Issue 21(3), 2021, pp. 1-18
https://doi.org/10.18757/ejtir.2021.21.3.4165

EJTIR
ISSN: 1567-7141
http://ejtir.tudelft.nl/

On the cost elasticity of inter-regional distribution structures: a case study for the Netherlands

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Several studies show that logistics facilities have spread spatially from relatively concentrated clusters in the 1970s to geographically more decentralized patterns away from urban areas. The literature indicates that logistics costs are one of the major influences on changes in distribution structures, or locations and usage of logistics facilities. Quantitative modelling studies that aim to describe or predict these phenomena in relation to logistics costs are lacking, however. This is relevant to design more effective policies concerning spatial development, transport and infrastructure investments as well as for understanding environmental consequences of freight transport. The objective of this paper is to gain an understanding of the responsiveness of spatial logistics patterns to changes in these costs, using a quantitative model that links production and consumption points via distribution centers. The model is estimated to reproduce observed use of logistics facilities as well as related transport flows, for the case of the Netherlands. We apply the model to estimate the impacts of a number of scenarios on the spatial spreading of regional distribution activity, interregional vehicle movements and commodity flows. We estimate new cost elasticities, of the demand

Publishing history

Submitted: 02 December 2019
Accepted: 28 June 2021
Published: 07 July 2021

Cite as

Davydenko, I.Y., Tavasszy, L.A., & Quak, H. (2021). On the cost elasticity of inter-regional distribution structures: a case study for the Netherlands. *European Journal of Transport and Infrastructure Research, 21(3)*, 1-18.

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for trade and transport together, as well as specifically for the demand for the distribution facility services. The relatively low cost elasticity of transport services and high cost elasticity for the distribution services provide new insights for policy makers, relevant to understand the possible impacts of their policies on land use and freight flows.

Keywords: *logistics sprawl, distribution structures, freight transport modelling, cost elasticities, spatial logistics.*

1. Introduction

Logistics facilities have spread spatially from relatively concentrated clusters in the 1970s to geographically more decentralized patterns around large urban areas. Distribution facilities have a significant impact on transport systems, the economy and the environment. Besides producing freight transport and commuting flows, distribution facilities have an indirect effects on local employment and external effects through e.g. emissions of transport (Dablanc and Rakotonarivo, 2010; Yuan et al., 2018). Suburban or rural areas are often the origin of distribution trips into cities and therefore are relevant for local sustainable urban policies, such as access regulations for low emission zones, or city logistics initiatives, such as consolidation centers (Quak and De Koster, 2009; Van Duin et al., 2013). The phenomenon of 'logistics sprawl', first defined by Dablanc and Rakotonarivo (2010) as the movement of logistics facilities outside the cities towards suburban areas, has been studied at different scales, but mostly at the level of large regional systems with 10-20 million inhabitants (see e.g. Dablanc (2013) for Paris, Los Angeles and Atlanta, Sakai et al. (2015) for Tokyo and Heitz et al. (2017) for the Randstad area). There is a growing amount of empirical and conceptual research focusing on about spatial patterns of logistics settlements and sprawling. The framing of the phenomenon has been extended beyond the traditional interpretation of neighborhood level studies of suburbanization in radial patterns, to include larger scales of analysis and different spatial configurations (Aljohani and Thompson, 2016). Our focus in this paper is on larger spatial systems, typically a mega-region or country, and the broader definition of the sprawl phenomenon, also including movement of facilities towards more rural areas that are not necessarily part of the urban system. In terms of logistics we focus on distribution facilities, where goods are stored, bundled and re-packed. Our subjects of research are empirical spatial-economic models that help to explore changes in the use of distribution facilities in different regions. As such, these models contribute to our knowledge about the process of logistics sprawl. We introduce the case of the Netherlands for empirical analysis, where we study the move of distribution facilities away from the main Randstad conurbation into the rural areas.

