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Integrated urban mobility policies in metropolitan areas: A system dynamics approach for the Rhine-Ruhr metropolitan region in Germany

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ABSTRACT

In today's world, urban systems play an important role in sustainable economic development. In particular, urbanisation trends and the increasing demands of urban mobility place additional pressure on existing transportation infrastructure, and this creates new challenges for urban planners in terms of developing integrated and sustainable urban mobility policies. Here, we take a novel and holistic approach to analysing transformative pathways towards sustainable urban mobility, considering the complex dynamics in metropolitan regions. To achieve this, we develop a toolset to assess the impact of potential measures to be taken by decision makers. Our innovative approach is based on the introduction of a new system framework to link the interrelated sector parameters of mobility systems by considering the effects of innovative mixed methods (both qualitative and quantitative) on scenario development and evaluation on the basis of global trends at the macro scale and their specific influences on the mobility sector at the local scale. To this end, we used a participatory modelling approach to develop scenarios and evaluate them as integrated simulation runs via a comprehensive and holistic system dynamics (SD) model. Thus, we estimated dynamic interdependencies between all of the factors relating to the mobility sector and then assigned business decision-making criteria to the urban systems. Furthermore, we introduced a sustainable net present value framework to estimate the sustainability outcomes of government investment in urban mobility infrastructure. A case study relating to the Rhine-Rhine-Ruhr metropolitan region in Germany was applied in order to simulate four scenarios co-created with stakeholders involved in our study, namely, Smart City, Sustainable/Healthy City, Deurbanisation and Business-as-Usual (BaU), which served as a solid basis from which to quantify path dependencies in terms of policy implementation. At the same time, recommendations were derived for sustainable mobility transformation within metropolitan regions.

1. Introduction

Rapid urbanisation and economic growth in recent years have caused a significant increase in urban transportation and mobility demands, and this, in turn, has fostered the development of efficient, integrated, just-in-time and system-based sustainable mobility concepts (Ambrosino, Nelson, Boero, & Pettinelli, 2016; Jittrapirom et al., 2017). Studies have shown that the transportation sector and urban areas are responsible for about 24 % and 67 % of energy-related greenhouse gas emissions, respectively (Ashnani, Miremadi, Johari, & Danekar, 2015; IPCC (Intenational Panel on Climate Change), 2015), and this is likely to play a crucial role in whether or not the European Union will reache its target of a 60 % reduction in greenhouse gas emissions by 2050 (Gota, Huizenga, Peet, Medimorec, & Bakker, 2019; Pichler et al., 2017). In order to overcome the prevailing issues relating to inefficiency and non-sustainability, urban mobility needs to change, and this will require enhanced transparency, coordination, competitiveness, cooperation and creative effort in terms of redesigning our

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communities, businesses and governance systems. A major change will also require links to existing solutions, such as the 'Smart City' concept (Garau, Masala, & Pinna, 2016; Neirotti, De Marco, Cagliano, Mangano, & Scorrano, 2014; Serrano-Lopez, Linares-Unamunzaga, & San Emeterio, 2019; Zawieska & Pieriegud, 2018). However, the fragmentation of mobility service providers and lack of coordination among actors in the policy design process are currently hindering the development and adoption of improved urban mobility solutions (Spickermann, Grienitz, & von der Gracht, 2014).

Against this background, our objective is to develop a toolset for designing sustainable urban mobility solutions, while simultaneously exploring potential transformation pathways towards achieving net-zero greenhouse gas (GHG) emissions in metropolitan areas. In this context, we define transformation as improved efficiency and sustainability of the entire urban mobility ecosystem by exploring its innovation potential within metropolitan areas (for example, new sharing economy business models, inclusive governance approaches and the sustainability impact of advanced digital technologies). To achieve this goal, we developed a system dynamics (SD) model for the mobility sector in metropolitan areas and applied it to a case study of the Rhine-Ruhr metropolitan region in Germany. Research has shown that using a systematic participatory approach whereby stakeholders are included in the scenario co-creation and modelling process has been successful in identifying more appropriate integrated solutions likely to gain a higher level of acceptance in communities (Voinov & Bousquet, 2010; Voinov et al., 2016). Thus, in conjunction with stakeholders from the Rhine-Ruhr region, we started the modelling process by co-creating narratives of urban mobility scenarios and evaluating the descriptive factors of these narratives using the social, technological, economic, environmental and political (STEEP) method. Based on these narratives, a holistic SD model was created, which represented the causal interdependencies between the relevant factors influencing the mobility system in metropolitan areas. We then applied the SD model to estimate dynamic changes within the system boundaries for current and potential future regional developments, relying on a systematic literature analysis (a scientific estimation of the future development of system-relevant variables) as well as other mathematical model estimations (developed by the project partners cooperating with us).

The paper is structured as follows: First, in Section 2.1, we discuss the theoretical background and position of our paper within the literature on global urbanisation, which is one of the main explanatory trends for mobility turnover. The effect of urbanisation on the economy is then analysed in Section 2.2 from an ecological economics perspective, and alternative urban economic indicators are defined. Sections 2.3 and 2.4 deal with innovative mobility concepts as best case examples and also with the history of dynamic modelling in the mobility sector; additionally, these sections highlight the contribution of our paper to the body of international literature. In Section 3, which focusses on the research design, we provide a graphic illustration of the concept and structure of the paper. In Sections 3.1 and 3.2, we describe the scenario development method, STEEP, and the SD modelling technique, respectively. To test the model, we applied it to a case study of the Rhine-Ruhr metropolitan region in Germany, as described in Section 3.3, and this provides the input data for the SD model. The results of scenario development and the scenario-based simulation runs are presented in Section 4. We then discuss the results and provide some concluding remarks in Section 5. Also in this section, we discuss the potential for implementing our model framework in other metropolitan areas and address the limitations of the model.

2. Theoretical background

In recent times, rapid urbanisation rates have led to increased mobility demands, which has hastened the need to develop sustainable, integrated and holistic urban mobility strategies that can be designed and implemented on the basis of sustainable and inclusive urban governance (Hodson, Geels, & McMeekin, 2017).

To address this need, we contextualise our research by reviewing international scientific literature on the sustainable urban systems that relate to the mobility patterns. In this paper we used the system components, which are described in the literature as follows:

- socially inclusive and transformative cities (Haase et al., 2017; Marana et al., 2019; Nevens, Frantzeskaki, Gorissen, & Loorbach, 2013);
- participatory and sustainable governance of cities (Hendricks et al., 2018; Seo & Joo, 2019; Zhuang, Qian, Visscher, Elsinga, & Wu, 2019);
- environmental transportation and mobility patterns in metropolitan regions (Soria-Lara, Tarriño-Ortiz, Bueno, Ortega, & Vassallo, 2019; Zandiatashbar, Hamidi, & Foster, 2019; Zhao & Hu, 2019);
- technological cities (Camboim et al., 2018; Rodrigues & Franco, 2019);
- cities as business incubators (Blank, Ribeiro, & Anzanello, 2019).

This literature review is then used to identify the trends, factors and parameters of an urban system, which have the greatest impact on sustainable mobility transitions and their related dynamics based on ecological economic theories. These trends, factors and parameters are then combined with the co-created narratives (using the STEEP method) and serve as the basis for the SD model development.

Therefore, one part of our theoretical contribution is a review of the sustainability factors relating to open/social innovation (for example, sharing economy business models), sustainable governance, as well as advanced technologies and their acceptance by users, all of which serve as a basis for estimating the effects of scenario-based simulation runs on efficient urban mobility policies. A further contribution is linking the different advanced qualitative and quantitative approaches used in international literature to run scenario-based simulations.

2.1. Urbanisation as a global phenomenon that impacts mobility

In essence, urban systems are the engines of economic, social and cultural development. The increase in urban land cover during the first three decades of the twenty-first century is expected to be higher than the cumulative level of urban expansion in all of human history (IPCC, 2014). Currently, 55 % of the world's population lives in urban areas, and this figure is projected to rise to 68 % by 2050 (UN, 2018).

The term urbanisation describes more than simply an increase in the urban population, and in recent years, new frameworks have been proposed to capture the multiple dimensions of the concept of urbanisation (Boone et al., 2014). Instigators of urbanisation include increased birth rates in urban areas and people moving from rural areas, causing cities to grow in population and physical size. Population growth rates are often proportionally lower than the increase in developed urban land, which typically indicates an expansive pattern of urban growth (Seto, 2011). This phenomenon–referred to as urban sprawl–remains a complex and elusive concept (Galster et al., 2001). However, key attributes of urban sprawl include extension of the city area beyond walkable range (Rahman, 2016), a decline in urban densities (Ewing, Hamidi, & Grace, 2016), increased consumption of land resources by urban dwellers (Huang, Yeh, & Chang, 2010), ongoing suburbanisation (Koch et al., 2019) and fragmentation of open spaces as well as built-up areas (Oueslati, Alvanides, & Garrod, 2015; Dorning et al., 2014). Numerous studies have identified the primary factors that drive urban sprawl, including a rise in household incomes, individual preferences, technological progress in the automobile industry, affordability of vehicles and a decline in commuting costs (Deng et al., 2008; Patacchini & Zenou, 2009; Seto, 2011; Oueslati et al., 2015). In this sense, our Deurbanisation scenario is strongly tied to the idea of urban sprawl, assuming increased housing costs in city centres and a good mobility infrastructure to allow convenient commuting.

2.2. Alternative urban economic indicators as a basis for mobility transformation

Studies have shown that increased urbanisation rates are frequently associated with economic growth, specifically with the formation of agglomeration economies, increased trade volumes, technological development and productivity gains, as well as socio-ecological benefits such as a reduction in poverty, inequality and pollution (Brülhart and Sbergami, 2009; World Bank, 2009; Sekkat, 2017; Frick & Rodríguez-Pose, 2018). However, the resulting overall positive urban economic effects are uncertain, since urban diseconomies of scale, such as congestion, social inequality, unemployment, the digital divide, political and social conflicts, are often neglected (Frick & Rodríguez-Pose, 2018). Hence, strategic urban planning must respond to the current challenges associated with social equity, mobility patterns, global competitiveness and energy efficiency (Seto, 2011; OECD, 2018). It is estimated that transformative urban change in transportation systems has the potential to reduce GHG emissions by up to 1.5 billion CO_{2eq} by 2030 (New Climate Economy, 2016). Moreover, it is essential to develop inclusive concepts of urbanisation that guarantee access to infrastructure, social services, housing, education, health care, fair employment and a safe environment for all residents (Palanivel, 2017).

Thus, concepts of urban growth no longer fit with the value creation principles of the new techno-economic paradigm (Camboim et al., 2018). To address this gap, we set new indicators for alternative urban economic development, defining citizen access to innovative mobility concepts, given to current technological progress (digital divide and social fairness, as well as net present value of public investments), instead of estimating only economic profitability and digital enhancement of these concepts (Kresl & Singh, 1999; European Union (EU), 2018). However, while considerable work has been done at the community, national and international level to identify suitable indicators, there is no consensus on a universal measure of sustainable urban development (Rodrigues and Franco, 2009). Gross Domestic Product (GDP) is frequently used because of its transparency and replicability (Michael, Noor, & Figueroa, 2014), but given the non-linear interactions between the economic, socio-environmental and infrastructural components within urban systems, there is a need for interdisciplinary approaches to measuring sustainability in those systems.

In the research presented here, we used the idea of the Genuine Progress Indicator (GPI) and its descriptors to model the urban mobility ecosystem. The GPI concept is designed to account for income, the three dimensions of sustainability, and other aspects of capital relevant to human, social, built and natural welfare (Huang, Wu, & Yan, 2015). Of the twenty monetarily assessed components of GPI, there are multiple parameters that are highly influenced by mobility patterns, and those parameters account for, among other things, the cost of travel between home and the workplace, the cost of traffic accidents, damages relating to air pollution, the cost of noise damage, substitution costs generated by the exploitation of non-renewable resources, and the cost of damages from GHG emissions (Cobb et al., 2001). An example for Germany displays clearly the difference between the GDP and GPI indicators: if GDP has risen steadily, GPI peaked around 2000 and has fallen ever since (Diefenbacher et al., 2016). The same trend was observed in the state of North Rhine-Westphalia, where a study between the years 1999 and 2013 revealed that the components accounting for the cost of travel between the home and the workplace and the cost of traffic accidents each contributed to a 5% decrease in GPI (Rodenhäuser et al., 2013).

Nevertheless, efficiency assessments that have been carried out regarding public government investment still lack a social and environmental dimension, particularly concerning CO_2 savings. In this context, Zore, Cucek, Sirovnik, Pintaric, and Kravanja (2018) proposed a framework on sustainability net present value (SNPV), which takes into account economic, social and ecological aspects for assessing investments made by companies. Specifically, SNPV represents the responsibility of companies for preventing pollution and relies on a fair consideration of favourable/adverse environmental effects from a global/ideal viewpoint. Relying on this concept, we propose a sustainable net present value (SNPV) framework to estimate the sustainability outcomes of government investment in urban mobility infrastructure, utilising some of the descriptive parameters of GPI, such as cost of underemployment and cost of air pollution and environmental damage (Costanza et al., 2004). Based on this innovative framework, a rescaling of governments' primary concern with greenhouse gases towards wider and more comprehensive economic and social isses could help to root environmental accounting more deeply in industrial and market structures (Jordan & Bleischwitz, 2020).

