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Analysing the environmental impact of transport activities on the last mile for in-store and online shopping from a system dynamics perspective

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Abstract

The growing popularity of online shopping affects current transport processes. Particularly in urban areas, the increasing demand for transport is high due to population density. In in-store shopping, consumers drive to the store themselves; in online shopping, the goods are transported to the consumer. Depending on the modal split, many of these activities cause greenhouse gas (GHG) emissions. An increase in GHG emissions leads to climatic changes, which in turn can affect various sectors. This paper aims to provide an overview of the factors that can influence the level of emissions. In order to cope with the complexity of the interrelations between the factors, system dynamics (SD) was chosen as the methodological approach. Causal loop diagrams (CLD) as well as stock and flow diagrams (SFD) help to visualize the coherences. This work demonstrates the complex interactions between online and offline channel. Furthermore, the effects of emissions on demand are shown. The development of demand determines the level of expenditure in the two channels, which is related to the scope of transport activities. The results allow insights into the interrelationships from different perspectives, create a better understanding of overriding influences and form a structural basis for carrying out simulations.

Keywords: online shopping, in-store shopping, transport, GHG emissions, system dynamics

1. Introduction

New opportunities in telecommunications are changing our shopping behaviour. In addition to traditional ways of shopping, where consumers come to the stores themselves, the popularity of online shopping has increased in recent years (International Post Corporation, 2017). Transport activities are necessary for online shopping and in-store shopping, and cause greenhouse gas (GHG) emissions. In 2017, the transport sector was responsible for 27% of total EU-28 GHG emissions. Compared to 1990, GHG emissions from the transport sector were 28% higher in 2017 (European Environment Agency, 2019). The level of emissions depends on a large number of factors, creating a very complex situation. It is not only within transport activities that the extent of the various variables influences the level of emissions, but they can also be affected by other areas. One reason for this may be that transport processes are usually carried out for a specific purpose. To our knowledge, there is no comprehensive analysis that sheds light on the topic of this work from different perspectives and analyses systemic relationships. Therefore, this work does not only deal with last mile transport activities in the online and offline channel, but also analyses the interactions between the two channels as well as the generated emissions and their effects in a single model. Comprehensive knowledge of the causal relationships and a better understanding of the system behaviour are necessary to be able to take measures that influence the system in the desired way.

The remainder of this paper is organized as follows: Section 2 presents the literature relevant to this work and describes the research gap. Section 3 explains SD as a methodological approach. Section 4 presents the results. Subchapter 4.1 deals with the CLD, in subchapter 4.2. the SFD is presented in a more detailed way. Finally, in section 5 the most important findings of this work are summarized and limitations are listed.

2. State of the art

There are some scientific studies that deal with the different environmental impacts of transport activities in in-store and online shopping. Case studies and calculations on the extent of emissions in these research projects usually relate exclusively to transport activities and closely related factors. In most cases, online shopping is described as more environmentally friendly. Carling et al. (2015) developed a method for measuring transport related carbon dioxide emissions (CO_2) focusing on the shortest routes and calculated the emissions for purchasing electronic products in online and offline channel for a Swedish region. Edwards et al. (2010) analysed small non-food products at the last mile and model the emissions per excel spreadsheet. They considered drop density, distance of delivery tour, type of vehicle, failed deliveries and returns. van Loon et al. (2015) investigated CO_2 emission from online retailing using a life cycle analysis and identified consumer transport, parcel network, physical stores and the transportation between the factory and the distribution centre as critical factors. Wiese et al. (2012) compare in their sensitivity analysis the CO_2 emissions of online and in-store shopping for clothing. Looking at supply chains, online shopping generates fewer emissions than in-store shopping. If the distance of consumers to the stores, delivery processes, return rates, use of public transport and additional journeys caused by information behaviour are also considered, the results are more complex. The emissions of the two channels vary according to the extent of these variables. Mangiaracina et al. (2015) found in their literature review on environmental implication of B2C e-commerce that the organisation of transport planning and management, warehousing, packaging and distribution networks have a major impact on the environment. To assess the environmental impact energy use, gas emissions, waste generation and traffic mileage were considered. Pålsson et al. (2017) carried out a literature review and content analysis in regard to energy efficiency of different distribution systems. The considered areas often go beyond mere transport activities, but are closely linked to the supply chain. Smidfelt Rosqvist and Winslott Hiselius (2016) found in their data analysis on whether online shopping could reduce CO_2 emissions in passenger transport a potential for a 22% reduction in CO_2 emissions in 2030. Their calculations considered the number of trips, the duration of the trip and the choice of transport mode. They also compare effects of mode choice on trip length for shopping purposes and other errands.