Understanding the possible future spatial patterns of distribution structures is important for effective regional as well as local policies concerning spatial development and planning, social policy, transport and infrastructure investments as well as for the reduction of the environmental consequences in these densely populated areas. In the case of the Netherlands, distribution centers generate at least 14% of all Heavy Goods Vehicle (HGV) ton volumes and at least 12% of all HGV trips (Davydenko, 2011). In recent years, the spatial dynamics of distribution facilities has gained new interest. McKinnon (2009) and Allen et al. (2012) qualitatively explore the functional relationships between logistical activities and their locations. Friedrich et al. (2014) define the term distribution structures as the distribution chains between places of production and consumption, including distribution centers and the connecting transport flows. An important aspect of changes in distribution structures is that direct transport, i.e. without a distribution center, is an immediate alternative to re-settlement of centers. This response should also be taken into account when assessing the impacts of policies. Several studies have observed and measured, on a case level, changes through time in spatial patterns, labelling these changes as Logistics Sprawl (Dablanc et al., 2014; Dablanc and Ross, 2012; Heitz and Dablanc, 2015; Giuliano et al., 2016; Heitz et al., 2017; Dablanc and Browne, 2019). Woudsma et al. (2016) proposed a method for the analysis of spatial patterns related to logistics activities in and around large cities. The above efforts all provided new insights for the analysis of observed logistics sprawl patterns, but did not provide quantitative explanations on how sprawl manifests itself at the national level. Also, the models lacked predictive capabilities. Our aim is to help fill this void by means of an empirical analysis of changes in spatial distribution structures. There has been very little work on empirical models aiming at predicting changes in location patterns of logistics facilities in a larger, multi-region system. The direction taken in this paper is that of quantitative modelling, to explain the intensity of logistical activities in a region, and changes therein as a function of logistics costs. The practical application for the Netherlands provides a unique estimation of combined demand cost elasticity for distribution structures, in addition to demand cost elasticity for the services of distribution facilities, extending the scant knowledge on demand cost elasticities (e.g. de Jong et al., 2010 and Jourquin et al., 2014).

The remainder of the paper is structured as follows. We review the existing modelling work in this area in more detail below in Section 2. Section 3 introduces the specification of the model. We apply the model in Section 4 to the case of the Randstad. The model is applied in Section 5, showing the effects of policies on settlement patterns, and inferring elasticities of changes in transport costs. Section 6 completes the paper with the main conclusions on the distribution and warehousing modeling and scenario assessments in the model.

2. Literature review

The traditional 4-step freight models do not capture logistics aspects of freight transport. Usually it is assumed that spatial patterns of transport flows equal those of trade flows. Freight flows, however, do not always move directly from producer to consumer. Therefore, a geographically accurate modeling of logistics activities requires an explicit account of distribution centers. Modelling these explicitly has a number of advantages. First and foremost, accurately modelling these activities implies better support for planning and policy evaluation. Secondly, if external factors (such as fuel costs, labor costs, costs of facilities, rents) change, the model is able to capture the expected responses in logistics activities. Thirdly, such a model allows for a more realistic estimation of the costs involved in producer-consumer interactions, which is important for the estimation of trade flows between regions, as well as for logistics performance measurement.

Recent reviews of freight transportation models (De Jong et al, 2014; Friedrich et al., 2013; Tavasszy et al., 2012) indicate that the capabilities of freight models to represent distribution structures are still in a very early stage of development. There have been only a limited number of initiatives to spatially model the use of distribution centers and the transport flows using them. We review the relevant ones below, concluding that none of these is suited to calculate cost elasticities of distribution structures.