2.3. Innovative mobility concepts enabled by digital technologies

A number of factors today place additional pressure on urban mobility systems and drive the need for innovative mobility solutions; these include legal requirements, new participants entering the sector, the emergence of disruptive technologies, and strict national emission targets. As with organisational innovations and societal changes, the development of new mobility concepts is heavily influenced by technological innovations (Kamargianni, Li, Matyas, & Achäfer, 2016), for example, the replacement of combustion engine cars with electrical (EV) or alternative vehicles (Gass, Schmidt, & Schmid, 2014). Similarly, the main driver of new mobility solutions within the transportation sector is digital innovation, which satisfies stakeholders' requirements for changing mobility patterns, regulations, competition and investment structures (Pangbourne, Stead, Mladenović, & Milakis, 2018). Furthermore, digitisation provides more transparency and process efficiency, and it can also facilitate cost reduction, rapid co-development of innovative business models, increased communication, and sustainability (Gunasekaran et al., 2017). Considering rapidly emerging disruptive technologies, two main aspects can be observed within the context of new urban mobility solutions (Bouteil, 2019), as follows:

a) *Increased diversity in the services offered*

A taxonomy of diversified new mobility services for eleven categories has recently been established: traditional ride sharing (carpooling); car sharing; bike sharing; microtransit; employee buses; sequential sharing; concurrent sharing; taxi apps (E-Hail); aggregator apps; parking/navigation apps; and mobile payment for transportation services.

b) *New players attracted to the sector*

The second important aspect of new mobility concepts is the entrance of new players to the sector. Table 1 shows the top eight start-ups specialising in new mobility services. These start-ups have received massive funding from corporate stakeholders in the ICT industry, highlighting the ongoing digitisation of the mobility sector (Bouteil, 2019).

In summary, shared mobility concepts play a significant role within existing urban mobility systems and increasingly rely on directly responsive participants, namely, users and vehicles that foster the implementation of digital applications (Stiglic, Agatz, Savelsbergh, & Gradisar, 2018). Moreover, new mobility providers are flexible in terms of switching to more sustainable solutions, because 'green' and 'clean' technological solutions require business feasibility and also quantifiable long-term profitability, efficiency and sustainability (Leonardi, Browne, Allen, Bohne, & Ruesch, 2014). Thus, one of the central scenarios of sustainable urban mobility transformation in this paper is the 'Smart City' scenario, which applies the social component of the sharing society to achieve mobility transformation. However, even though the relationship between the smart city concept and sustainable urban transport has been analysed from a CO_2-saving perspective in international literature (Zawieska & Pieriegud, 2018), a holistic approach to

Table 1
Top eight mobility start-ups over the past decade (modified from Bouteil, 2019).

Company name	Headquarters	Founded	Funding	Corporate investors from ICT (excerpt)
Didi Chuxing	Beijing, China	2012	$18.1 bil	Sina Weibo, Tencent Holdings, Alibaba Group, Apple, Uber, Foxconn Technology Company
Uber	San Francisco, USA	2009	$16.4 bil	Google Ventures, Baidu, Microsoft, Didi Chuxing
Grab	Singapore	2012	$4.64 bil	Qunar, Didi Chuxing, Uber
Lyft	San Francisco, USA	2012	$3.96 bil	Facebook fbFund, Tencent Holdings, Didi Chuxing, Alibaba Group, Rakuten
Ola	Bangalore, India	2010	$3.80 bil	Didi Chuxing, Tencent Holdings
Ofo	Beijing, China	2014	$2.28 bil	Xiaomi, Didi Chuxing, Alibaba Group
Mobike	Beijing, China	2015	$2.01 bil	Foxconn Technology Company, Ctrip, Qualcomm Ventures
Go-Jek	Jakarta, Indonesia	2010	$1.75 bil	Rakuten Ventures, Tencent Holdings, Samsung Ventures, Google

the complex dynamics in other sectors (for example, the energy sector) and the impact of sharing mobility concepts on the environment has not yet been considered. This gap is addressed by the given paper.

2.4. System dynamics and sustainable mobility solutions

The flow of high-quality information on mobility solutions between urban planners, the industrial sector (mobility/technology/infrastructure providers) and consumers can be improved by advanced tools and platforms, which serve to enable the flow of information and support the decision-making process in terms of mobility planning. One method for improving information flow and decision support is the system dynamics (SD) approach. This has been successfully applied for decision support in participatory settings in a wide range of disciplines (Tako & Robinson, 2012) and has a high potential for transition research and applications in disruptive areas, such as urban mobility and transport (Marsden & Docherty, 2013). In addition, SD has been applied to explore the interactions between societal, technological, managerial, urban and ecological systems, all of which are driven by, and driving, changes in the behaviour patterns of the stakeholders involved in urban mobility (Bernardino & van der Hoofd, 2013).

For the research presented here, we chose the SD approach for the following reasons:

1 The SD approach aims to develop process theories while using case studies as part of a longitudinal research design (Morrison and Oliva, 2017; Papachristos, 2018). Hence, SD benefits from real-world cases.
2 Qualitative data is one of the most important sources when it comes to modelling participatory decision-making processes (Forrester, 1961; Groesser and Schaffernicht, 2012). In this context, the SD approach can be applied to describe qualitative research as narrative scenarios, and it can also be used to develop mid-term hypotheses (Schwaninger and Grosser, 2008) and therefore identify a trade-off between quantitative and qualitative data. Moreover, it can make use of the other data sources, such as qualitative analyses carried out using the STEEP method or other quantitative data inputs (for example, agent-based modelling).
3 The SD approach offers a structured method of public/stakeholder involvement (using mental maps such as causal loop diagrams); it also functions as a tool to focus on a problem and the related policy levers, aims to identify issues with the structure of a system, and offers opportunities to learn about and document the policy process (Stave, 2002).

Many examples of SD application for policy making illustrate the power of SD in the development and evaluation of integrated mobility scenarios combining qualitative and quantitative information. For example, Bernardino and van der Hoord (2013) presented an SD model assessing the effectiveness of parking policies without compromising the service level offered. Similarly, Mei, Lou, Zhang, Zhang, and Shi (2017) evaluated parking policies using an SD model, examining the effects of parking charges and supply policy on traffic speed in Hangzhou, China. Guzman, de la Hoz, and Monzon (2014) assessed the influence of mobility policies on a decision-making process that saw the integration of forecasting and optimisation procedures in a strategic land use-transport interaction (LUTI) model. The SD model proposed by Liu et al. (2015) analysed the impact of the motorisation process under Beijing's urban traffic conditions and CO_2 emissions according to different government policies. In a case study of the London metropolitan area based on the application of an SD model, Sabounchi et al. (2014) simulated the impact of different factors on the dynamics of traffic congestion, examining both the short- and long-term mitigating effects of an area-based congestion pricing policy. Thus, in summary, the SD approach has been successfully applied to analyse several interrelated elements of urban mobility, including the efficiency of traffic, parking management, energy consumption and CO_2 emissions, urban economy, and congestion. For these reasons, the SD method is an obvious choice for implementing participatory approaches in the development of policy solutions within the mobility sector.

3. Research design

In order to develop a toolset for developing and assessing sustainable urban mobility patterns, while simultaneously exploring potential transformation pathways towards net-zero greenhouse gas (GHG) emissions in metropolitan areas, we utilised a mixed method based on qualitative and quantitative analyses. The mixed method comprised a series of workshops with the stakeholders aimed at developing scenarios using the STEEP method (§3.1). Further, an SD simulation model was applied as a quantitative tool with the aim of running simulations based on scenario parametrisation for future development of the descriptive parameters. We demonstrated the model's functionality in the context of a study case on the Rhine-Ruhr metropolitan region in Germany. Fig. 1 provides a visual description of the workflow of the presented research, addressing the interplay between the qualitative and quantitative analyses. This innovative approach can be applied as a framework in other metropolitan areas around the world, using local specifications and data, as well as the political and societal requirements for mobility transformation in those areas.

3.1. STEEP method to develop scenarios for urban mobility

The co-creation of scenarios was implemented based on a participatory approach during a series of workshops attended by the relevant stakeholders from the region, including citizens, policy makers from the city governments of Bottrop and Essen, transport association[1] and experts with extensive experience in the mobility sector of the region. Within the workshops, global trends that could have a significant impact on the region were discussed in detail and served as a basis for the scenarios, in conjunction with the application of the STEEP method. The aim of this method is to identify external factors that are outside the control of the decision maker but have a significant impact on transport and mobility operation within a complex system of

[1] https://www.vrr.de/en/informationpage-local-traffic-coronavirus/

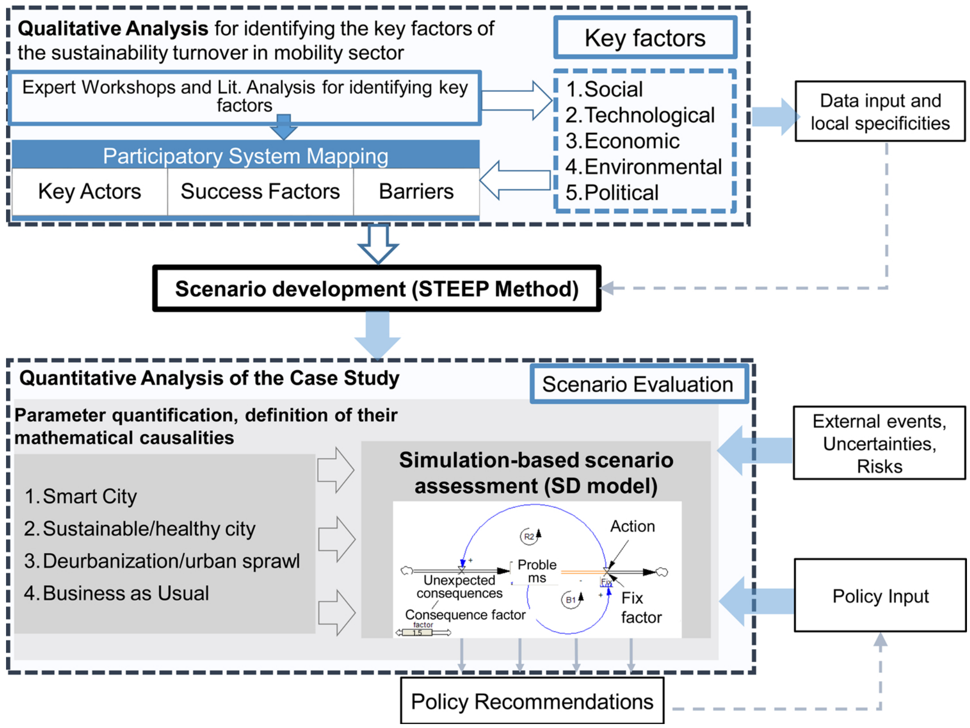

Fig. 1. Simulation-based scenario assessment framework developed in this paper.

interactions. With its emphasis on the mixed-method approach, STEEP comprises qualitative techniques, such as participatory and brainstorming techniques, while also utilising several statistical tools, for example, CIB (cross-impact balance analysis) and multidimensional scaling (Lorenz & Veenhoff, 2013; Melkonyan et al., 2019). While CIB is used to analyse both the qualitative and quantitative impact of networks in order to construct consistent images of the network's behaviour, the multidimensional scaling (MDS) technique helps to analyse the similarities between data relating to a set of objects used in several fields (such as traffic behaviour, the ecological impact of mobility, public investment in traffic etc.), based on the incorporation of intercorrelations, ratings or indices of any kind. The MDS technique provides a graphical visualisation of the data structure and displays the information essential to dealing with the extreme complexity of an urban mobility system featuring numerous elements. Thus, utilising the STEEP method, we analysed the trends and their descriptive parameters and combined them to form scenarios. This method also allows the potential future development of these parameters within the scenarios to be evaluated, which, in terms of the Rhine-Ruhr case (§3.3), meant combining the stakeholder assessment with a literature review. The parametrisation results, which are presented in Table 3, provided a solid basis for carrying out the simulation runs following development of the complex and holistic SD model.

3.2. System dynamics modelling

In essence, the development of an SD model combines the use of qualitative methods (causal-loop diagrams, CLD) and quantitative methods (stock-flow diagrams, SFD) (Bossel, 2007). Qualitative methods are used to make initial statements about the underlying system behaviour and to create logical models, while quantitative methods are used to formulate predictive mathematical models. Hence, the first step in developing an SD model is to map out the system components and the corresponding relationships and feedback in the form of a CLD. The identified feedback mechanisms comprise either negative (compensation) or positive (amplification) loops (Bossel, 2007; Georgiadis, Vlachos, & Iakovou, 2005). A negative feedback loop represents a target-seeking behaviour; in other words, as soon as a disturbance occurs, the system works to restore the original (or a new) equilibrium. In contrast, a positive feedback loop in the system leads to deterioration, destabilising the system if a disturbance occurs and leading to further change.

The second stage of developing an SD model involves extracting the stocks and flows from the CLD and translating them to an SFD (Bossel, 2007). To do this, an in-depth study of the interactions and relationships between the system components is necessary, and this process can lead to an increase in the number of variables involved initially, making system representation more complex.

