are solely applicable in scenarios with LSP deliveries, directly depend on the individual demand structures within a given scenario. Shipping procedures across supply chain level 1, supply chain level 2, and last-mile system elements depend on the fulfillment scenario, with four potential fulfillment points (FFC, CEP SF, SO, and spoke). Based on the given scenario as well as on the specified behavioral rules (e.g., shopping frequency), households either generate an order agent, which is passed on to the concerned fulfillment point (Scenario 2–6), or spawn a purchase agent (representing a shopping list), which is, depending on the stochastic car utilization rate for grocery shopping, passed on to a car agent. In delivery scenarios, fulfillment points are responsible for the collection of customer orders and generate a shipment list for the concerned vehicle fleet. The list will then be passed on to the HDT (Scenario 4) or LCV (Scenario 1–3 and Scenario 5–6), which distributes the items to the order recipients. To model a realistic inventory planning and shipping process, shipment agents are processed by the FFC in Scenario 2, RW in Scenario 3 and 5, CW in Scenario 4 and SO in Scenario 6.

Table 3: Model parameter categories, values, unites and sources.

Category	*Value*	*Unit (type)*	*Sources*
Average basket value per order	68	Euro (fixed)	Trott et al. (2021)
Capacity HDT	700	Orders (fixed)	Industry Partner
Capacity LCV Retailer (min/mean/max)	16/18/19	Orders (stochastic)	Industry Partner
Capacity LCV LSP (min/mean/max)	110/120/130	Orders (stochastic)	Figliozzi (2020)
Capacity MDT (min/mean/max)	160/180/190	Orders (stochastic)	Industry Partner
Car utilization rate (mean/SD)	60 /15	Percentage (stochastic)	Trott et al. (2021)
Daily delivery frequencies: CEP DC-SF/CW-CEP DC/RW-CEP SF	1 - 3/ 0 - 1/ 1 - 2	Trucks (variable)	Thaller et al. (2019)
Daily shopping frequency	51	Percentage (fixed)	Trott et al. (2021)
Daily supply frequencies: CW-RW/RW-FFC/RW-SO	0 - 2/ 0 - 2/ 1 - 3	Trucks (variable)	Ge et al. 2019
Delivery capacity MDT	3	SOs (fixed)	Hübner et al. (2016)
Delivery time windows	12/4/3/2	Hours (variable)	von Viebahn et al. (2020)
Location of CEP DC	50.129162, 8.593324	Coordinates (fixed)	Paketda (2021)
Location of CEP SF	52.357312, 9.875634	Coordinates (fixed)	Paketda (2021)
Location of CW	50.051605, 8.658582	Coordinates (fixed)	Industry Partner
Location of FFC	52.447304, 9.697542	Coordinates (fixed)	Industry Partner
Location of RW	52.358022, 10.120982	Coordinates (fixed)	Industry Partner
Location of spoke	52,397905, 9,739369	Coordinates (fixed)	Industry Partner
Service time HDT and MDT (mean/SD)	60/10	Minutes (stochastic)	Industry Partner
Service time LCV (mean/SD)	7/2	Minutes (stochastic)	Industry Partner
SO infrastructure	14	Locations (fixed)	Trott et al. (2021)
Vehicle speed inner city (mean/SD)	30/5	km/h (stochastic)	Seitz 2013
Vehicle speed outer city (mean/SD)	70/10	km/h (stochastic)	Seitz 2013
Working days/ Working hours	6/7.8	Days/hours (fixed)	Hübner et al. 2018