The SMILE model (Tavasszy, 1998) first included warehouse logistics explicitly as a distinct step in the translation of trade flows into transport flows. This has been done using the concept of logistics chains, representing a discrete choice problem between various ways of shipping goods from the production to consumption points. This approach has also been used for the UK Trans-Pennine model (Williams, 2005) and EU level operational models such as the TRANS-TOOLS and the SCENES models (see Chen, 2011; TRANS-TOOLS, 2008 and SCENES, 2000). Due to a lack of data on warehousing activities, the calibration of the above models could only be carried out indirectly on transport data. Maurer (2008) proposed a logistics optimization model in the context of emissions estimation from freight transport in Great Britain. The modeling was done for only one commodity (drinks) and was validated using a commercial software for the determination of optimal warehouse locations. Friedrich (2010a, 2010b) performed a detailed study for 3 food retail chains in Germany. His model searches for a stable-state situation, where locations of DCs serving these shops are determined. The model is based on actor interaction modeling in meso-structures (Liedtke 2006 and Liedtke 2009). The proposed simulation system includes detailed logistic optimization of retailing companies as well as simplified optimization of adjacent logistic systems. The resulting simulation model SYNTRADE was able to reproduce logistic structures in food retailing in Germany. Its application to broader freight demand models would be cumbersome, however, as the data needs cannot be fulfilled.

Recently Sakai et al. (2018, 2019) show that a regional commodity flow survey data (Tokyo Metropolitan Area) can be used together with the establishment data to estimate commodity flows through different distribution channels. This model does not apply a logistics cost logic, however. Thus this model would not be suited for calculation of cost elasticities. Also, the capability of the model to reproduce inter-regional flows was not demonstrated. Davydenko (2013) developed the first empirically validated, aggregate, logistics costs based choice model for the estimation of freight flows generated by distribution facilities. This model was not estimated on transport flows however while this would be necessary to predict impacts on volumes transported (tonnes) and transport performance (tonne-km). In summary, we identify a research gap concerning descriptive models of distribution structures that apply a logistics costs logic.

The model and applications presented in sections 3-5 build on the Davydenko and Tavasszy (2013) model, extending it to estimate interregional flows and applied to allow the assessment of spatial spreading of distribution activities in and around densely populated areas. In the next section, we provide the functional specification of the model and describes the two main sub-models: the gravity model (estimation of trade flows) and the logistics chain model (estimation of transport flows). Section 4 provides information on the input data used in the model. We further describe interaction between these two models and provide information over the calibration process. As a case study, we interpret logistics sprawl as distribution and warehousing activities relocating from the Dutch Randstad region to the surrounding regions. In section 5 a number of spatially specific cost scenarios are introduced that are expect to influence distribution structures. Section 5.1 provides information on the scenarios that are computed model to estimate the impact on distribution structures, regional logistic activities and freight flow volumes. Section 5.2 presents the model scenario outcomes and section 5.3 discusses the general lessons that can be drawn from these outcomes. Section 6 concludes the paper.

3. Model description

We use a two-step modeling approach to model regional warehouse and distribution systems. Regional production volumes are matched with regional consumption volumes using a gravity model. The gravity model estimates interregional goods flows in a matrix form, namely the production-consumption flow or PC flow, essentially representing the physical trade flow between regions. Second, a logistics chain model is used to estimate how the PC flow is physically moved between production and consumption locations. We use an aggregate logit specification to split the PC flow between direct shipments and shipments via distribution centers or warehouses, into three types of interregional flow: production-to-distribution (P2D flow), production-to-consumption (P2C flow) and distribution-to-consumption (D2C flow). The model is calibrated on transport survey data, minimizing root-mean-square deviation (RMSD) between observed and estimated OD flows. The lack of observed inter-regional trade data requires an endogenous construction of the trade flows. The working of the model is summarized in Figure 1.