The following questions must be answered to decide whether a parameter is a stock: (1) Does it accumulate? (2) Can it be measured at every time step? (3) Can it be stored somewhere and used at a different point in time? (Binder et al., 2004). All components that do not qualify as stock are either flows or auxiliary parameters. The compounds entering and leaving stocks can be considered as flows if they can be measured as a rate (that is, x per unit of time). The other explanatory variables are then the auxiliary parameters (Lane & Husemann, 2008).

The third stage of developing an SD model is the quantification of the SFD by providing initial values for all stocks and by formulating mathematical dependencies between the SFD components (Binder et al., 2004). The latter is represented by a system of equations, which are then solved by model simulation (Georgiadis et al., 2005).

To build the SD model for the given case study, we chose the parameters based on the following:

1) trends in population dynamics and urban economics (dynamics were modelled using a different planning model based on the turbulence theory, namely, multiscale urban modelling (MURMO), as discussed by Lengyel & Friedrich, 2019);
2) traffic dynamics (cumulative travelled distance simulated using the agent-based multi-agent transport simulation (MATSim) model (https://www.matsim.org/);
3) the newly developed SNPV framework (relying on GPI indicators);
4) sharing economy models in the mobility sector (the societal requirements to use these concepts were estimated by the focus

groups, while the political requirements were set following interviews conducted with government representatives of four cities in the region).

The MURMO and MATSim models and their precise descriptions and development processes are not within the scope of this paper (see references above); however, Table A1 in Appendix shows the output parameters of these models serving as input parameters for our SD model.

The innovativeness of the SD model in our paper is based on a new system framework that links together the interrelated parameters of the mobility and energy sectors, while simultaneously considering advanced approaches relating to ecological economics at the macro scale (alternative indicators of urban economics) as well as new socio-economic dynamics in sharing economy models at the local scale.

3.3. Application example: Rhine-Rhine-Ruhr metropolitan region, Germany

The Rhine-Ruhr region, located in the state of North Rhine-Westphalia in Germany, is a metropolitan urban complex of closely located cities with a post-industrial character. The individual cities are set apart by social, economic and spatial variances that define the lifestyle, design and mobility of the area. Due to economic and structural changes in the region, the dense transport infrastructure that drove industrialisation processes was abandoned or shut down over time, and new connections emerged to fulfil the needs of modern society. In the intervening period, the Rhine-Ruhr region has developed a unique, car-oriented mobility infrastructure featuring dense highway and road networks, waterways, railways and multimodal hubs of European importance for freight transportation (IHK, 2013). However, infrastructural capacity reached its limits many years ago, causing environmental problems for the region (IHK, 2013). Furthermore, dependency on private motor vehicles has created congestion issues and challenges relating to the environment, energy consumption, public health, and social and spatial segregation (Frank, 2000). In 2012, more than every other trip undertaken in the Ruhr area was made using a private motor vehicle, accounting for 53 % of all trips, while 23 % of trips were made on foot, 8% by bicycle and 16 % by public transport (Grindau & Sagolla, 2012). These proportions are almost equal to the average modal split in Germany, even though the urban structure of the Rhine-Ruhr region lends itself to car-free mobility (Müller. et al., 2017).

Innovative mobility solutions to increase efficiency in the transportation system can be enabled in this region by implementing emerging new digital technologies, reflected mainly in the ‘Smart City’ concept. According to the German Economic Institute (IW, 2018), the Rhine-Ruhr region is well prepared for a digital future; indeed, it could easily become the leading smart city region in Europe. The ‘Digital Administration NRW’ and ‘Law for the Promotion of Electronic Administration in North Rhine-Westphalia (EGovG NRW)’ programmes are good examples of how city administrations can be digitised through information technologies and organisational changes (Ministry for Economy, Innovation, Digitization and Energy, NRW). One of the cities in the region, Bochum, aims to become a Gigabit City by connecting commercial areas to fibre-optic networks with a view to making the city an attractive economic location for international investment (AGV, 2018). Other cities in the region, for example, Duisburg and Gelsenkirchen, are cooperating with the Chinese ICT company Huawei to modernise their digital infrastructure. This cooperation is even more relevant for Duisburg, since its inland port, which is the biggest in Europe, is an essential part of the ‘Belt and Road Initiative’ (Hunag, 2016). The city of Dortmund follows a different approach to digitisation; in addition to technological solutions, its Smart City approach is based on citizen involvement and focusses on holistic urban development rather than just on infrastructure. Furthermore, it is building on a Masterplan of Energy Turnover that links digitisation with climate protection measures.

However, even though some innovative solutions are being implemented in different cities in the Rhine-Ruhr region, there are no universal guidelines or strategies that take account of all the dynamics of socio-economic development in the region. Digitising administrative processes is an important starting point, but it needs to be followed by joint infrastructure projects (Angelidou, 2015). Moreover, one of the prerequisites for the successful implementation of smart solutions in the mobility sector is behavioural changes among citizens (Sochor, Strömberg, & Karlsson, 2015). Following the emerging trend of mobility as a service that provides seamless and multimodal mobility, citizens need to switch from owning assets such as cars and bikes to renting them on demand, hence fostering sharing economy models (Cohen & Kietzmann, 2014; Jittrapirom et al., 2017). Going forward, the emergence of sharing mobility concepts will also be enhanced by the ongoing shift towards driverless cars (Lavieri et al., 2017). All of these changes have critical implications for the organisation of public spaces and roads and require new forms of collaboration among players in the mobility system.

3.3.1. SD model parametrisation for the case study

The SD model in the study was parameterised and applied for the Rhine-Ruhr metropolitan region based on data received from various statistical agencies of the federal government and on the literature analyses described above. It should be borne in mind that the parameters derived from the literature analyses were classified into scenarios using the STEEP method, and not by reference to the original classification schemes used in the literature. The types of variables, as well as their units, initial values and literature sources, are presented in Appendix 1 (Table A1), and these were then used for the base case scenario (Table 3). The parameter values for the other scenarios used in the simulation runs were derived from the outputs of the MATSim and MURMO models, as well from the expert assumptions systematically analysed within the scenario development and evaluation workshops by applying the STEEP method. These sources are also differentiated in Table A1 in the Appendix. In addition, the Table A1 also displays equations describing the interdependencies between the parameters, which were derived through a systematic literature review.

These comprehensive and novel analyses, when integrated into the holistic SD model, transform regional dynamic processes into a decision support tool for policymakers in the Ruhr Region, allowing them to test the impact of decisions on the system components or on the system as a whole. This tool development process can also be applied elsewhere in the world.

4. Results

We developed a comprehensive system dynamics simulation model for the mobility sector, which aimed to provide a ‘virtual laboratory’ for testing potential transformation pathways towards net-zero greenhouse gas (GHG) emissions in metropolitan areas. The model and the corresponding test case were designed in conjunction with stakeholders from the Rhine-Ruhr metropolitan region in Germany using STEEP, a development and evaluation method for participatory scenarios, and the results of the process are presented in Section 4.1 below.

4.1. Scenario development using the STEEP method

The results of the intensive literature analysis on current trends influencing urban mobility were discussed with the stakeholders during the workshop series, with a view to prioritising the trends with the greatest influence on mobility in the Rhine-Ruhr region.

The results of the trend analysis are presented in Table 2. Mainly, these trends relate to 1) population dynamics (including high urbanisation rates and demographic changes); 2) digitisation and the application of advanced digital technologies in mobility; 3) open innovation in the mobility sector (new business and working models) and 4)

Table 2
: Trends and their descriptive attributes clustered using the STEEP method.

Megatrends Influencing Mobility Sector				
Population Dynamics (Demographics, Urbanisation)	Digitisation (Advanced Digital Technologies)	Open Innovation in Mobility Sector (New Business and Working Models)	Climate Change/Air Pollution	
STEEP Parameters Describing the Global Trends (Relevant for Local Case)				
Social	**Technological**	**Economic**	**Environmental**	**Political**
Mobility and consumption patterns	Internet coverage	Employment rate	Use of non-motorised (low-emission) traffic	Internalisation of externalities in form of CO_2 taxes
Stakeholder environmental awareness	Data Security and ownership (cyber security)	Population income	Traffic-related air pollution level (GHG emission, other air pollutants)	Investment in public transport infrastructure
Sharing society (lending instead of owning)	Transparency in mobility sector (seamless and connected/integrated multi-modal mobility)	Urban economics development (GDP alternatives)	Energy demand per capita	Political measures for mobility turnover (city toll, parking price and management)
Public participation in mobility solutions (co-creation)	Autonomous driving	Shared mobility business models	Share of renewable energy in mobility sector	Attractiveness of public transport (modal split; smart cards)
Digital divide	Real-time (big) data infrastructure	Net present value of investments in mobility	Land use changes related to mobility infrastructure	Sustainable Urban Mobility Plans

Table 3
Scenarios and their descriptions (using parameters clustered into STEEP spheres).

Business as Usual
- Focus on private transport: Cars per person (Environment and Economy)
- No shared mobility concepts and less investments in public transport: high level of Air Pollution (Environment)
- High share of unemployment: Unemployment Rate (Society and Economy)
- Inefficient spaces: Conversion to City area (Economy)
- Social disturbance: Unrest due to people problems (Society)

Smart City
- Interactive digital networks strengthen integrated multi-modal transport system: ***Cyber Infrastructure (Technology)***
- Autonomous driving leads to a better public transportation: ***Public Transport Attractiveness (Policy)***
- ***Intelligent parking reduces searching time causing reduced traffic: Parking Fare Attractiveness (Technology)***
- Multi-purpose areas enhance social interaction: ***Social attractiveness of mixed-land use*****(Social)**
- Increased renewable energy production and its use in the mobility sector: ***Renewable Energy produced (Environment)***

Sustainable/Healthy City
- Environmentally aware citizens reduce their consumption (energy-intensive products and services): ***Energy requirement per Capita (Environment)***
- Sustainable lifestyles and high level of social interaction public participation in creating new urban planning concepts for more public room in the cities: ***mixed-used public spaces (Social)***
- Fossil fuels and parking in urban cores are expensive or banned, internalization of externalities is the efficient fiscal policy: ***CO_2 price (Policy)***
- Soft mobility is dominant: ***Investment in public transport or bike infrastructure (Politics)***
- Shared mobility business models are efficiently developed and accepted: ***Effect of car sharing (Economy)***

Deurbanisation/Urban Sprawl
- Lack of investment in urban cores: Fraction of investments in urban infrastructure (Politics)
- Less economic growth accompanied with high living prices in urban cores: Development index (Economy)
- New digital technologies lead to more remote working job models and less commuting distances: Total cumulative distance travelled (Economy and Environment)
- Local actors are better off: Daily distance by car (Environment)

climate change and air pollution (Table 2). These trends and their impact on mobility were described verbally by the stakeholders so that the key attributes or factors relating to each trend could be identified. The factors were then classified into five clusters based on the STEEP method, which are described in Table 2 below.

After creating the table, the stakeholders were asked to describe possible of the key factors in the Rhine-Rhine-Ruhr metropolitan region and combine them into a matrix, creating a portfolio with four possible options for each factor (using a rating scheme from high to low). To this end, we first provided information on scoping the scenario field, the possible impact of trends on the mobility sector, as well as defined system boundaries. The possible combinations of four options for four trends are presented in Fig. 2 and are described below. As shown in Fig. 2 d), political measures for mobility turnover and traffic-related air pollution release were the factors describing the Climate change trend, and future developments regarding these factors were combined to form four options:

Option A: Strict policy regulations, such as the introduction of city tolls, internalisation of externalities in the form of CO_2 taxes, strict loading and unloading conditions, and increased parking fares, could cause a significant decrease in the levels of air pollution released, especially in the mobility sector.

Option B: Despite fiscal policies in the form of penalties, the mobility sector still causes high levels of air pollution due to the expansion of traffic infrastructure relating to economic growth. This infrastructure expansion causes both high levels of air pollution, and land-use changes.