Mobility effects such as substitution and complementary effects are rarely considered in the quantitative studies already presented. These effects are discussed in detail in numerous other studies, which, however, are mostly on a qualitative level (Farag et al., 2006; Mokhtarian, 2003, 2004; Rotem-Mindali & Weltevreden, 2013; Visser & Lanzendorf, 2004; Weltevreden & Rotem-Mindali, 2009; Zhang et al., 2016). The presented literature demonstrates that environmental impacts of transport processes in online and in-store shopping are already considered, but within relatively narrow limits. Connections of the emission level with other areas such as demand, consumer behaviour or climatic changes are not considered, as they require an analysis from a higher perspective. In addition, qualitative studies usually include linear calculations that neglect systemic developments.

3. Materials and Methods

Mangiaracina et al. (2015) considered 56 scientific publications in their literature analysis on the topic of environmental sustainability in e-commerce. Of these, 11 studies used simulation methods, with a focus on multi-agent, discrete event and Monte Carlo simulations, no study used SD as method. As shown in chapter 2 state of the art, the level of emissions is influenced by numerous factors. Since the factors can also influence each other, a very complex system is created. It therefore seems reasonable to broaden the view to related areas. Systemic approaches are well suited to incorporate not only causal links between variables but also drivers into a model.

SD is primarily interdisciplinary and shall help to solve real world problems. It is based on the perception of the complex interaction between variables and focusses on the underlying causes of problems and the dynamic behaviour of systems. Systems are always dynamic, because variables perceived as static become dynamic if the appropriate time horizon is chosen. It often falls short to focus on one variable to achieve the desired results, because the other variables must be hold constant in order not to cause other effects. A changing variable in a system affects related variables due to nonlinear relationships and feedback loops and thus leads to dynamic complexity. A consideration over time helps to include effects that may occur with a time delay. This delay can be the cause for the realization of unintended side effects. The behaviour of a system can be surprising at the first glance, because the dynamics can emerge endogenously due to the inherent structure of the system. Complex behaviour often results of feedback loops, where a distinction can be made between self-reinforcing (R) and self-balancing loops (B) (Sterman, 2009). Causal loop diagrams show cause-effect relationships and feedback processes. In this paper, the two variables connected by cause-and-effect relationships are linked by an arrow with a continuous line when they change in the same direction. Variables that change in different directions are connected with an array with a dotted line. In a next step, the CLD can be converted into a stock and flow diagram (SFD) that allow quantitative simulations. The processes behind causal links are described with mathematical equations. In this work SFD are depicted, but the relationships are not yet numerically represented. Nevertheless, the visualization as SFDs has advantages, because this modelling process requires a greater accuracy in the depiction of causalities, which leads to more clarity (Morecroft, 2015). Therefore, SFDs are a useful tool in this step to illustrate the model assumptions made and also clarify which data is required.

Small changes in systems can have large consequences. To make effective changes in systems it is important to find high leverage points. The so-called archetypes are structures that can often be found in many different real-life situations. Finding archetypes for the described problem can help to identify high and low leverage points, because the archetypes already show areas of high and low leverage (Senge, 2006).

When modelling systems, it is important to define clear model boundaries. The model represents a generic model that should be valid for all Western European cities. The focus of this work is on the final step of the transport of goods to the customers' place of residence. In online shopping, products are delivered to the customers by a delivery service as part of a delivery tour. For in-store shopping, the distance between the store and the customers' place of residence is considered. The consumers usually handle this transport themselves. In this work only B2C deliveries are included, since deliveries on the last mile and trips of consumers to the stores are of particular interest for the generation of emissions. The authors are aware that the systems presented are more complex in reality. These limitations have been accepted as the power of system dynamics lies in an abstract view and simplifications are necessary to create usable models.

The modelling process is iterative and can be divided into five steps (Hovmand, 2014) :

- Problem definition
- Conceptualization of the system
- Model formulation
- Validation and analysis
- Transferring insights

When more knowledge about the behaviour of the system has been gained, it may be necessary to go back to an earlier stage of the process (Hovmand, 2014). As this paper represents the preliminary status of the work, the entire process has not yet been completed. The results presented relate to the conceptualization of the system.