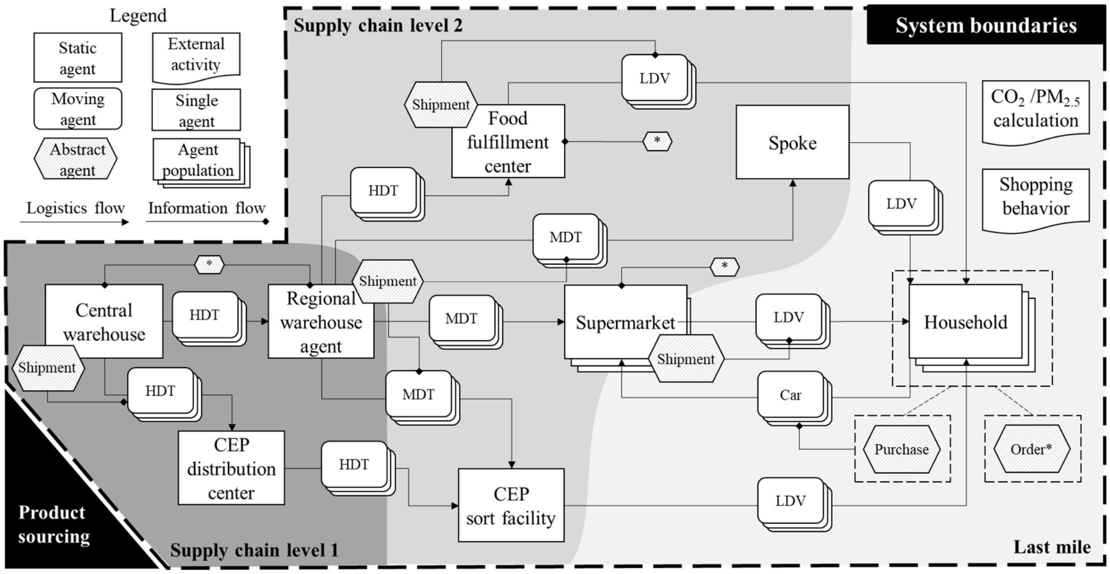


Figure 3: Conceptual simulation model.

The individual capacities of MDTs and LCVs can be stochastically varied to account for different order content compositions, while HDT capacities have been fixed, because these are less sensitive to individual order peculiarities. Physical agents (e.g., CW, FFC, HDT) are placed in a geospatial environment, where distance-based navigation and routing procedures are conducted in line with a cluster- and time-window-based k-Nearest-Neighbor algorithm (Dudani 1976). Routes between households are chosen by a distance-based cost function and CW, RW, FFC, and SOs are considered as unlimited supply and storage sources.

4 RESULTS

To assess the environmental impact of e-grocery fulfillment, the proposed simulation model has been employed for multiple simulation experiments. For each scenario, we followed a Monte Carlo approach with 11,000 runs per scenario to distribute delivery frequencies, vehicle capacities, car-utilization (Scenario 1 only), service times, and vehicle speeds proportionally to the insights generated by our literature review, WCA, and interviews. To increase the usability of our results, we have performed case analyses based on the potential e-grocery utilization rate for each conceptual scenario, starting with 1 % (utilization in Germany before COVID-19; e.g., Trott et al. 2020) and then ranging from 10 % to 100 % (Table 4).

Depending on the respective shopping frequency determined by the priory specified parameter as well as the individual e-grocery utilization rate, a total of 40.5 to 140.4 kilometers (1 % utilization) or 1,066.1 to 2,054.4 kilometers (100 % utilization) occurs within the simulates scenarios. In cases with less than 100 % utilization, the mileages from HDTs are calculated based on the respective utilization share, as it is assumed that the remaining capacities can be used for other tasks within the fulfillment system (e.g., supplying stationary SOs). Across all conceptual scenarios, the dropshipping scenario (Scenario 4) features the lowest degree of mileages, outperforming the concepts of click & collect (Scenario 1) by 50 %, FFC delivery (Scenario 2) by 48 %, CEP delivery (Scenario 3) by 19 %, Spoke delivery (Scenario 5) by 37 %, and Store delivery (Scenario 6) by 44 % on average. As highlighted in Figure 4, Scenario 1 and Scenario 2 lead to comparable mileages, especially for e-grocery utilization rates between 30 % and 70 %.