Option C: Air pollution in the sector could still be decreased

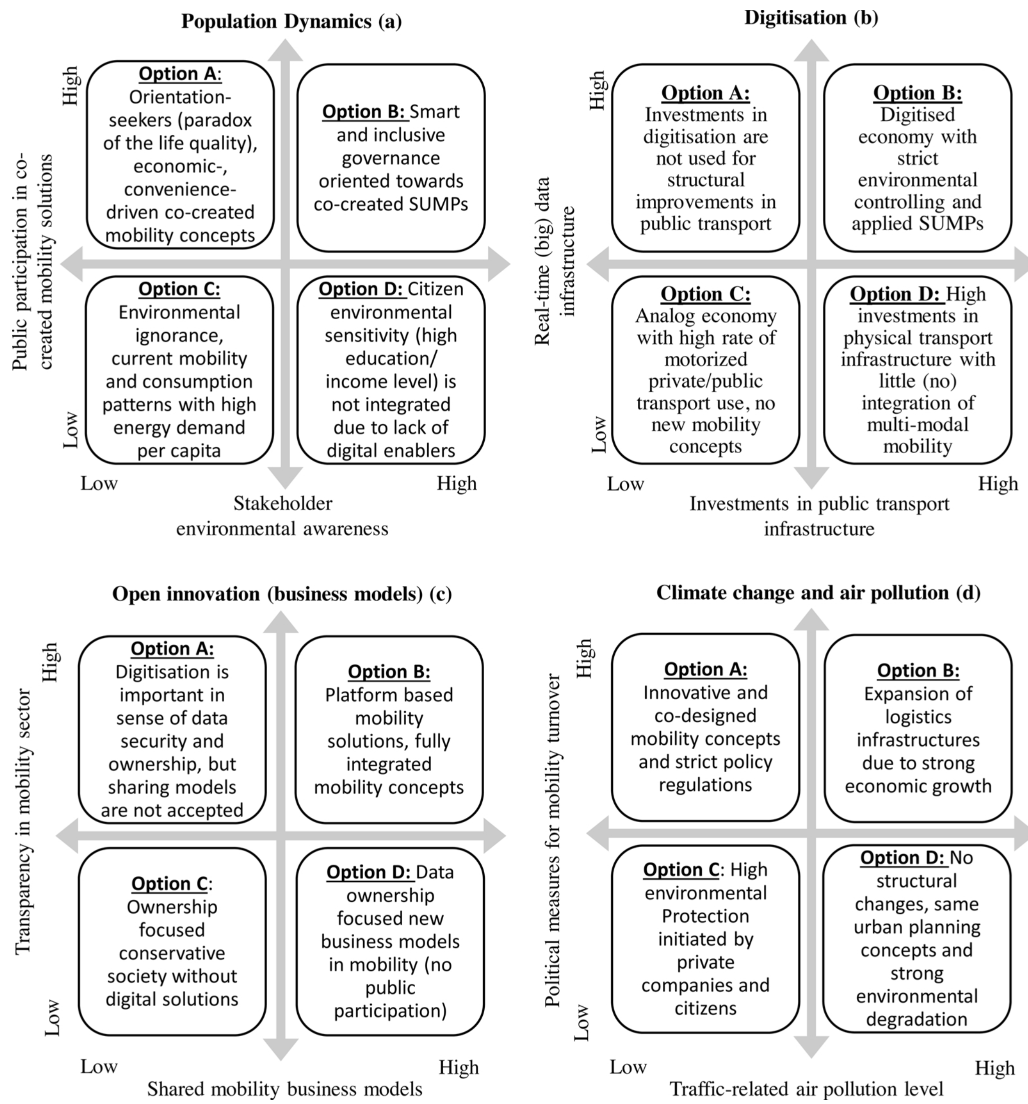

Fig. 2. Four portfolio options relating to the trends: (a) Population dynamics; b) Digitisation; c) Climate change/air pollution and (d) Open innovation (business models).

significantly despite policy regulations. Such a decrease could be explained by private investment in alternative vehicle engines or in innovative mobility concepts based on a high level of digital technology aimed at facilitating the use of shared, connected and seamless traffic modes.

Option D: If there is no public or private interest in innovative, low-emission mobility concepts, this will likely cause environmental degradation in urban areas.

In relation to all four of the trends clustered using the STEEP method, all possible related portfolios were created using the logic described above, which served as a basis for the next step, namely, scenario development. The optional future states for each key parameter (options A to D in the previous example) were checked pair-wise with the other options for all four trends by applying an evaluation range of -2 to +2. If the coexistence of two states was estimated to be unrealistic, -2 was attached, and +2 indicated common occurrence in two portfolios of randomly chosen factors. This analysis caused the development of a 16 × 16 matrix (four trends with four options each). The options estimated as mutually exclusive combinations (-2 and -1) were eliminated to create consistent scenarios, and the remaining options were then combined into clusters and a multidimensional scaling analysis was applied. As a result, four clusters of future options were identified to describe scenarios of urban mobility (Table 3).

Table 4 displays the parameters and their values for the scenarios, along with the relevant factors for decision making. These decision factors were selected to represent the environmental dimension (total CO_2 emissions and land conversion), population dynamics (percentage of sharing society), mobility dynamics (cumulative travelled distance and ratio of public/private transport usage) and economic aspects (sustainable net present value of public urban investment).

4.2. SD model description

The SD model developed and applied for the example of the Rhine-Rhine-Ruhr metropolitan region is presented in Fig. 3. It comprises major socio-demographic, economic, environmental, technological and mobility dynamics. We validated the model for the output parameters of the BaU scenario, correlating those with the real data within the period of 2012–2018. The correlation between real data and SD simulated data for the net population and cumulative travelled distance show a perfect fit with R^2 being equal to 0.75 and 0.78, respectively (the goodness of the model is reflected in the Appendix Fig. A1).

One of the most important dynamics in the SD model (Fig. 3) is the change in *population characteristics,* which is presented through three stocks: population below the age of 18, population between 18 and 65, and population above the age of 65. The flows affecting the population

Table 4

Parameters and their values for different scenarios. The simulation results for the different scenarios were evaluated and compared based on the chosen parameters, listed here. *dmnl stands for dimensionless.

Scenario describing parameters used for simulation runs				
Scenarios	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Parameters	Business as Usual	Smart City	Sustainable/Healthy city	Deurbanisation/ Urban Sprawl
Fraction in urban investment	50 % (2 bil)	80%	80%	40%
Average investment in public infrastructure (per capita/year)	1000 Euro	3000 Euro	5000 Euro	1000 Euro
Fraction in car infrastructure investment	40%	60%	20%	60%
Parking management	4 (dmnl)	8 (dmnl)	8 (dmnl)	5 (dmnl)
Public transport attractiveness	4 (dmnl)	9 (dmnl)	10 (dmnl)	9 (dmnl)
Unrest due to people problems	0.02	0.01	0.01	0.01
Growth factor	0.05	0.15	0.1	0.1
City toll	0 Euro	2.5 Euro	5 Euro	0 Euro
Parking fare	2 Euro/hour	3 Euro/hour	5 Euro/hour	3 Euro/hour
Fuel price	1 Euro/litre	2 Euro/litre	3 Euro/litre	1 Euro/litre
Fraction of renewable energy used in motorized vehicles	14,7 %	60%	90%	50%
Energy requirement per capita	7140 kWh	15000 kWh	6000 kWh	7140 kWh
Cost per ton of CO2	0 Euro	50 Euro	100 Euro	0 Euro
Internet coverage fraction	70%	100%	80%	80%
Output parameters selected as indicators relevant for decision making				
Total CO2 emissions	Land conversion		Percentage of sharing society	
Total cumulative distance motorized	Public/Private transport use		Sustainable Net Present Value of Public Investments	

characteristics are birth and mortality rates, immigration rate, the ratio of females to males and net emigration. These components also influence the net population variable, which has an initial value of 5.1 million. The second central process represented in the SD model is *land-use change*. This process includes new urban areas that are needed for land conversion from rural to urban, and this is calculated based on land conversion and land reclamation rates. Land-use change is influenced by population dynamics and by *investment in urban infrastructure* (1000 euro/person). In the model, investment in infrastructure is defined as investments made in roads, bicycle lanes and smart city concepts (fraction of internet coverage, for example). Fraction of internet coverage is parameterised at 70 % for the Ruhr region and is set to reach 100 % within the next two to three decades. Other important investment types represented in the model include *investment in renewable energy*, which is expressed in produced renewable energy and its share in motorised vehicles (10 %). The *mobility dynamics* process is highly dependent on the energy sector and urbanisation (expressed in land expansion), which influences the total commuting distance of inhabitants. On the other hand, *mobility dynamics* are also responsive to public investment in *smart solutions*, such as cyberinfrastructure and internet connectivity. In turn, smart solutions are influenced by the *economic development* of the region, which goes on to initiate the development of sharing economy models in mobility. Sharing economy models in mobility and their application possibilities depend on population characteristics (for example, education levels and age). Within mobility dynamics, we defined the modal split as the ratio between

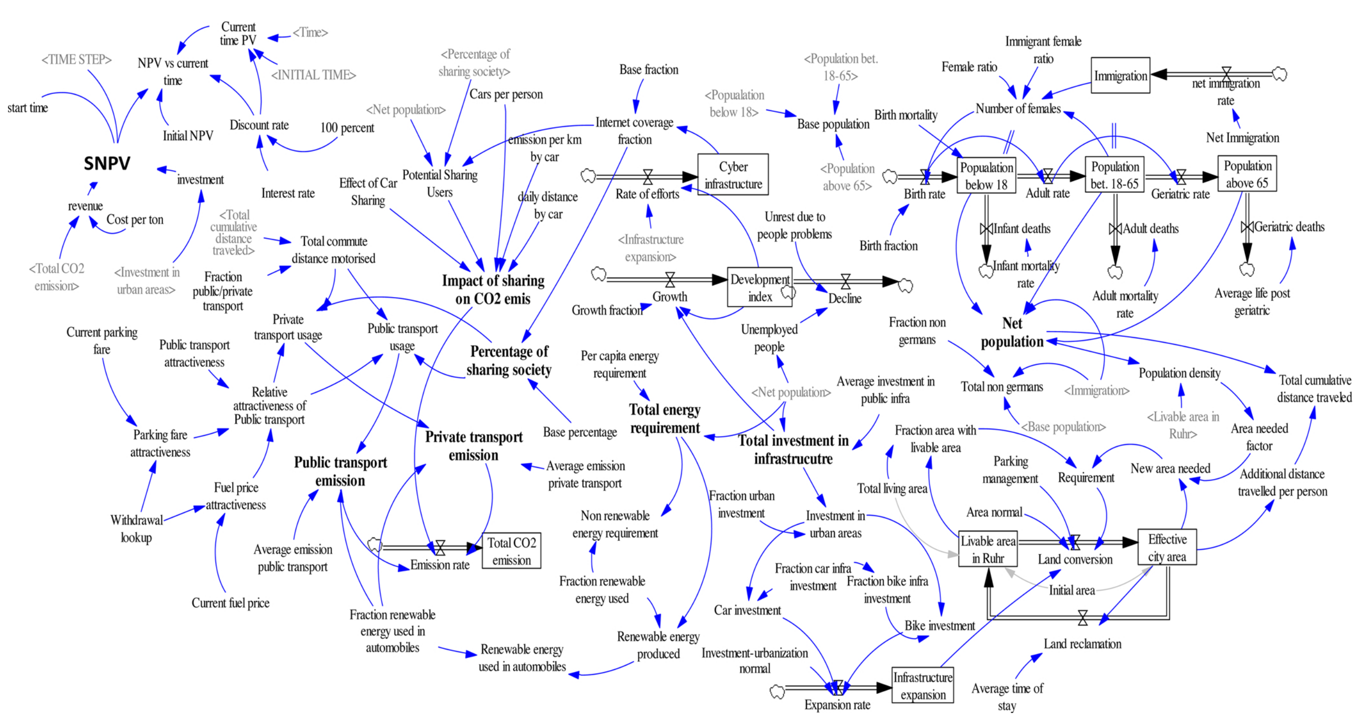

Fig. 3. System dynamics simulation model of sustainable urban mobility turnover in the case of the Rhine-Ruhr metropolitan area.

public and private transport usage as a dependent variable from the perspective of public transport attractiveness, which can be defined based on fuel price (1.5 euro/litre) and parking fees (2 euro/hour). In addition to economic parameters and the distance to be travelled, we defined the modal split as being dependent on a *sharing society*, which was identified as the percentage of the population that is receptive to changing its mobility patterns in terms of public transport or sharing business model concepts such as Uber (Table 1). Moreover, we estimated the impact of sharing concepts on *CO2emissions (six million tonnes of* CO_2 from the mobility sector) as being dependent on the sharing society (20 %), the motorisation rate (40 %), emissions/car (0.14 kg CO_2/car), and the number of cars substituted by a shared car (3).

The interconnections and complex dynamics described above are highly sensitive to political decisions, which are represented in the model by urban infrastructure investment. We quantify the sustainability of governmental decisions on urban investment as being dependent on the *sustainable net present value of the investment (SNPV)* (see Section 2.2). The SNPV represents the economic aspects of any investments made, such as interest rate and revenues. Moreover, we defined revenues not only as government income from taxes (dependent on population dynamics), but also as alternative CO_2 costs that can be saved through sustainable investment (for example, renewable energy sources, alternative vehicle engines or cycling networks).

4.3. Scenario simulation runs

Fig. 4 shows the development of a sharing society and its impact on CO_2 emissions in the transportation sector for the BaU, Smart City, Sustainable/Healthy City, and Deurbanisation scenarios over the simulation period of 2019 – 2030. The development of the sharing society is presented as a scatter and line plot on the right-hand side, while the inset graph displays the correlation between total CO_2 emissions and the percentage of the sharing society as simulated for the Deurbanisation scenario.

In contrast to the BaU scenario, where no significant changes were projected, the other three scenarios showed a strong trend towards a sharing society, with the largest increase in the case of the Deurbanisation scenario (up to 70 %). The reason why the percentage of the sharing society is estimated to be at its highest in the Deurbanisation scenario is that people commuting in their own cars will face greater costs due to longer commuting distances.

The sharing economy rates for the Deurbanisation scenario are consistently at the highest level, The Sustainable City scenario will also be at a high level due to the higher costs of parking fees, city tolls etc.