4. Results and Discussion

In the following subchapters two models are depicted. The CLD shows causal relationships between main variables at a very abstract level in order to be able to show the underlying structure of the model at a glance. In the SFD different parts of the first model are elaborated in more detail, thus providing first insights into a possible system behaviour.

4.1. Causal Loop Diagram

In figure 1 below the CLD is depicted. For modelling, the distinction of the influencing factors into endogenous variables and exogenous parameters is relevant. Parameters are used to integrate relevant effects into the system without having to consider the underlying relationships. The parameters used in the CLD are briefly explained below.

- Basket value online order, basket value in-store purchases: The model requires data on the total number of purchases. The closest approach would be via the frequency of purchases. Since the data available for this variable usually refer to specific groups of buyers and not to society as a whole, another way was chosen. In this context, the parameter basket value in online and in-store shopping is used as an auxiliary parameter. Together with the extent of consumer expenditures in the two channels, the number of online orders and in-store purchases can be estimated. Since the necessary data is often easier to obtain, this approach is preferred.
- Delivery failure rate: If the parcel cannot be successfully delivered on the first delivery attempt, a second attempt will be made. The number of total delivery attempts is therefore often higher than the total number of packages delivered (van Loon et al., 2015).
- Trip chaining rate: This refers to the situation when people make an in-store purchase on a car trip that was undertaken for a different purpose, for example on the way home from work (Buldeo Rai et al., 2019; Mokhtarian, 2004). As these trips would take place independently of the in-store purchase, they should not be included in the total emissions.
- Attractivity online channel, attractivity offline channel: Consumers’ decision to prefer online or in-store shopping depend on various factors, such as convenience, product range, spatial and temporal restraints or the possibility of a prior examination of the product (Chaparro-Peláez et al., 2016; Iglesias-Pradas et al., 2013; To et al., 2007). They are included as exogenous parameters, since the decision-making process does not need to be described in such detail for this work. This would only unnecessarily increase the complexity of the

model.