In terms of emissions, the simulation results (Figure 5) suggest similar proportions across the investigated scenarios, with Scenario 4 featuring the lowest emissions outputs of 15.28 kg in the 1 %, 399.81 kg in the 50 % and 782,43 kg in the 100 % case (CO_2) as well as 0.0001 kg in the 1 %, 0.002 kg in the 50 % and 0,004 kg in the 100 % case (PM2.5). Concerning the average relative differences on emissions across the scenarios for all utilization rates cumulated, Scenario 4 undercuts Scenario 1 by 39 %, Scenario

2 by 30 %, Scenario 3 by 21 %, Scenario 5 by 31 %, and Scenario 6 by 34 % for CO_2 and Scenario 1 by 66 %, Scenario 2 by 27 %, Scenario 3 by 15 %, Scenario 5 by 24 %, and Scenario 6 by 27 % for PM2.5.

Finally, Figure 6 outlines the share of mileages by vehicle type for the 100 % utilization case in Scenario 1 to 6 to provide an overview about the conceptual traffic elements affected by each scenario and outline the individual impact of different e-grocery fulfillment scenarios on the utilization of these vehicle types.

Table 4: Simulation results.

Scn.	**Indicator**	**E-Grocery utilization**										
		1 %	*10 %*	*20 %*	*30 %*	*40 %*	*50 %*	*60 %*	*70 %*	*80 %*	*90 %*	*100 %*
1	Mileage (km)	140.38	411.03	596.91	773.57	945.32	1,118.33	1,293.43	1,484.12	1,700.43	1,880.12	2,054.37
	PM2.5 (kg)	0.0004	0.0016	0.0027	0.0038	0.0049	0.0059	0.0070	0.0081	0.0093	0.0104	0.0115
	CO_2 (kg)	102.87	272.62	374.08	467.98	559.49	652.09	745.10	849.31	974.46	1,070.89	1,163.27
2	Mileage (km)	83.14	340.82	524.99	733.04	927.74	1,098.90	1,285.33	1,471.53	1,650.62	1,832.66	2,009.16
	PM2.5 (kg)	0.0001	0.0007	0.0012	0.0017	0.0023	0.0028	0.0033	0.0038	0.0043	0.0048	0.0054
	CO_2 (kg)	26.73	144.53	249.35	360.22	466.91	568.43	673.82	779.15	882.68	986.96	1,089.84
3	Mileage (km)	87.77	192.24	315.78	458.36	574.79	707.16	827.59	940.19	1,074.45	1,186.38	1,316.60
	PM2.5 (kg)	0.0002	0.0006	0.0010	0.0015	0.0019	0.0024	0.0028	0.0032	0.0037	0.0041	0.0046
	CO_2 (kg)	51.30	125.95	210.62	323.99	406.12	508.16	600.77	682.89	793.93	875.65	978.78
4	Mileage (km)	40.60	142.23	262.70	355.29	468.57	568.34	668.83	778.10	862.40	971.19	1,066.09
	PM2.5 (kg)	0.0001	0.0004	0.0008	0.0012	0.0016	0.0020	0.0024	0.0028	0.0032	0.0036	0.0040
	CO_2 (kg)	15.28	87.35	169.17	243.94	323.23	399.81	476.57	555.56	628.22	707.09	782.43
5	Mileage (km)	102.84	273.74	420.81	617.74	748.24	914.37	1,064.77	1,195.58	1,375.49	1,498.25	1,652.33
	PM2.5 (kg)	0.0002	0.0007	0.0011	0.0017	0.0021	0.0027	0.0031	0.0036	0.0041	0.0046	0.0051
	CO_2 (kg)	63.38	154.87	245.51	380.91	466.60	580.95	685.67	775.62	903.27	988.17	1,098.50
6	Mileage (km)	136.47	338.15	492.68	698.24	837.18	1,019.94	1,190.97	1,328.26	1,527.20	1,664.66	1,840.70
	PM2.5 (kg)	0.0003	0.0007	0.0012	0.0018	0.0022	0.0028	0.0033	0.0037	0.0043	0,0047	0.0053
	CO_2 (kg)	75.78	175.60	268.14	406.80	491.46	608.45	719.88	806.92	941.64	1,029.84	1,144.64