The dynamic increase of sharing society percentage within the

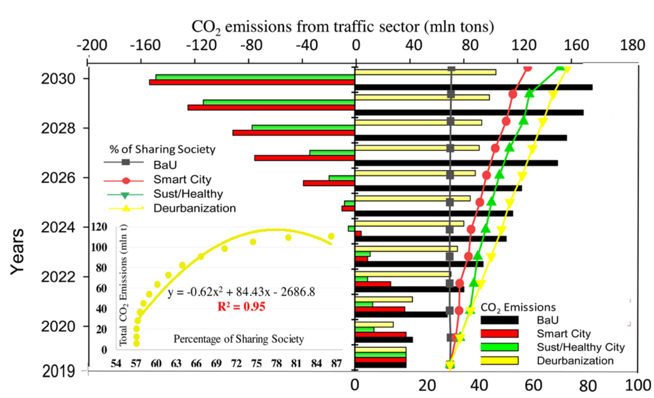

Fig. 4. Percentage of the sharing society, its impact on CO_2 emissions and the development of the sharing society (as a scatter and line plot on the right-hand side), simulated for the scenarios BaU, Smart City, Sustainable/Healthy City, and Deurbanisation.

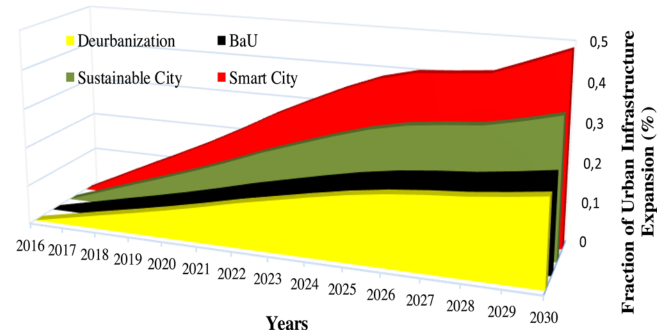

Fig. 5. Expansion of urban infrastructure by 2030, displayed for the four tested scenarios.
In the case of Smart City and Sustainable City, the infrastructure expansion amounts to 50 % and 30 %, respectively. This increase can be explained by public investment in urban infrastructure, which creates an incentive for additional population to settle in the metropolitan region.

Smart City Scenario can be explained by the fact that the SD model representation of a sharing society is dependent on population dynamics (such as age group) and on internet coverage, which enables shared mobility concepts to be applied; the latter is highest for the Smart City scenario.

Fig. 4 also presents the scenario simulation results with regard to total CO_2 emissions. Since the percentage of the sharing economy will be highest within the Deurbanisation scenario, the correlation between these two factors is presented for that scenario. The correlation between the percentage of the sharing society and total CO_2 emissions is significantly positive, with an R^2 value of 0.95. This relates to the fact that despite their willingness to share mobility patterns within the Deurbanisation scenario, inhabitants will be travelling longer distances both for work and leisure purposes. The effect of urban expansion is also visible in an expanded view of the urban infrastructure (for example, impervious surfaces), which is displayed in Fig. 5.

While the projections for the Smart City and Sustainable City scenarios indicate detrimental effects on the environment due to land-use changes and an increase in sealed surface areas (Fig. 5), the projections also indicate a sharp decrease in CO_2 emissions. This difference compared to the BaU and Deurbanisation scenarios (Fig. 4) may be as a result of efficient development strategies implemented in the Smart City and Sustainable City scenarios. Thus, CO_2 emission savings could reach values up to 160 million tonnes by 2030 due to strategies supporting investment in renewable energies (also used in motorised private transport) as well as incentives for using public transportation (for example, increased fuel and parking costs).

Fig. 6 shows the total cumulative distance travelled and the ratio between public and private transportation use for all scenarios over the simulation period of 2019–2030.

Overall, the Deurbanisation scenario results in the lowest values, and the Smart City scenario shows the highest values for total cumulative distance travelled. The fact that the ratio between public and private transportation use reaches values of around 0.9, representing an almost equal amount of public and private transportation use explains the decrease in CO_2 emissions from the transportation sector within the Smart City scenario (Fig. 4).

The Sustainable City scenario shows the highest values for the ratio between public and private transportation use, reaching a value of around 2.3 by 2030, while the total cumulative distance travelled only shows a moderate increase for this scenario. This is related to the increased percentage of the sharing society (Fig. 4) and the appeal of public transportation in the Sustainable City scenario, driven mainly by public investment in sustainable urban mobility concepts. However, the decrease in CO_2 emissions is more significant in the Smart City scenario compared to the Sustainable City scenario, given the greater effect of digital technologies on efficient public transport infrastructure, as well

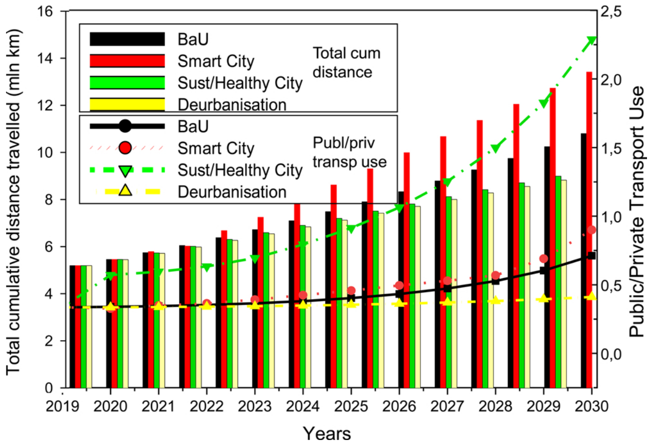

Fig. 6. Total cumulative distance travelled and public/private transportation use.

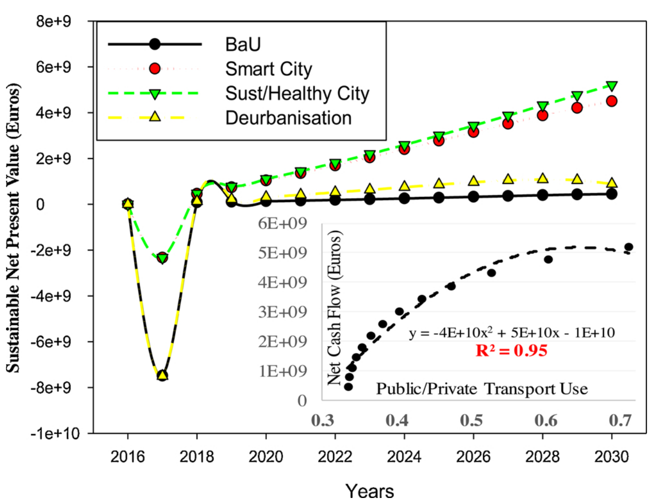

Fig. 7. Sustainable net present value of public investment in the urban mobility infrastructure and its correlation with the modal split for the Business-as-Usual scenario.

as the use of sharing economy concepts. The simulations for the BaU scenario show the second highest values for total cumulative distance travelled, which is linked with a strong increase in CO_2 emissions from the transportation sector due to the relatively low increase in the ratio of public to private transportation use.

To reach high levels of sustainability, public investment in urban mobility infrastructure has to be economically, socially and environmentally viable. Hence, we calculated the sustainable net present value (SNPV measured in euro) of public investment based on revenues from taxes (for example, income taxes and tolls) and on saved CO_2 emissions (sustainable infrastructure and sustainable traffic modes). The scenario simulations show the highest SNPV (in euro) for the Smart City and Sustainable City scenarios, with a clear increasing trend over the simulation period (Fig. 7). The negative SNPV values in the first year are due to high investment costs, for example, in infrastructure and digitisation. However, the potential upside, once the investment begins to generate revenue, may well outweigh the downside of a temporarily poor cash flow. The BaU and Deurbanisation scenarios display SNPV values at a considerably lower level and do not show an increasing trend. The inset graph in Fig. 7 displays a positive correlation between the modal split and the sustainable feasibility (socio-economic and environmental viability) of public investment for the BaU scenario.

5. Discussion and conclusion

We introduced a new simulation tool that can be applied to design low-emission urban mobility solutions in the given paper. The development of the simulation model combined a thorough literature review of relevant factors and processes in the mobility and transportation sector with a participatory modelling approach using STEEP and CLD. Furthermore, we displayed the functionality of the simulation model using the example of the Rhine-Rhine-Ruhr metropolitan region in Germany. To do this, we co-created and simulated four scenarios (Smart City, Sustainable/Healthy City, Deurbanisation/Urban Sprawl and Business-as-Usual) that differed regarding their assumptions on city planning and mobility concepts. One key innovation applied in our model was a novel combination approach using the scenario co-creation method STEEP. Another innovation within the model was the consideration of sharing society concepts, which allowed the model to simulate and compare the effects of innovative mobility concepts on indicators relevant to policymakers, such as land conversion, CO_2 emissions and the sustainable net present value (SNPV) of public investment (Table 4). The SNPV also represents a novel component for which we used alternative urban economics indicators in the simulation. This simulation-based scenario assessment tool is of particular importance for the development of policy recommendations on public investment in order to achieve sustainable urban mobility turnover. The key outcomes of the paper are presented below.

1 One key outcome of our research is the **SD simulation tool** itself. While the SD model was designed in conjunction with policymakers from the Rhine-Rhine metropolitan region, it was implemented in a generic manner, which makes it *transferrable to other metropolitan regions* aiming to develop sustainable transportation and mobility. The research design presented in Fig. 1 can be adopted by any other region. Even though the scenario narratives were co-created with the stakeholders, in the first instance, the logic behind the creation process is transferrable. After carrying out a trend analysis based on the literature, the trends and their descriptive parameters, as clustered in the STEEP framework, should be intensively discussed with stakeholders in the region. Scenarios could then be developed with local or regional stakeholders, following participatory approaches such as the storyline-and-simulation approach (Alcamo, 2001). This could be combined with existing approaches to stakeholder involvement in scenario planning for urban mobility (Chu, Anguelovski, & Carmin, 2016). Second, the scenarios used in this paper were generalised so that they could be adapted to global sustainable urban development pathways like Smart City (Laufs, Borrion, & Bradford, 2020), for example, or so that sustainable mobility strategies could be developed to solve the problem of urban sprawl, comparable to the Deurbanisation scenario in this case (Wey, 2019). Parameterisation using empirical data for a new study area could follow our literature review (see Section 2) and could be combined with regional surveys on major model parameters, for example, studies on people's willingness to pay for parking versus public transportation (Van Ommeren, Wentink, & Dekkers, 2011; Barata, Cruz, & Ferreira, 2011; Ballantyne, Lindholm, & Whiteing, 2013) or on the maximum distance people are willing to travel using non-motorised vehicles such as bicycles (Scheiner, 2010; Rahul & Verma, 2014).

2 The **simulation-based scenario assessments** for the Rhine-Ruhr metropolitan region in Germany represent another important result of the research presented here. In particular, the Deurbanisation scenario stood out because it had the highest value for the sharing society (Fig. 4) and the lowest value for the ratio between public and private transportation use (Fig. 6). This explains why the Deurbanisation scenario did not lead to a decrease in CO_2 emissions but rather displayed an increase in emissions which levelled off towards the end of the simulation period (Fig. 4). The simulations for the

BaU scenario showed the highest CO_2 emissions, the lowest percentage for the sharing society (Fig. 4) and the lowest values for sustainable net present value (Fig. 7), indicating that the current trends in the mobility sector (BaU) might be the worst option for reaching sustainable mobility. The Smart City and Sustainable City scenarios displayed considerably better values for the indicators tested. Both showed an increase in sharing society combined with a decrease in CO_2 emissions (Fig. 4). Also, the results for these two scenarios showed the highest values for land conversion in the form of urban infrastructure expansion resulting from the major investment in urban infrastructure assumed for these scenarios. While this initially leads to a moderate decrease in net present values, starting in 2019, it also causes a linear increase in SNPV, which continues until the end of the simulation period (Fig. 7). The major difference between these two scenarios is visible in the total cumulative distance travelled, which is considerably higher for the Smart City scenario (Fig. 6) and is directly linked to the higher values for urban infrastructure expansion (Fig. 5). Both scenarios also display savings in CO_2 emissions (Fig. 4), which can be attributed to the high proportion of public transportation use (Fig. 5); for example, under the Sustainable City scenario, more than twice the distance travelled is accounted for by public means of transport as compared to private transportation. The CO_2 emission savings strongly influence the SNPV, since we consider savings in payments of a CO_2 tax of 50 euro/ton in our simulation model.

3 In summary, according to our simulations and the assumptions tested under the four scenarios, the **mobility transformation** within the **Smart City** and **Sustainable City** scenarios might be the most efficient. Yet there are slight differences between these scenarios; careful consideration is required in order to avoid detrimental and potentially irreversible outcomes. For example, in terms of public investment in urban infrastructure, even if it aims to increase the environmental sustainability of the system (alternative vehicles and high rate of digitisation), it may have a negative impact on the environment. Moreover, it may lead to fragmentation of the landscape and the potential loss of urban green spaces (Dorning, Koch, Shoemaker, & Meentemeyer, 2015; Sanesi, Colangelo, Lafortezza, Calvo, & Davies, 2017). These findings are also in line with those of Xing et al. (2019), who established an SD model for the Chinese city Wuhan, a rapidly growing metropolitan region and an area with a similar history of steel production and population density as the Rhine-Ruhr region. In their research, those authors identified a conflict between economic development and sustainable development, namely, that a negative impact on the environment and on human well-being may restrict economic development. However, they suggested increasing areas with natural vegetation and optimising industrial structures, thereby reducing the competition between economic development and environmental protection (Xing et al., 2019).