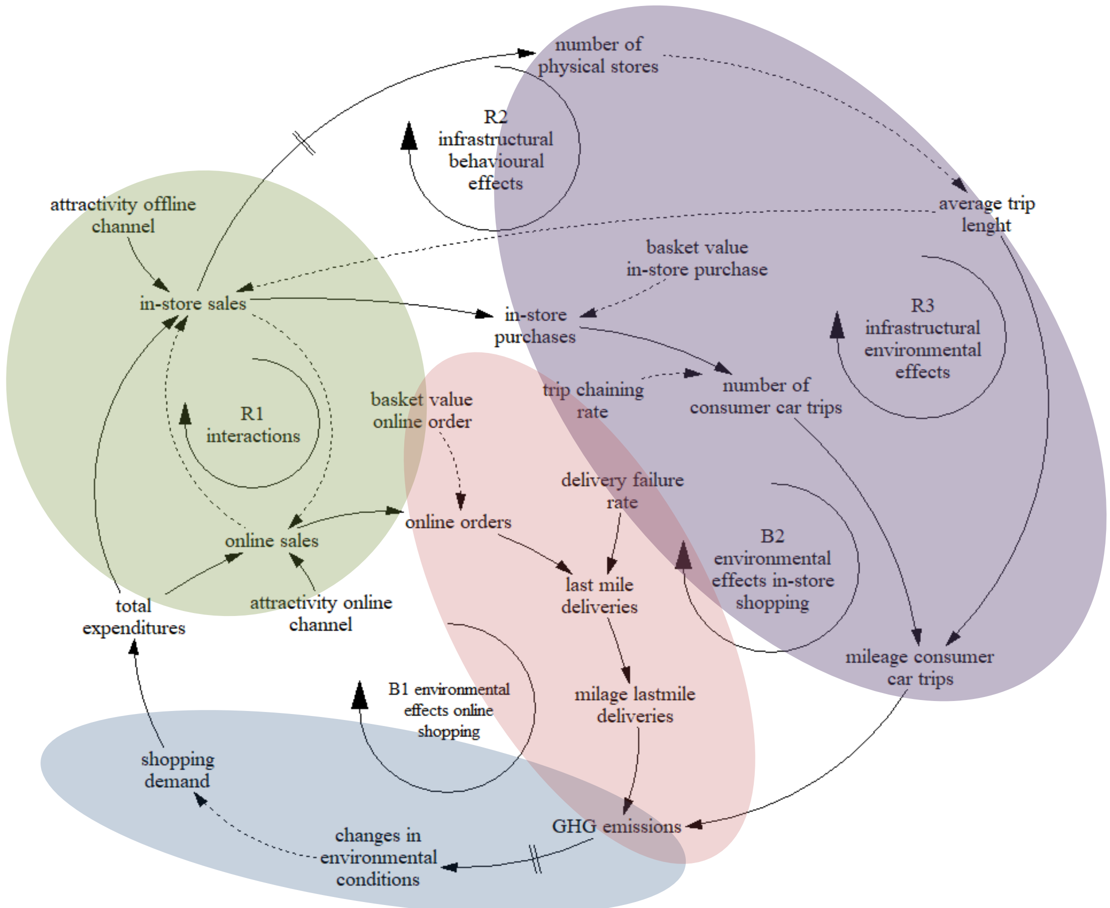

Figure 1. Coherences and effects of transport processes in the online and offline channel

Figure 1 contains five causal loops that result from the structure of the model. There are two balancing loops, mainly due to the link between emissions, climate change and economic consequences. As the effects in this context usually do not occur immediately, a delay is included. The first reinforcing loop (R1) refers to interactions between the online and offline channel. This enables the illustration of substitution effects. These effects occur when the purchase of certain products is completely shifted from one channel to another (Salomon, 1986). There are two more reinforcing loops (R2, R3) in the CLD. When in-store sales decline, store owners react after a certain period of time by closing physical stores (Zhang et al., 2016). This leads to an increase in the average distance from consumers to the stores, whereby consumers will adjust their purchasing behaviour, if the trip length exceeds a certain limit (Visser & Lanzendorf, 2004).

It is assumed that consumers set themselves a certain time budget for car trips. If it is exceeded, they try to reduce the time spent on this activity. This could be achieved by reducing the number of shopping trips. Assuming that the value of the shopping basket remains constant, this development will lead to a decrease of in-store sales. If total consumer expenditures remain stable, spending will shift to online retailing as this channel increase its attractiveness. In figure 1 different areas of the model are coloured. These areas are discussed in more detail in the following subchapter. The model areas are assigned to the following thematic units: GHG emissions and economics, interactions between offline and online channels and transport and GHG emissions.

4.2. Stock and Flow Diagrams

In this subchapter the different parts of the model are described in more detail. For a better understanding of the position of the partial model, there are some overlaps between the individual model parts.

4.2.1. *GHG emissions and economy*

Figure 2 below depicts the coherences of GHG emissions and economic development. In stationary retailing, the customers collect the goods from the store themselves. Therefore, driving a car for this task causes GHG emissions. In online retailing, the goods ordered are transported directly to the consumer. The delivery of parcels via the so-called last mile also causes GHG emissions. Since the removal of GHG emissions from the atmosphere is extremely small compared to the GHG emissions produced and, in addition, the GHG remain in the atmosphere for a long period of time, only inflows are depicted.