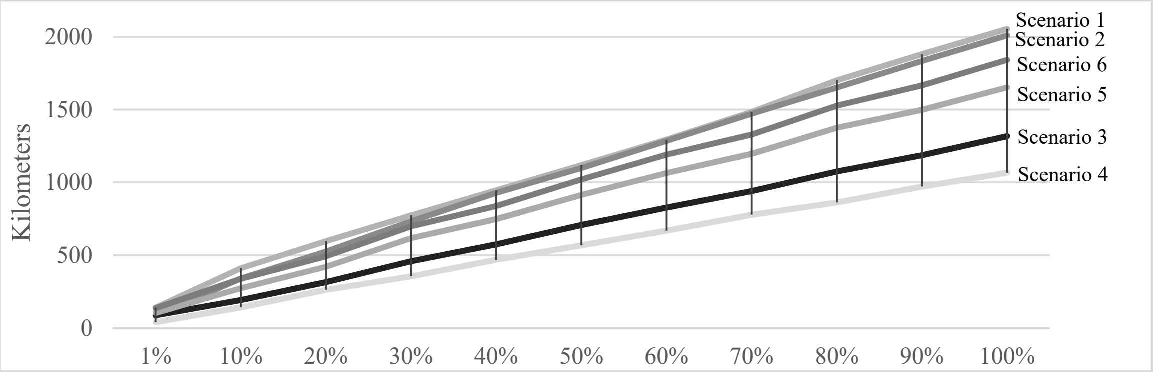


Figure 4: Total mileages in kilometers per simulation scenario and utilization case.

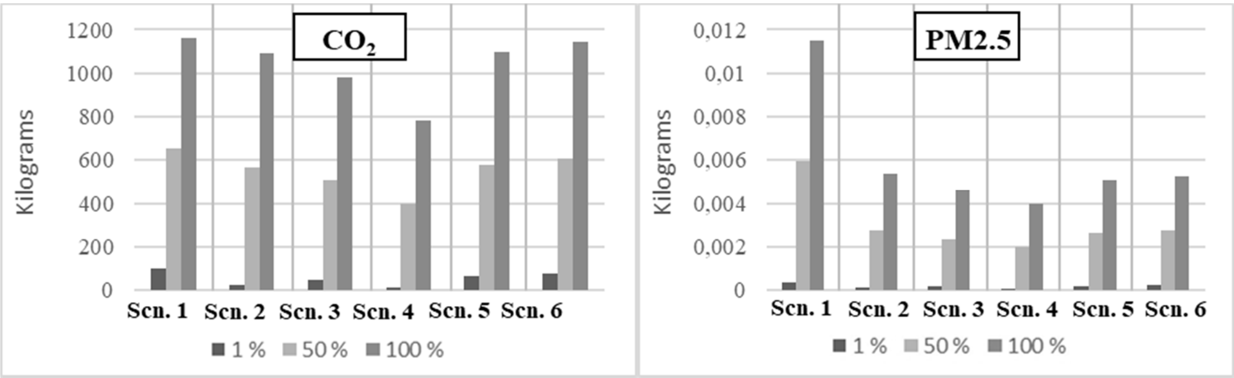
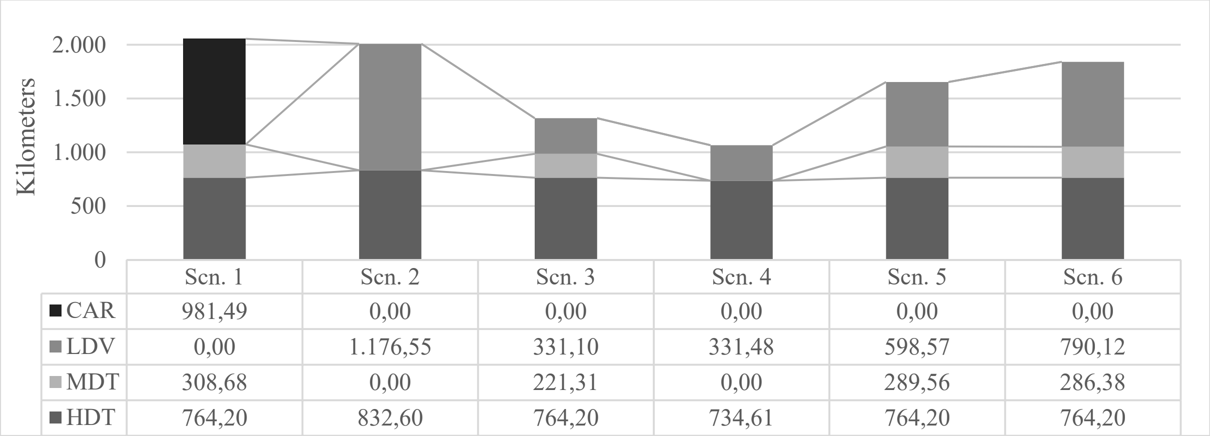