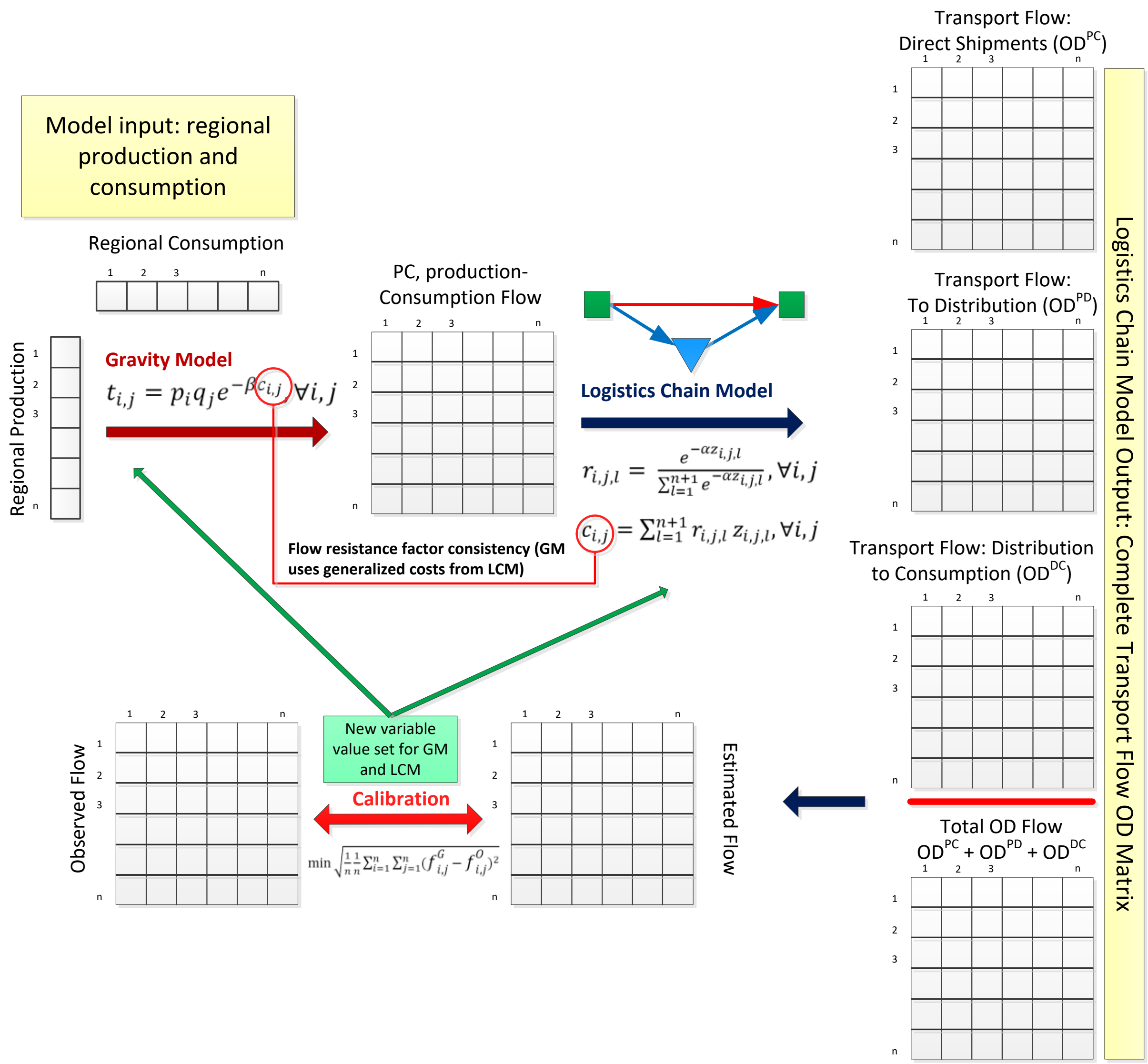

Figure 1. Conceptual representation of gravity and logistics chain combined model

The next subsections describe the mathematical specification of the trade model, the logistic chain model and their combined operation.

3.1. Trade patterns

Let P_i denote regional production volumes loaded into road Heavy Goods Vehicles (HGV) and expressed in ton units, $i = 1,..,n$. In the Dutch model application case, the Netherlands is divided into 40 NUTS3 regions, so-called COROP regions, therefore, $n = 40$. Let C_j denote regional consumption volumes offloaded from HGV vehicles, $j = 1,..,n$ and P_i denote regional production volumes loaded to HGV vehicles, $i = 1,..,n$. The Gravity Model (GM) used to obtain the PC flow is defined in the following form (1).

$$t_{i,j} = p_i q_j e^{-\beta c_{i,j}}, \forall i,j \quad (1)$$

where $t_{i,j}$ represent estimated individual cells of the PC matrix, p_i and q_j are estimated parameters of the gravity model representing regional production and attraction.