5.1. Policy recommendations

Based on the boundary conditions and scenario assumptions tested, we summarised a set of policy recommendations that resulted from simulation runs. In general, our findings imply that to make the transition towards sustainable urban mobility, policymakers should focus on initiating pulling effects rather than pushing effects, while taking a proactive role in shaping future urban mobility. Even though this would require a large initial investment in public transportation infrastructure, our simulations show that within an interval of only three to four years, an increased sustainable net present value would result (Fig. 7). A significantly high positive SNPV can be attributed to savings in CO_2 emissions and, as a result, savings in payments of CO_2 taxes (100 euro/tonne), which might be implemented in the near future. Hence, to reduce the total amount of CO_2 emissions, we provide the following recommendations:

1 The percentage of renewable energy use in motorised vehicles with electrical engines should be at least 80 % in order not to generate rebound effects.

2 Economic growth (20 % increase in the number of goods and services produced per head of the population over 20 years) can play a significant role in the reduction of CO_2 emissions if investments are carried out in a target-oriented manner. For example, an increase from 1000 euro/capita/year in public infrastructure investment currently to 3500 euro/capita/year could lead to a decrease in total cumulative CO_2 emissions from 60 million tonnes to 20 million tonnes. A public infrastructure investment of 4000 euros/capita/year could lead to the mobility sector becoming CO_2-neutral by 2030.

3 Increasing the attractiveness of public transportation by improving the quality, coverage, price and timing of services could lead to a direct reduction in all CO_2 emissions, making the transportation sector CO_2-neutral and contributing to better air quality by the mid-2030s.

5.2. Study limitations and next steps

We introduced a new SD modelling approach that is transferable to different metropolitan areas, and we applied the model to the Rhine-Ruhr metropolitan region in order to facilitate the development of policy recommendations for sustainable and transformative mobility pathways. The key factor in the success of the approach is to make public transportation attractive by using new sustainable (agile and digital) pricing systems and by relying on environmental and ecological macroeconomic models (alternative urban economics indicators). The research presented here is a first attempt to model and detangle the complexities in urban mobility. However, there are some limitations to our modelling approach, such as the use of more complex and holistic mobility parameters (dynamic pricing systems or traffic accidents etc.), as well as macroeconomic parameters such as GDP by sector, which should then be more precisely adjusted using GPI parameters. This is in line with the research of Melo, Teotónio, Silva, and Cruz (2020), who studied the impact of the transportation infrastructure on economic growth. Their findings suggest that in the short run, there is no causality between the two variables at the national level; however, a unidirectional causality from economic development to infrastructure investment exists in the long run. These outcomes shed light on the fact that infrastructure investment per se is not sufficient on its own to boost economic activity. An investment package is needed, targeting not only infrastructure but also social and technological development. This delay of applied political changes and their impact on output variables within this paper is too quick. We applied changes in the same timestep, given the fact that it is almost impossible to get an access to the data on the delay caused in implementation of policy changes, representing modelling limitation.

Another limitation of our research is linked with the SD modelling approach, which is well suited to evaluating the temporal dynamics of a system but has limited capability for analysing a system's spatial dynamics. As a result, model completeness is a limitation. The current model studied the effects of population dynamics, economic growth, infrastructure development and pollution on sustainable urban mobility. While the feedback loops captured specific issues such as development index decline, the impact of sharing mobility concepts on CO_2 emissions and so on, these issues are not studied for their sensitivity in the SD model. Another limitation is the use of assumptions based on expert opinion and the related mental models, even though they were generated using a STEEP method designed to develop advanced scenarios. As it is not possible to obtain empirical data for all variables, some level of subjectivity and assumptions cannot be ruled out. Even though these assumptions were tested during model testing, they are not empirically derived.

While we were able to consider some spatial characteristics in our simulation model (for example, travel distance or an increase in impervious surfaces), the SD approach does not allow the simulation of location and spatial configurations for these spatial characteristics. For example, when calculating land conversion, we were able to calculate when and how much additional impervious surface would be needed under the different scenarios, but we did not calculate where it would be located and how it would interfere with other land cover of environmental importance, such as public green spaces. While an ambitious undertaking, one way to address this limitation would be a combination of an SD approach with cellular automata (CA) models (Santé, García, Miranda, & Crecente, 2010). There have been some studies combining SD models with CA models (Lauf, Haase, Hostert, Lakes, & Kleinschmit, 2012; Neuwirth, Peck, & Simonović, 2015), in which powerful tools were developed that combined the simplicity and elegance of SD models with the spatial detail and context sensitivity of CA approaches (Chen et al., 2020). Turning a model such as that one, which includes innovative components for the sharing economy and its effect on CO_2 emissions, into an SD-CA model with a spatially explicit representation of land-cover change, would offer a holistic way of analysing environmental effects.

Author declaration

We wish to draw the attention of the Editor to the following facts which may be considered as potential conflicts of interest and to significant financial contributions to this work. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We understand that the Corresponding Author is the sole contact for the Editorial process (including Editorial Manager and direct communications with the office). She is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs. We confirm that we have provided a current, correct email address which is accessible by the Corresponding Author and which has been configured to accept email from (ani.melkonyan-gottschalk@uni-due.de).

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Appendix A

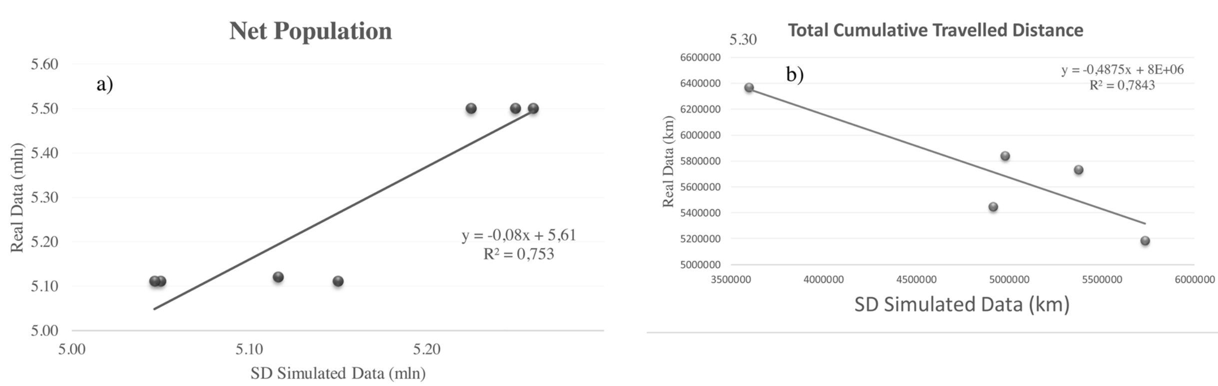

Fig. A1. SD Model Validation for the output parameters a) Net Population and b) Total Cumulative Travelled Distance with the real data within the period of 2012-2018.

Table A1
List of variables used in the SD model along with the data units, the used data sources, and mathematical formulas representing the causal interdependencies among the parameters.

	Parameter	Unit	Source
1	Additional distance travelled per person = Effective city area/4435	Dmnl	MATSim
2	Adult deaths = Adult mortality rate	People/Year	Amtliche Sterbetafeln[a]
3	Adult mortality rate = RANDOM NORMAL(1000,2000,1500,2,1500)	1/Year	Amtliche Sterbetafeln[a]
4	Adult rate = DELAY1(Birth rate, 18)	People/Year	
5	Area needed factor = Population density/4000	Dmnl	
7	Average emission in non renewable energy production = Non renewable energy requirement*Average emission per MWh	kg CO_2	
8	Average emission per MWh = 820/1e+06	kg/kWh	UBA[b]
9	Average emission private transport = 5	kg/km	UBA[c]
10	Average emission public transport = 0.8	kg/km	UBA[c]
11	Average investment in public infra = 1000	Euros/Person	BMVId

(continued on next page)

Table A1 (*continued*)

	Parameter	Unit	Source
12	Average life post geriatric = RANDOM NORMAL(65,100,70,3,72)	Year	Amtliche Sterbetafeln[a]
13	Average time of stay = 10	Year	Stakeholder assumption
16	Base population = Popualation below 18 + Population above 65 + "Population bet. 18-65"	People	MURMO
17	Bike investment = Investment in urban areas*Fraction bike infra investment	Euros	
18	Birth fraction = RANDOM UNIFORM(0.5,2,1.6)	Dmnl	Derived from birth statistics
19	Birth rate = Number of females*Birth fraction	People/Year	
20	Car investment = Investment in urban areas*Fraction car infra investment	Euros	
21	Cost per ton = 162	Euros	IFO[e]
22	Current fuel price = 1	Euros/litre	Statista[f]
23	Current parking fare = 2	Euros/hour	Inrix Studie[g]
24	Current time PV = exp(Discount rate*(Time-INITIAL TIME))	Dmnl	
25	Cyber infrastructure = INTEG (Rate of efforts,0.5)	Dmnl	
26	Decline=(Unemployed people/100000)*Unrest due to people problems	Dmnl	
27	Development index = INTEG (Growth-Decline,1)	Dmnl	
28	Discount rate = Interest rate/"100 percent"	1/Year	
29	Effective city area = INTEG (Land conversion-Land reclamation,Initial area)	sq kms	
30	Emigration = INTEG (Emigration rate,0)	People	
31	Emigration rate = DELAY1(Population density*1000,0.5)	People/Year	
32	Emission rate = Average emission in non renewable energy production + Private transport emission + Public transport emission	Dmnl	
33	Expansion rate="Investment-urbanization normal"*DELAY1(Car investment + Bike investment,1.5)	Dmnl	
34	Female ratio = 0.508	Dmnl	Knoema World Atlas[h]
36	Fraction area with liveable area = Liveable area in Ruhr/Total living area	Dmnl	
37	Fraction bike infra investment = 1-Fraction car infra investment	Dmnl	
38	Fraction car infrastructure investment = 0.6	Dmnl	Stakeholder assumption
39	Fraction non germans = 0.157	Dmnl	Kreisergebnisse Ausländische Bevölkerungi
40	Fraction public/private transport = 0.5	Dmnl	Stakeholder assumption/STEEP
41	Fraction renewable energy used = 0.147	Dmnl	UBA[d]
42	Fraction renewable energy used in automobiles = 0.1	Dmnl	UBA[c]
43	Fraction urban investment = 0.5	Dmnl	Stakeholder assumption/STEEP
44	Fuel price attractiveness = Withdrawal lookup(Current fuel price)	Dmnl	
45	Geriatric deaths = Population above 65/Average life post geriatric	People/Year	Amtliche Sterbetafeln[a]
46	Geriatric rate = DELAY1(Adult rate,57)	People/Year	
47	Growth = DELAY1I((Growth fraction*Development index) + Total investment in infrastructure/1e + 10,1,0.3)	Dmnl	
48	Growth fraction = 0.05	Dmnl	Stakeholder assumption
49	Immigrant female ratio = 0.51	Dmnl	Kreisergebnisse Ausländische Bevölkerung[i]
50	Immigrant size = 70000	People/Year	Integrationsmonitoring[j]
51	Immigration = INTEG (Immigration rate,0)	People	MURMO
52	Immigration rate = Immigrant size	People/Year	MURMO
53	Increase in jobs=(Development index/100)*Jobs	Dmnl	MURMO
54	Infant deaths = Infant mortality rate	People/Year	Amtliche Sterbetafeln[a]
55	Infant mortality rate = 0.51	Dmnl	Amtliche Sterbetafeln[a]
56	Infrastructure expansion = INTEG (Expansion rate/1e + 08,0)	Dmnl	
57	Initial area = 4435	Sqkms	Ruhrgebiet in Zahlen[k]
58	Initial NPV = 0	Euros	
59	Interest rate = 0.01	percent/Year	
60	Internet coverage fraction = Base fraction*(1 + Cyber infrastructure)	Dmnl	
61	Investment = Investment in urban areas	Euros	
62	Investment in urban areas = Fraction urban investment*Total investment in infrastructure	Euros	
63	Investment-urbanization normal = 0.001	Dmnl	
64	Jobs = INTEG (Increase in jobs,2.322e + 06*0.92)	Dmnl	RVR[l]
65	Land conversion = (Requirement/Area normal)/(1 + (Parking management/100))*(1 + Infrastructure expansion)	sq kms/Year	
66	Land reclamation = Effective city area/Average time of stay	sq kms/Year	
67	Liveable area in Ruhr = INTEG (Land reclamation-Land conversion,Total living area-Initial area)	sq kms	MURMO
68	Mobile internet connectivity=(Internet coverage fraction*Effective city area)*(1 + Infrastructure expansion)/ 12000	Dmnl	
69	Modal split = MIN(0.8*(1 + Non motorized infrastructure/100), 1)	Dmnl	MATSim
70	Net cash flow=-investment/TIME STEP*PULSE(start time,TIME STEP) + STEP(revenue, start time)	Dmnl	
71	Net population = Popualation below 18 + Population above 65 + "Population bet. 18-65" + Immigration-Emigration	People	
72	New area needed = Effective city area*Area needed factor	sq kms	Stakeholder assumption/STEEP
73	Non motorised infrastructure rating = 3	Dmnl	Stakeholder assumption
74	Non renewable energy requirement = Total energy requirement*(1-Fraction renewable energy used)/1e + 06	MWh	
75	NPV vs current time = NPV(net cash flow, Discount rate, Initial NPV, Current time PV)	Dmnl	
76	Number of females=("Population bet. 18-65"*Female ratio) + (Immigrant female ratio*Immigration)	People	MURMO
77	Parking fare attractiveness = Withdrawal lookup (Current parking fare)	Dmnl	Stakeholder assumption/STEEP
78	Parking management rating = 4	Dmnl	Stakeholder assumption/STEEP
79	Per capita energy requirement = 7140	kWh	Stromvergleichsstudiem
80	Percentage of sharing society = Base percentage*(1 + Mobile internet connectivity)	Dmnl	Stakeholder assumption/STEEP
81	Population below 18 = INTEG (Birth rate-Adult rate-Infant deaths,676000)	People	Knoema World Atlas[h]
82	Population above 65 = INTEG (Geriatric rate-Geriatric deaths,1.118e + 06)	People	Knoema World Atlas[h]
83	Population bet. 18-65 = INTEG (Adult rate-Adult deaths-Geriatric rate,2.23093e + 06)	People	Knoema World Atlas[h]