Figure 5: Total emissions in kilograms per simulation scenario for different utilization rates.



	Scn. 1	Scn. 2	Scn. 3	Scn. 4	Scn. 5	Scn. 6
■ CAR	981,49	0,00	0,00	0,00	0,00	0,00
■ LDV	0,00	1.176,55	331,10	331,48	598,57	790,12
■ MDT	308,68	0,00	221,31	0,00	289,56	286,38
■ HDT	764,20	832,60	764,20	734,61	764,20	764,20

Figure 6: Mileages in kilometers per vehicle type and scenario with 100 % utilization rate.

5 DISCUSSION AND CONCLUSION

In our contribution, based on the conceptual e-grocery fulfillment strategies of von Viebahn et al. (2020), we present a simulation model to assess the impact of different e-grocery fulfillment strategies alongside the entire supply chain on sustainability metrics such as driving distances and emission outputs. Employing a Monte Carlo approach with 66,000 simulation runs, we conducted multiple simulation experiments on the underlying fulfillment scenarios based on an exemplary use case in Germany. Our results show a strong favor for e-grocery models using CEP services (Scenario 3 and Scenario 4) rather than own delivery modes in terms of minimizing fulfillment-related emissions and driving activities. Especially the case of Drop-shipping (Scenario 4) features particularly low emissions outputs and mileages, outperforming Scenario 3 by 19 % (mileage), 21 % (CO_2), and 15 % (PM2.5) as well as Scenario 1, Scenario 2, Scenario 5, and Scenario 6 by at least 37 % (mileage), 30 % (CO_2) and 24 % (PM2.5). These results indicate and confirm the potential of e-grocery to establish more-efficient and sustainable grocery and fast-moving consumer goods supply routines (van Loon et al. 2015, Trott et al. 2020). Retailers can build on these results and establish fulfillment models that fit their business needs (see Table 1) and yield a high environmental value.

Nevertheless, referring to a wider scope, the insights of our study should be extended by means of further analyses related to additional metrics, possibly influencing the overall sustainable values of the given concepts (e.g., cooling requirements for fresh produce). Moreover, we modelled sourcing processes as black box, ignoring potential impacts of prior supply chain levels on the performance of the entire system. Both, model as well as simulation experiments are based on a particular use case featuring a particular CW and RW as well as a CEP distribution center and a CEP sorting facility responsible for the e-grocery order fulfillment. To improve the robustness and transferability of our results, these model peculiarities should be extended by implementing additional locations for the physical infrastructure and test our model and results in different geographical scenarios. Ultimately, due to the fact that e-grocery has incontrovertibly profited by the outbreak of the COVID-19 pandemic, both, in terms of growth as well as profitability (e.g., Dannenberg et al. 2020), this industry segment is likely to experience major operational and conceptual adaptions in the near future to be able to cope with the increasing demand structures as well as the altering business requirements. Hence, future research needs to monitor upcoming trends closely and extent our simulation model and results with the arising characteristics and exigencies.