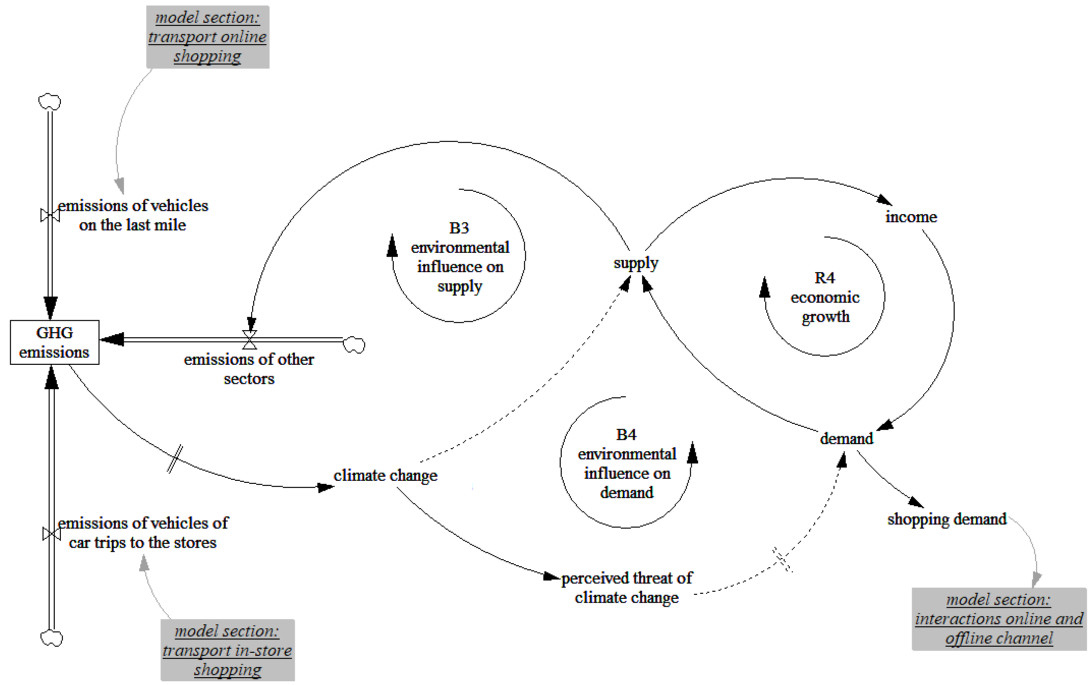

Figure 2. Economic model: SFD for coherences between GHG emissions and economic development

Rising GHG emissions affect climatic conditions above a certain threshold. Since these changes do not occur immediately and are only perceptible after a certain time, a delay was included in the model. Climate change, which has a direct impact on production factors such as labour, land and natural resources and capital, resulting in losses of GDP and a decline in productivity (OECD, 2015).

The issue of climate change also continues to push into the public eye as the changes become more visible to society and thereby the perceived threat increases. This can lead to more environmentally friendly behaviour with more conscious and sustainable consumption. As changes in behaviour do not usually manifest themselves fully and immediately, a delayed effect of these on demand was assumed. Climate change can also lead to global migration, civil conflicts and crises, which can cause periods of uncertainty. All these developments can influence the economic system (OECD, 2015).

In a very abstract and simplified view, the economic system is represented by three variables: Rising demand leads to rising supply as companies try to maximize their sales. Increasing supply leads to higher employment rates and increasing income of potential consumers, which in turn increases overall purchasing demand. This result in economic growth (R4). The links between the variables that represent the economic model in this work correspond to the structure of the system archetype limits to growth. This archetype is characterized by the fact that a reinforcing feedback loop leads to an accumulation process. However, at a certain point in time, this causes a balancing loop to gain power (Senge, 2006). For better understanding, the archetype is depicted in figure 3 below.

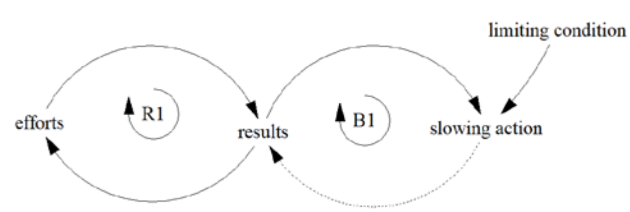

Figure 3. Structure of the archetype limits to growth

In this work, the reinforcing loop corresponds to economic growth (R4). The slowing action, which leads to a weakening of this loop, is due to the effects of climate change. In this case the reinforcing loop is even opposed by two balancing loops (B3, B4).

4.2.2. Interactions between offline and online channel

There is a broad discussion in the scientific literature about the interaction between online and in-store sales. Weltevreden (2007) shows in his literature analysis that most studies assume interactions between the two channels, which can lead to different mobility effects. Therefore, it seems reasonable to depict both channels in a joint model. The corresponding SFD model is depicted below in figure