(*continued on next page*)

Table A1 (*continued*)

	Parameter	Unit	Source
84	Population density = Net population/Livable area in Ruhr	People/sq kms	MURMO
85	Private transport emission = Average emission private transport*Private transport usage*(1-Fraction renewable energy used in automobiles)	kg CO_2	MATSim
86	Private transport usage = Total commute distance motorised*(1-Percentage of sharing society)*(1-"Fraction public/private transport")*Relative attractiveness of Public transport	Dmnl	MATSim
87	Public transport attractiveness = 4	Dmnl	Stakeholder assumption/STEEP
88	Public transport emission = Average emission public transport*Public transport usage*(1-Fraction renewable energy used in automobiles)	kg CO2	MATSim
89	Public transport usage = (Total commute distance motorised*Percentage of sharing society*"Fraction public/private transport")/Relative attractiveness of Public transport	Dmnl	MATSim
90	Rate of efforts = (0.001 + Development index)*Infrastructure expansion/10	Dmnl	
91	Relative attractiveness of Public transport = (0.4*Fuel price attractiveness) + (0.3*Parking fare attractiveness) + (0.3*Public transport attractiveness)	Dmnl	
92	Renewable energy produced = Total energy requirement*Fraction renewable energy used	MWh	Stromvergleichsstudie[m]
93	Renewable energy used in automobiles = Renewable energy produced*Fraction renewable energy used in automobiles	MWh	
94	Requirement = Fraction area with livable area*New area needed	sq kms	
95	revenue = DELAY1(Cost per ton*(Total CO2 emission-50)*0.05,1)	Euros/Year	
96	Total CO2 emission = INTEG (Emission rate,1e + 06)	kg CO2	
97	Total commute distance motorised = Total cumulative distance traveled by people*Modal split	Dmnl	MATSim
98	Total cumulative distance traveled by people = Net population*Additional distance travelled per person	Dmnl	MATSim
99	Total energy requirement = Net population*Per capita energy requirement	kWh	
100	Total investment in infrastructure = Average investment in public infra*Net population	Euros	
101	Total living area = 7268	sq kms	
102	Total non germans = (Base population*Fraction non-Germans) + Immigration	People	
103	Unemployed people = Net population-Jobs	People	MURMO
104	Unrest due to people problems = 0.02	Dmnl	Stakeholder assumption/STEEP
105	Withdrawal lookup ([(0,0)-(10,1)],(0,1),(1,0.95),(2,0.8),(3,0.65), (4,0.5),(5,0.3),(6,0.2),(7, 0.16),(8,0.13),(9,0.09),(10,0.06))	Dmnl	

[a] https://www.destatis.de/DE/Methoden/WISTA-Wirtschaft-und-Statistik/2011/03/amtliche-sterbetafeln-032011.pdf?_blob=publicationFile.
[b] https://www.umweltbundesamt.de/themen/co2-emissionen-pro-kilowattstunde-strom-sinken.
[c] https://www.umweltbundesamt.de/themen/verkehr-laerm/emissionsdaten#handbuch-fur-emissionsfaktoren-hbefa.
[d] https://www.bmvi.de/SharedDocs/DE/Artikel/G/investitionen-statistik.html.
[e] http://www.ifo.de/DocDL/sd-2019-16-blum-etal-oekonomenpanel-co2-bespreisung-2019-08-22.pdf.
[f] https://de.statista.com/statistik/daten/studie/776/umfrage/durchschnittspreis-fuer-superbenzin-seit-dem-jahr-1972/.
[g] http://www2.inrix.com/research-parking-2017.
[h] https://knoema.com/atlas/Germany.
[i] https://www.it.nrw/nrw-auslaenderzahl-erreichte-ende-2018-einen-neuen-hoechststand-94904.
[j] http://www.integrationsmonitoring.nrw.de/integrationsberichterstattung_nrw/berichte_analysen/Zuwanderungs-_und_Integrationsstatistiken/7_Zuwand-u_Integrations_NRW_ONLINE.pdf.
[k] http://www.integrationsmonitoring.nrw.de/integrationsberichterstattung_nrw/berichte_analysen/Zuwanderungs-_und_Integrationsstatistiken/7_Zuwand-u_Integrations_NRW_ONLINE.pdf.
[l] https://www.rvr.ruhr/daten-digitales/regionalstatistik/beschaeftigte-und-erwerbstaetige/.
[m] https://www.stromvergleich.de/durchschnittlicher-stromverbrauch.

References

AGV (2018). *Arbeitgeberverbände Ruhr/Westfalen: „Das Ruhrgebiet zur führenden „Smart City "Europas entwickeln"*.

Alcamo, J. (2001). *Scenarios as a tool for international environmental assessments. Environmental issue report No 24*Copenhagen: European Environmental Agency p. 31.

Ambrosino, G., Nelson, J. D., Boero, M., & Pettinelli, I. (2016). Enabling intermodal urban transport through complementary services: From flexible mobility services to the shared use mobility agency: Workshop 4. Developing inter-modal transport systems. *Research in Transportation Economics, 59*, 179–184.

Angelidou, M. (2015). Smart cities: A conjuncture of four forces. *Cities, 47*, 95–106.

Ashnani, M. H., Miremadi, T., Johari, A., & Danekar, A. (2015). Environmental impact of alternative fuels and vehicle technologies: A life cycle assessment perspective. *Environmental Sciences, 30*, 205–210.

Ballantyne, E. E. F., Lindholm, M., & Whiteing, A. (2013). A comparative study of urban freight transport planning: Addressing stakeholder needs. *Journal of Transport Geography, 32*, 93–101.

Barata, E., Cruz, L., & Ferreira, J. P. (2011). Parking at the UC campus: Problems and solutions. *Cities, 28*(5), 406–413.

Bernardino, J. P. R., & van der Hoofd, M. (2013). Parking policy and urban mobility level of service – System dynamics as a modelling tool for decision making. *European Journal of Transport and Infrastructure Research, 13/ 3* ISSN 1567-7141.

Bernardino, J. P. R., & van der Hoord, M. (2013). Parking policy and urban mobility level of service. System dynamics as a modeling tool for decision making. *European Journal of Transport and Infrastructure Research, 13*(3), 239–248.

Blank, M., Ribeiro, J. L. D., & Anzanello, M. (2019). A relational exploratory study of business incubation and smart cities - Findings from Europe. *Cities, 88*, 48–58.

Boone, C., Redman, C., Blanco, H., Haase, D., Koch, J., Lwasa, S., Nagendra, H., Pauleit, S., Pickett, S. T., Seto, K. C., & Yokohari, M. (2014). *Reconceptualizing land for sustainable urbanity. Rethinking global land use in an urban era.* MIT Press313–330.

Bossel, H. (2007). *Systems and models: Complexity, dynamics, evolution, sustainability.* BoD–Books on Demand.

Chen, Y., Wang, C., Li, H., Yap, J. B. H., Tang, R., & Xu, B. (2020). Cellular automaton model for social forces interaction in building evacuation for sustainable society. *Sustainable Cities and Societies, 53*, Article 101913. https://doi.org/10.1016/j.scs.2019.101913.

Chu, E., Anguelovski, I., & Carmin, J. A. (2016). Inclusive approaches to urban climate adaptation planning and implementation in the Global South. *Climate Policy, 16*(3), 372–392. https://doi.org/10.1080/14693062.2015.1019822.

Cohen, B., & Kietzmann, J. (2014). Ride on! Mobility business models for the sharing economy. *Organization & Environment, 27*(3), 279–296. https://doi.org/10.1177/1086026614546199.

Costanza, R., Erickson, J., Fligger, K., Adams, A., Adams, C., Altschuler, B., et al. (2004). Estimates of the genuine progress Indicator (GPI) for Vermont, Chittendon County, and Burlington from 1950 to 2000. *Ecological Economics, 51*, 139–155.

Deng, X., et al. (2008). Growth, population and industrialization, and urban land expansion of China. *Journal of Urban Economics, 63/1*, 96–115.

Diefenbacher, H., et al. (2016). *Aktualisierung und methodische Überarbeitung des Nationalen Wohlfahrtsindex 2.0 für Deutschland 1991 bis 2012.* Umweltbundesamt.

Dorning, M. A., Koch, J., Shoemaker, D. A., & Meentemeyer, R. K. (2015). Simulating urbanization scenarios reveals tradeoffs between conservation planning strategies.