REFERENCES

Agatz, N. A., M. Fleischmann, and J. A. van Nunen. 2008. "E-fulfillment and Multi-channel Distribution – A Review". *European Journal of Operational Research* 187(2):339–356.

Auf der Landwehr, M., M. Trott, and C. von Viebahn. 2020. "Simulation-based Assessment of Grocery Shopping in Urban Areas". *Simulation News Europe* 30(4):145–158.

Cagliano, A. C., L. Gobbato, R. Tadei, and G. Perboli. 2014. "Its for E-Grocery Business: The Simulation and Optimization of Urban Logistics Project". *Transportation Research Procedia* 3:489–498.

Dannenberg, P., M. Fuchs, T. Riedler, and C. Wiedemann. 2020. "Digital Transition by COVID-19 Pandemic? The German Food Online Retail". *Tijdschrift voor Economische en Sociale Geografie* 111(3):543–560.

Dudani, S. A. 1976. "The Distance-Weighted k-Nearest-Neighbor Rule". *IEEE Transactions on Systems, Man, and Cybernetics* SMC-6:325–327.

Durand, B., and J. Gonzalez-Feliu. 2012. "Urban Logistics and E-Grocery: Have Proximity Delivery Services a Positive Impact on Shopping Trips?" *Procedia – Social and Behavioral Sciences* 39:510–520.

Figliozzi, M. A. 2020. "Carbon Emissions Reductions in Last Mile and Grocery Deliveries Utilizing Air and Ground Autonomous Vehicles". *Transportation Research Part D: Transport and Environment* 85:1–12.

Fikar, C. 2018. "A Decision Support System to Investigate Food Losses in E-Grocery Deliveries". *Computers & Industrial Engineering* 117:282–290.

Ge, D., Y. Pan, Z.-J. Shen, Di Wu, R. Yuan, and C. Zhang. 2019. "Retail Supply Chain Management: A Review of Theories and Practices". *Journal of Data, Information and Management* 1:45–64.

Gómez-Cruz, N. A., I. Loaiza Saa, and F. F. Ortega Hurtado. 2017. "Agent-based Simulation in Management and Organizational Studies: A Survey". *European Journal of Management and Business Economics* 26:313–328.

Grashuis, J., T. Skevas, and M. S. Segovia. 2020. "Grocery Shopping Preferences During the COVID-19 Pandemic". *Sustainability* 12(13):5369–5379.

Hardi, L., and U. Wagner. 2019. "Grocery Delivery or Customer Pickup – Influences on Energy Consumption and CO2 Emissions in Munich". *Sustainability* 11:641.

Hays, T., P. Keskinocak, and M. De López. 2005. "Strategies and Challenges of Internet Grocery Retailing Logistics". In *Applications of Supply Chain Management and E-commerce Research*, edited by J. Geunes, E. Akçali, P. M. Pardalos, H. E. Romeijn, and Z.-J. M. Shen, 217–252. Boston: Springer.

Hübner, A., A. Holzapfel, H. Kuhn, and F. Obermair. 2019. "Distribution in Omnichannel Grocery Retailing: An Analysis of Concepts Realized". In *Operations in an Omnichannel World*, edited by S. Gallino and A. Moreno, 283–310. Cham: Springer.

Hübner, A., H. Kuhn, and J. Wollenburg. 2016. "Last Mile Fulfilment and Distribution in Omni-Channel Grocery Retailing". *International Journal of Retail & Distribution Management* 44:228–247.