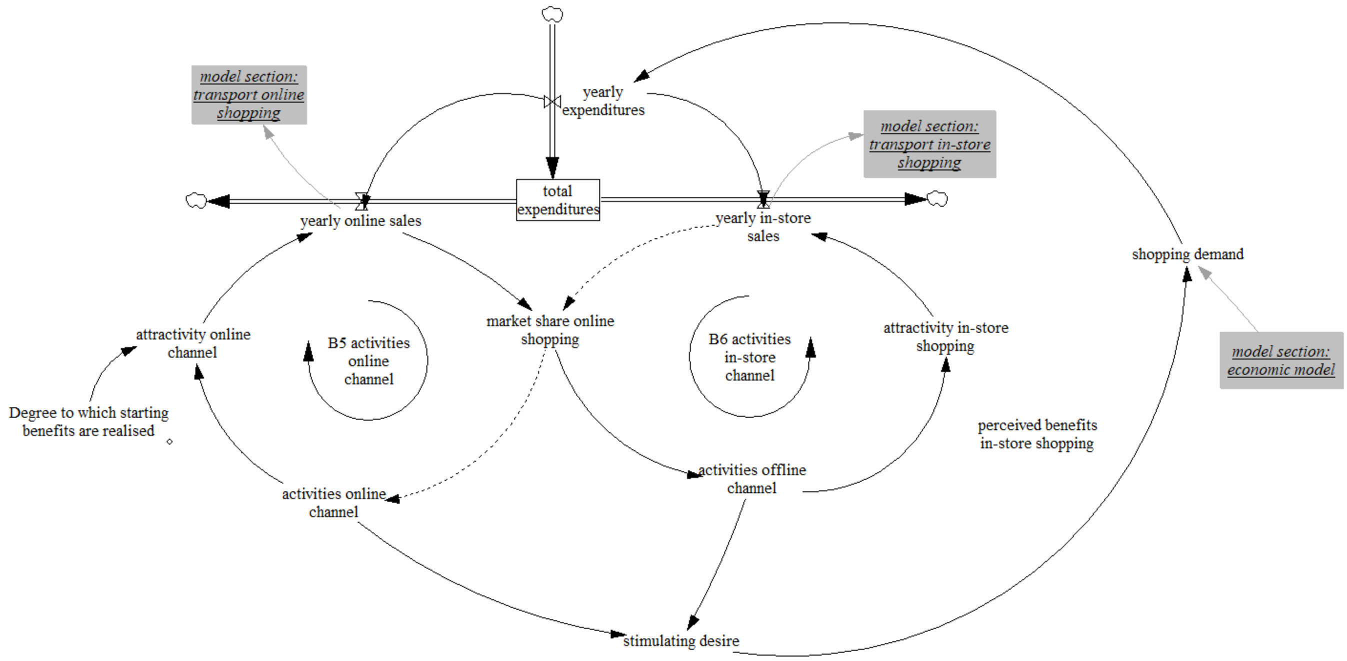

Figure 4. Interactions online and offline channel: Substitutive and complementary effects

Complementary effects arise when a particular situation does not result in the old activities being replaced by new ones, but when additional activities occur (Salomon, 1986). With regard to online shopping, complementary effects would emerge in the following example: A prerequisite for the rise of online shopping were developments in telecommunications. These enabled customers not only to buy products online, but also to have easy access to data and information about offered products. This, in turn, may lead to an increased need for consumption by consumers, resulting in additional new activities (Mokhtarian, 2004).

The breakdown of total annual expenditure into online shopping and in-store shopping expenditure is based on the balancing loops B5 and B6. The growing share of online shopping as a proportion of total market volume influences the number of yearly in-store sales and online sales. In order to compete with the online market, the companies in the in-store channel take additional measures to make this channel more attractive to consumers. This increases their revenues and reduces the market share of online shopping. In this way, the situation for the offline channel is eased and fewer market stimulating activities are carried out. In the online channel the same process takes place as before in the offline channel. This structure corresponds to the archetype escalation. The two balancing loops lead to a self-reinforcing behaviour and thus to exponential growth of the stocks under consideration (Senge, 2006). The growth of online sales and in-store sales is always limited by yearly expenditures and shopping demand, but this can be influenced by the level of activities in the two channels. These coherences reflect complementary effects.

Substitution effects can also be depicted via the model structure. It is assumed that substitution effects occur primarily at the beginning of the growth of the online market, as this market is inherently more attractive in certain situations. This is represented in the model by the external parameter, which can strongly increase the attractiveness of the online channel at the beginning. As a result, the overwhelming attractiveness of online shopping compared to in-store shopping at the beginning determines market growth. Above a certain percentage, however, this parameter loses influence.