Landscape and Urban Planning, 136, 28–39.
European Union (EU) (2018). *Science for environment policy (2018) indicators for sustainable cities. In-depth report 12*Available at:. Bristol: Produced for the European Commission DG Environment by the Science Communication Unit, UWE. http://ec.europa.eu/science-environment-policy.
Ewing, R., Hamidi, S., & Grace, J. B. (2016). Urban sprawl as a risk factor in motor vehicle crashes. *Urban Studies, 53*(2), 247–266.
Frank, L. D. (2000). Land use and transportation interaction: Implications on public health and quality of life. *Journal of Planning Education and Research, 20*(1), 6–22. https://doi.org/10.1177/073945600128992564.
Frick, S., & Rodríguez-Pose, A. (2018). Urban concentration and economic growth. *World Development, 105*, 156–170.
Galster, G., Hanson, R., Ratcliffe, M. R., Wolman, H., Coleman, S., & Jason Freihage, J. (2001). Wrestling Sprawl to the Ground: Defining and measuring an elusive concept. *Housing Policy Debate, 12/4*, 681–717. https://doi.org/10.1080/10511482.2001.9521426.
Garau, C., Masala, F., & Pinna, F. (2016). Cagliari and smart urban mobility: Analysis and comparison. *Cities, 56*, 35–46.
Gass, V., Schmidt, J., & Schmid, E. (2014). Analysis of alternative policy instruments to promote electric vehicles in Austria. *Renewable Energy, 61*, 96–101.
Georgiadis, P., Vlachos, D., & Iakovou, E. (2005). A system dynamics modeling framework for the strategic supply chain management of food chains. *Journal of Food Engineering, 70/3*, 351–364.
Gota, S., Huizenga, C., Peet, K., Medimorec, N., & Bakker, S. (2019). Decarbonising transport to achieve Paris Agreement targets. *Energy Efficiency, 12/2*, 363–386.
Grindau, G., & Sagolla, W. (2012). *Nahverkehr – Lokales verkehrswesen.* Retrieved from http://www.bochum.de/C12571A3001D56CE/vwContentByKey/W28RZDQG323BOLDDE/$FILE/Anlage1_Memorandum_Gruene_Hauptstadt_Europas.pdf, Accessed 22.3.2016.
Gunasekaran, A., Papadopoulos, T., Dubey, R., Wamba, S. F., Childe, S. J., Hazen, B., et al. (2017). Big data and predictive analytics for supply chain and organizational performance. *Journal of Business Research, 70*, 308–317.
Guzman, L. A., de la Hoz, D., & Monzon, A. (2014). Optimal and long-term dynamic transport policy design: Seeking maximum social welfare through a pricing scheme. *International Journal of Sustainable Transportation, 8/4*, 297–316.
Haase, D., Kabisch, S., Haase, A., Andersson, E., Banzhaf, E., Baró, F., et al. (2017). Greening cities – To be socially inclusive? About the alleged paradox of society and ecology in cities. *Habitat International, 64*, 41–48.
Hendricks, M. D., Meyer, M. A., Gharaibeh, N. G., Van Zandt, S., Masterson, J., Cooper, J., Jr., et al. (2018). The development of a participatory assessment technique for infrastructure: Neighborhood-level monitoring towards sustainable infrastructure systems. *Sustainable Cities and Society, 38*, 265–274.
Hodson, M., Geels, F. W., & McMeekin, A. (2017). Reconfiguring urban sustainability transitions, analysing multiplicity. *Sustainability, 9/2*, 299.
Huang, L., Wu, J., & Yan, L. (2015). Defining and measuring urban sustainability: A review of indicators. *Landscape Ecology, 30/7*, 1175–1193.
Huang, S.-L., Yeh, C.-T., & Chang, L.-F. (2010). The transition to an urbanizing world and the demand for natural resources. *Current Opinion in Environmental Sustainability, 2/3*, 136–143.
Hunag, Y. (2016). Understanding China's belt & road initiative: Motivation, framework and assessment. *China Economic Review, 40*, 314–321.
IHK (2013). *Verkehrspolitisches positionspapier der industrie- und handelskammern im ruhrgebiet.* Hagen und Nord Westfalen: Industrie- und Handelskammern im Ruhrgebiet Bochum, Dortmund, Duisburg, Essen. https://www.essen.ihk24.de/blueprint/servlet/resource/blob/2103072/cf66546045399b11dc9a1c108100aae7/ruhrgebiets-ihks-verkehrspolitisches-positionspapier-data.pdf.
IPCC (2014). In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, ... J. C. Minx (Eds.). *Climate change 2014: Mitigation of climate change. Contribution of working group III to the Fifth assessment report of the intergovernmental panel on climate change*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.
IPCC (Intenational Panel on Climate Change) (2015). *Assessment report 5.*IPCChttps://www.ipcc.com.
Jittrapirom, P., Caiati, V., Feneri, A.-M., Ebrahimigharehbaghi, S., Alonso González, M. J., & Narayan, J. (2017). Mobility as a service: A critical review of definitions, assessments of schemes, and key challenges. *Urban Planning, 2/2*, 13.
Jordan, N. D., & Bleischwitz, R. (2020). Legitimating the governance of embodied emissions as a building block for sustainable energy transitions. *Global Transitions, 2*, 37–46.
Kamargianni, M., Li, W., Matyas, M., & Achäfer, A. (2016). A critical review of new mobility services for urban transport. *Transportation Research Procedia, 14*, 3294–3303.
Koch, J., Dorning, M. A., Van Berkel, D. B., Beck, S. M., Sanchez, G. M., Shashidharan, A., Smart, L. S., Zhang, Q., Smith, J. W., & Meentemeyer, R. K. (2019). Modeling landowner interactions and development patterns at the urban fringe. *Landscape and Urban Planning, 182*, 101–113.
Kresl, P. K., & Singh, B. (1999). Competitiveness and the urban economy: Twenty-four large US metropolitan areas. *Urban Studies, 36/5-6*, 1017–1027.
Lane, D. C., & Husemann, E. (2008). System dynamics mapping of acute patient flows. *The Journal of the Operational Research Society, 59/2*, 213–224. https://doi.org/10.1057/palgrave.jors.2602498.
Lauf, S., Haase, D., Hostert, P., Lakes, T., & Kleinschmit, B. (2012). Uncovering land-use dynamics driven by human decision-making – A combined model approach using cellular automata and system dynamics. *Environmental Modelling & Software, 27*, 71–82.
Laufs, J., Borrion, H., & Bradford, B. (2020). Security and the smart city: A systematic review. *Sustainable Cities and Society, 55*, Article 102023. https://doi.org/10.1016/j.scs.2020.102023.
Lavieri, P. S., Garikapati, V. M., Bhat, C. R., Pendyala, R. M., Astroza, S., & Dias, F. F. (2017). Modeling individual preferences for ownership and sharing of autonomous vehicle technologies. *Transportation Research Record, 2665*(1), 1–10. https://doi.org/10.3141/2665-01.
Lengyel, J., & Friedrich, J. (2019). Multiscale urban modeling; A de-urbanization scenario in the Ruhr area. *Proceedings of Wissenschaftsforum 2019*.
Leonardi, J., Browne, M., Allen, J., Bohne, S., & Ruesch, M. (2014). Best practice factory for freight transport in Europe: Demonstrating how "Good" urban freight cases are improving business profit and public sectors benefits. *Procedia – Social and Behavioural Sciences, 125*, 84–98.
Lorenz, U., & Veenhoff, S. (2013). Integrated scenarios of sustainable food production and consumption in Germany. *Sustainability Science Practice and Policy, 9*(2), 92–104.
Marana, P., Eden, C., Eriksson, H., Grimes, C., Hernantes, J., Howick, S., et al. (2019). Towards a resilience management guideline - Cities as a starting point for societal resilience. *Sustainable Cities and Society, 48*, Article 101531.
Marsden, G., & Docherty, I. (2013). Insights on disruptions as opportunities for transport policy change. *Transportation Research Part A, Policy and Practice, 51*, 46–55.
Mei, Z., Lou, Q., Zhang, W., Zhang, L., & Shi, F. (2017). Modelling the effects of parking charge and supply policy using system dynamics method. *Journal of Advanced Transportation, 2017*, Article 6463586. https://doi.org/10.1155/2017/6463586 10.
Melkonyan, A., Krumme, K., Gruchmann, T., Spinler, S., Schumacher, T., & Bleischwitz, R. (2019). Scenario and strategy planning for transformative supply chains within a sustainable economy. *Journal of Cleaner Production, 231*, 144–160.
Melo, C., Teotónio, I., Silva, C. M., & Cruz, C. O. (2020). What's the economic value of greening transport infrastructures? The case of the underground passages in Lisbon. *Sustainable Cities and Societies, 56*, Article 102083. https://doi.org/10.1016/j.scs.2020.102083.
Michael, F. L., Noor, Z. Z., & Figueroa, M. J. (2014). Review of urban sustainability indicators assessment – Case study between Asian countries. *Habitat International, 44*, 491–500.
Ministry for Economy (2020). *Innovation, digitization and energy.* NRWhttps://www.wirtschaft.nrw/das-programm-digitale-verwaltung-nrw).
Müller, M., et al. (2017). Modal Split. In O. Reutter (Ed.). *Report on the State of the environment in the Ruhr metropolitan area. regionalverband Ruhr (RVR) regional Director, Essen*.
Multi-Agent Transport Simulation – MATSim Model (2020). https://www.matsim.org/.
Neirotti, P., De Marco, A., Cagliano, A. C., Mangano, G., & Scorrano, F. (2014). Current trends in Smart City initiatives: Some stylised facts. *Cities, 38*, 25–36.
Neuwirth, C., Peck, A., & Simonović, S. P. (2015). Modeling structural change in spatial system dynamics: A Daisyworld example. *Environmental Modelling & Software, 65*, 30–40.
Nevens, F., Frantzeskaki, N., Gorissen, L., & Loorbach, D. (2013). Urban Transition Labs: Co-creating transformative action for sustainable cities. *Journal of Cleaner Production, 50*, 111–122.
New Climate Economy (2016). *The sustainable infrastructure imperative - Financing for Better Growth and Development.* Washington, London: New Climate Economy.
OECD (2018). *Rethinking urban sprawl: Moving towards sustainable cities.* Paris: OECD Publishinghttps://doi.org/10.1787/9789264189881-en.
Oueslati, W., Alvanides, S., & Garrod, G. (2015). Determinants of urban sprawl in European cities. *Urban Studies, 52/9*, 1594–1614.
Palanivel, T. (2017). *Rapid urbanisation: Opportunities and challenges to improve the well-being of societies. Human development Reports.* UNDP - United Nations Development Programme.
Pangbourne, K., Stead, D., Mladenović, M., & Milakis, D. (2018). The case of mobility as a service: A critical reflection on challenges for urban transport and mobility governance. *Governance of the Smart Mobility Transition,* 33–48.
Patacchini, E., & Zenou, Y. (2009). Urban sprawl in Europe. *Brookings-Wharton Papers on Urban Affairs, 1*, 125–149.
Pichler, P.-P., Zwickel, T., Chavez, A., Kretschmer, T., Seddon, J., & Weisz, H. (2017). Reducing urban greenhouse gas footprints. *Scientific Reports, 7*, Article 14659.
Rahman, M. (2016). Detection of land use/land cover changes and urban sprawl in Al-Khobar, Saudi Arabia: An analysis of multi-temporal remote sensing data. *ISPRS International Journal of Geo-information, 5*(2), 15.
Rahul, T. M., & Verma, A. (2014). A study of acceptable trip distances using walking and cycling in Bangalore. *Journal of Transport Geography, 38*, 106–113.
Rodenhäuser, D., et al. (2013). *Der Regionale Wohlfahrtsindex für Nordrhein-Westfalen 1999 – 2013 und Leben in Nordrhein-Westfalen – subjektive Einschätzungen.* Heidelberg: Institut für interdisziplinäre Forschung (FEST). https://www.nachhaltigkeit.nrw.de/fileadmin/download/RWI_NRW_Studie.pdf.
Rodrigues, M., & Franco, M. (2019). Measuring cities' performance: Proposal of a composite index for the intelligence dimension. *Measurement, 139*. https://doi.org/10.1016/j.measurement.2019.03.008.
Sanesi, G., Colangelo, G., Lafortezza, R., Calvo, E., & Davies, C. (2017). Urban green infrastructure and urban forests: A case study of the Metropolitan Area of Milan. *Landscape Research, 42*(2), 164–175.
Santé, I., García, A. M., Miranda, D., & Crecente, R. (2010). Cellular automata models for the simulation of real-world urban processes: A review and analysis. *Landscape and Urban Planning, 96*(2), 108–122.
Scheiner, J. (2010). Interrelations between travel mode choice and trip distance: Trends in Germany 1976–2002. *Journal of Transport Geography, 18*(1), 75–84.
Sekkat, K. (2017). Urban concentration and poverty in developing countries. *Growth and Change, 48*, 435–458.
Seo, B. K., & Joo, Y.-M. (2019). Innovation or episodes? Multi-scalar analysis of governance change in urban regeneration policy in South Korea. *Cities, 92*, 27–35.

Serrano-Lopez, R., Linares-Unamunzaga, A., & San Emeterio, C. M. (2019). Urban sustainable mobility and planning policies. A Spanish mid-sized city case. *Cities, 95*, Article 201356.
Sochor, J., Strömberg, H., & Karlsson, I. C. M. (2015). Implementing mobility as a service: Challenges in integrating user, commercial, and societal perspectives. *Transportation Research Record, 2536*(1), 1–9. https://doi.org/10.3141/2536-01.
Soria-Lara, J. A., Tarriño-Ortiz, J., Bueno, P., Ortega, A., & Vassallo, J. M. (2019). A collaborative appraisal framework to evaluate transport policies for improving air quality in city centres. *Cities, 92*, 112–124.
Spickermann, A., Grienitz, V., & von der Gracht, H. (2014). Heading towards a multimodal city of the future? Multi-stakeholder scenarios for urban mobility. *Technological Forecasting and Social Change, 89*, 201–221.
Stave, K. A. (2002). Using system dynamics to improve public participation in environmental decisions. *System Dynamics Review: The Journal of the System Dynamics Society, 18*(2), 139–167.
Stiglic, M., Agatz, N., Savelsbergh, M., & Gradisar, M. (2018). Enhancing urban mobility: Integrating ride-sharing and public transit. *Computers & Operations Research, 90*, 12–21.
Tako, A. A., & Robinson, S. (2012). The application of discrete event simulation and system dynamics in the logistics and supply chain context. *Decision Support Systems, 52/4*, 802–815.
UN (2018). *World urbanization prospects: The 2018 revision. Population division of the united nations department of economic and social affairs (UN DESA)*.
Van Ommeren, J., Wentink, D., & Dekkers, J. (2011). The real price of parking policy. *Journal of Urban Economics, 70*(1), 25–31.
Voinov, A., & Bousquet, F. (2010). Modelling with stakeholders. *Environmental Modelling & Software, 25*(11), 1268–1281.
Voinov, A., Kolagani, N., McCall, M. K., Glynn, P. D., Kragt, M. E., Ostermann, F. O., Pierce, S. A., & Ramu, P. (2016). Modelling with stakeholders–next generation. *Environmental Modelling & Software, 77*, 196–220.
Wey, W.-M. (2019). Constructing urban dynamic transportation planning strategies for improving quality of life and urban sustainability under emerging growth management principles. *Sustainable Cities and Societies, 44*, 275–290.
World Bank (2009). *World development report 2009. Reshaping economic geography*Washington, DC: World Bank.
Zandiatashbar, A., Hamidi, S., & Foster, N. (2019). High-tech business location, transportation accessibility, and implications for sustainability: Evaluating the differences between high-tech specializations using empirical evidence from US booming regions. *Sustainable Cities and Society, 50*, Article 101648.
Zawieska, J., & Pieriegud, J. (2018). Smart city as a tool for sustainable mobility and transport decarbonisation. *Transport Policy, 63*, 39–50.
Zhao, P., & Hu, H. (2019). Geographical patterns of traffic congestion in growing megacities: Big data analytics from Beijing. *Cities, 92*, 164–174.
Zhuang, T., Qian, Q., Visscher, H. J., Elsinga, M. G., & Wu, W. (2019). The role of stakeholders and their participation network in decision-making of urban renewal in China: The case of Chongqing. *Cities, 92*, 47–58.
Zore, Z., Cucek, L., Sirovnik, D., Pintaric, Z. N., & Kravanja, Z. (2018). Maximizing the sustainability net present value of renewable energy supply networks. *Chemical Engineering Research and Design, 131*, 245–265.