Janjevic, M., and M. Winkenbach. 2020. "Characterizing Urban Last-mile Distribution Strategies in Mature and Emerging E-commerce Markets". *Transportation Research Part A: Policy and Practice* 133:164–196.

Kämäräinen, V., J. Saranen, and J. Holmström. 2001. "The Reception Box Impact on Home Delivery Efficiency in the E-Grocery Business". *International Journal of Physical Distribution & Logistics Management* 31:414–426.

Koç, Ç., T. Bektaş, O. Jabali, and G. Laporte. 2016. "The Impact of Depot Location, Fleet Composition and Routing on Emissions in City Logistics". *Transportation Research Part B: Methodological* 84:81–102.

Krehl, A., and S. Siedentop. 2019. "Towards a Typology of Urban Centers and Subcenters – Evidence from German City Regions". *Urban Geography* 40(1):58–82.

Landeshauptstadt Hannover. 2020. "Strukturdaten der Stadtteile und Stadtbezirke 2019: Statistische Auswertungen in Form von Karten, Grafiken und Tabellen". Hannover: Landeshauptstadt Hannover.

Martín, J. C., F. Pagliara , and C. Román. 2019. "The Research Topics on E-grocery: Trends and Existing Gaps". *Sustainability* 11(2):321.

Mkansi, M., C. Eresia-Eke, and O. Emmanuel-Ebikake. 2018. "E-Grocery Challenges and Remedies: Global Market Leaders Perspective". *Cogent Business & Management* 5:147.

Naidoo, M., and A. Gasparatos. 2018. "Corporate Environmental Sustainability in the Retail Sector: Drivers, Strategies and Performance Measurement". *Journal of Cleaner Production* 203:125–142.

Ntziachristos, L., and Z. Samaras. 2019. "EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019: 1.A.3.b.i-iv Road Transport 2019". Luxembourg: European Environment Agency.

Paketda. 2021. Paketzentren von DHL in Deutschland. www.paketda.de/paketdepot-dhl.html, accessed 12th February 2020.

Pan, S., V. Giannikas, Y. Han, E. Grover-Silva, and B. Qiao. 2017. "Using Customer-Related Data to Enhance E-Grocery Home Delivery". *Industrial Management & Data Systems* 117:1917–1933.

Pant, P., and R. M. Harrison. 2013. "Estimation of the Contribution of Road Traffic Emissions to Particulate Matter Concentrations from Field Measurements: A Review". *Atmospheric Environment* 77:78–97.

Punakivi, M., and J. Saranen. 2001. "Identifying the Success Factors in E-Grocery Home Delivery". *International Journal of Retail & Distribution Management* 29:156–163.

Saphores, J. D., and L. Xu. 2021. "E-shopping Changes and the State of E-grocery Shopping in the US-Evidence from National Travel and Time Use Surveys". *Research in Transportation Economics* 87.

Scott, J. E., and C. H. Scott. 2008. "Online Grocery Order Fulfillment Tradeoffs". In *Proceedings of the 41st Annual Hawaii International Conference on System Sciences*, edited by R. H. Sprague Jr., 712–722. Piscataway, NJ: IEEE.

Seitz, C. 2013. "E-Grocery as New Innovative Distribution Channel in the German Food Retailing". In *Proceedings of the Management, Knowledge and Learning International Conference 2013*, June 19th–21st, Zadar, Croatia, 125–133.

Siikavirta, H., M. Punakivi, M. Kärkkäinen, and L. Linnanen. 2002. "Effects of E-Commerce on Greenhouse Gas Emissions: A Case Study of Grocery Home Delivery in Finland". *Journal of Industrial Ecology* 6:83–97.

Tadei, R., E. Fadda, L. Gobbato, G. Perboli, and M. Rosano. 2016. "An ICT-Based Reference Model for E-grocery in Smart Cities". In *Smart Cities,* edited by E. Alba, F. Chicano, and G. Luque, 22–31, Cham: Springer International Publishing.