4.2.3. Transportation and GHG emissions

Figure 5 below shows the dependencies between transport activities for online shopping and in-store shopping and GHG emissions. As there are infrastructural effects that influence yearly in-store sales, the model section for interactions between online and offline channel is partly depicted. This allows the complete visualisation of the reinforcing loops R2 and R3. In transport activities for online shopping, the delivery demand is influenced by splitting orders. This is due to the fact that not every order is delivered in a single package. In particular, spatial circumstances (for example, products are not stored in the same warehouse) or time factors (for example, products have different delivery times) lead to split orders and thus to increased delivery demand. The total number of delivery attempts is relevant for the amount of GHG emissions produced. This variable is made up of successful, unsuccessful and second delivery attempts and is necessary for the calculation of total GHG emissions of online shopping. Click and collect orders are also depicted in the model. It is shown that they are linked to the same transport activities as purchases in shops, even if they are part of online orders.

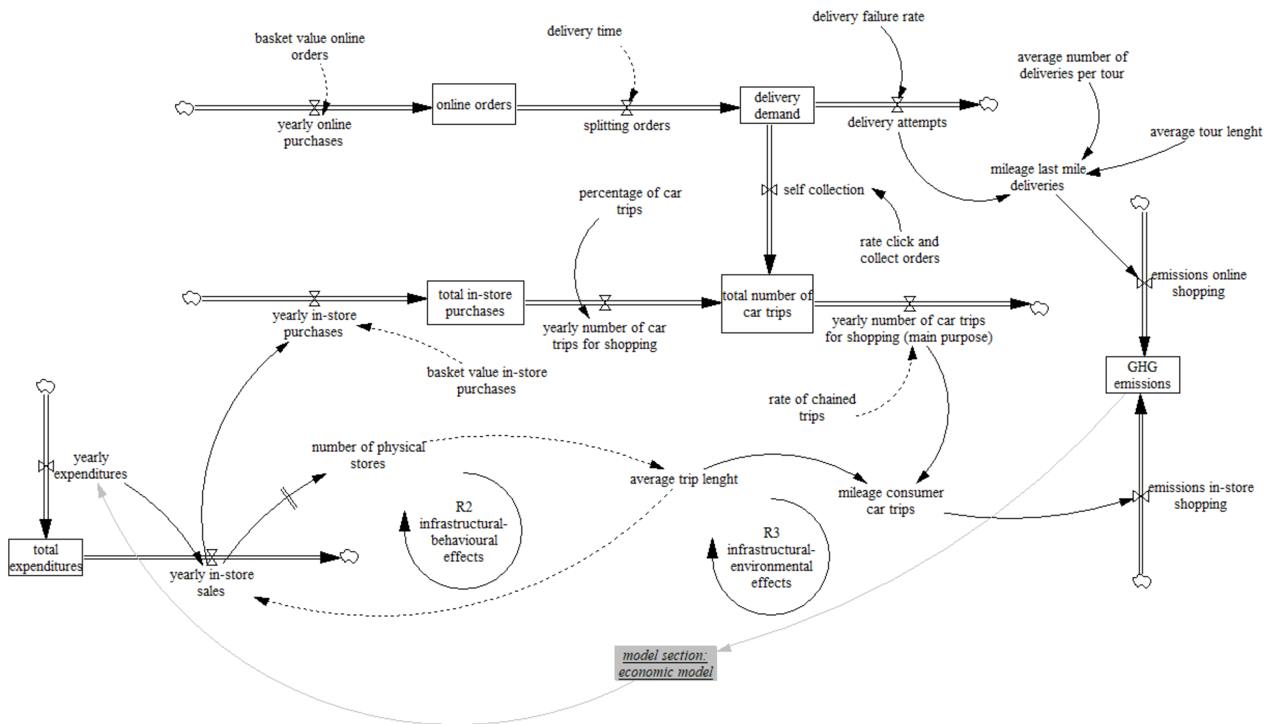

Figure 5. Transport for online shopping: effects of transport activities on the amount of GHG emissions

5. Conclusions

In this work it becomes clear that the environmental impacts of online and in-store shopping depend not only on different levels of factors within the transport processes of the two channels, but also on closely related areas. A better understanding of the interactions between the two channels and the consideration of economic changes make it possible to grasp the overall picture more clearly. This work shows also the process of deriving an SFD from a CLD. The mapping of the SFD sets an initial framework for data collection. Of course, this paper has also some limitations, especially since it only shows the current state of research. As further steps a comprehensive data collection and the formulation of the equations is necessary to allow first simulations. This will make coherences and system behaviour even clearer. We will continue with the phase of validation and verification. Dimensional consistency, comparisons of the results with observed data and analysing the model behaviour under extreme conditions will be important tools. Feedback processes with experts can be also of great value for the validation of the model.

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