Thaller, C., L. Papendorf, P. Dabidian, U. Clausen, and G. Liedtke. 2019. "Delivery and Shipping Behaviour of Commercial Clients of the CEP Service Providers". In *Interdisciplinary Conference on Production, Logistics and Traffic*, edited by U. Clausen, S. Langkau, and F. Kreuz, 205–220. Cham: Springer.

Trott, M., C. von Viebahn, and M. Auf der Landwehr. 2020. "Towards a More Sustainable Future? Simulating the Environmental Impact of Online and Offline Grocery Supply Chains". In *Proceedings of the 2020 Winter Simulation Conference*, edited by K.-H. Bae, B. Feng, S. Kim, S. Lazarova-Molnar, Z. Zheng, T. Roeder, and R. Thiesing, 1218–1229. Piscataway, NJ: IEEE.

Trott, M, M. Auf der Landwehr, and C. von Viebahn. 2021. "E-grocery of Tomorrow – Home Delivery of Food Between Profitability, Customer Acceptance and Ecological Footprint". *World Review of Intermodal Transportation Research* 10(1).

Van Loon, P., L. Deketele, J. Dewaele, A. McKinnon, and C. Rutherford. 2015. "A Comparative Analysis of Carbon Emissions from Online Retailing of Fast Moving Consumer Goods". *Journal of Cleaner Production* 106:478–486.

Von Viebahn, C., M. Auf der Landwehr, and M. Trott. 2020. "The Future of Grocery Shopping? A Taxonomy-Based Approach to Classify E-Grocery Fulfillment Concepts". In *Proceedings der 15. Internationalen Tagung Wirtschaftsinformatik 2020,* edited by N. Gronau, M. Heine, H. Krasnova, and K. Pousttchi, 955–971. Potsdam: GITO Verlag.

Waitz, M., A. Mild, and C. Fikar. 2018. "A Decision Support System for Efficient Last-Mile Distribution of Fresh Fruits and Vegetables as Part of E-Grocery Operations". In *Proceedings of the 51st Hawaii International Conference on System Sciences,* January 2nd-6th, Hawaii, USA, 1259–1267.

Webster, J., and R. T. Watson. 2002. "Analyzing the Past to Prepare for the Future: Writing a Literature Review". *MIS Quarterly* 26:13–23.

Wollenburg, J., A. Hübner, H. Kuhn, H., and A. Trautrims. 2018. "From Bricks-and-Mortar to Bricks-and-Clicks". *International Journal of Physical Distribution & Logistics Management* 48(4):415–438.

Zhang, L., R. Long, H. Chen, and J. Geng. 2019. "A Review of China's Road Traffic Carbon Emissions". *Journal of Cleaner Production* 207:569–581.

AUTHOR BIOGRAPHIES

MARVIN AUF DER LANDWEHR is a full-time Ph.D. student and researcher at the University of Applied Sciences and Arts of Hannover. He holds an honored M.Sc. in strategic corporate development. His research interests focus on the simulation of supply chains, urban logistics, and marketing operations. His e-mail address is marvin.auf-der-landwehr@hs-hannover.de.

MAIK TROTT is a part-time Ph.D. student at the University of Applied Sciences and Arts of Hannover and Innovation Manager at DB Schenker Deutschland AG. He holds a B.Sc. in Business Informatics and an honored M.Sc. in strategic corporate development. His interests focus on simulation, logistics, and enterprise innovations. His email address is maik.trott@hs-hannover.de.

CHRISTOPH VON VIEBAHN is a professor for business informatics at the University of Applied Sciences Hannover. He is specialized in Supply Chain Management, Business Administration, and dynamic Computer Simulation. In 2016, he was elected regional group spokesman for Lower Saxony by the Bundesvereinigung Logistik (BVL) and has been member of the urban logistics department since 2017. His email address is christoph-von.viebahn@hs-hannover.de. His website is http://www.scm-lab.de.