β is the sensitivity parameter of the gravity model

$c_{i,j}$ is the cost friction factor in the form of generalized logistics cost per ton shipped between production region i and consumption region j. The $c_{i,j}$ term in the gravity model is a constant, computed in the logistics chain model.

Our implementation of the GM is solved iteratively by searching for values p_i and q_j until the following two equations are satisfied:

$$\sum_{j=1}^{n} t_{i,j} - P_i < \varepsilon, \forall i \quad (2)$$

$$\sum_{i=1}^{n} t_{i,j} - C_j < \varepsilon, \forall j \quad (3)$$

Where $\mathcal{E}$ is an arbitrarily small value. The $\mathcal{E}$ value defines how accurate the gravity model solution is. Small values of ε lead to a very precise solution of the model, however, at the expense of extra iterations. Essentially, constraints (2) and (3) guaranty that the regional production outflow and regional consumption inflow in the estimated PC table are equal to the regional production P_i and regional consumption C_j respectively within the error margin ε.

3.2. Logistics Chains

The logistics chain model determines how the PC flow is physically transported between producing region i and consuming region j. For each i, j pair we determine the fraction of flow that is loaded into HGV vehicles in region i and unloaded in region j: these are direct shipments. A share of the flow between regions i and j is not shipped directly, but via warehouses in other regions. Therefore, we determine the share of goods that is shipped via warehouses in region k, thus creating logistics chains. For the Dutch case with 40 regions, there are 41 possible ways to ship goods between two arbitrary regions i and j, namely directly from i to j and via warehouse in region k, k = 1,..,40.

The logistics chains are modeled as two choices. The first choice is whether the shipment is direct or the shipment is carried out via distribution centers. Therefore, this top-level choice has two alternatives, direct shipment from region i to region j, or indirect shipment via a warehouse in the region k, thus following the chain $i \rightarrow k$, and $k \rightarrow j$.

Let $r_{i,j,l}$ denote the probability that products of region i are shipped to region j via chain l, l = 1,..,n+1. Index l takes the values in the range 1,.., n+1 due to the fact that the warehouse can be located in any of the n regions in addition to direct shipments between i and j. We assume that l = *1* value represents direct flow and l = k represents flow via warehouse located in k *-1* region. Flow conservation constraint is introduced (4) in order to guaranty that the flow from i to j is carried out (4).

$$\sum_{l=1}^{n+1} r_{i,j,l} = 1, \forall i, j \quad (4)$$

The probability of a direct shipment between i and j, $r_{i,j,1}$ is computed according to (5)

$$r_{i,j,1} = \frac{e^{-\alpha' \, LgSumDirect_{i,j}}}{e^{-\alpha' \, LgSumDirect_{i,j}} + e^{-\alpha' \, LgSumIndirect_{i,j}}}, \forall i, j \quad (5)$$

Where $LgSumDirect_{i,j}$ and $LgSumIndirect_{i,j}$ represent utility of the direct and indirect choices in the top-level logit discrete choice. These utilities are computed as logsum of the underlying nested alternatives. In case of direct shipments (6), it is one value; in case of indirect shipments, it is a logsum of 40 alternatives (7).

$$LgSumDirect_{i,j} = \ln e^{-\alpha z_{i,j,1}} \;, \forall i, j \quad (6)$$

$$LgSumIndirect_{i,j} = \ln \sum_{k=2}^{n+1} e^{-\alpha z_{i,j,k}} \;, \forall i, j \quad (7)$$

Similarly to equation (5) computing the probability of direct shipments $r_{i,j,1}$, equation (8) computes probability for indirect shipments ($l \neq 1$).

$$r_{i,j,l} = \frac{e^{-\alpha z_{i,j,l}}}{\sum_{l=2}^{n+1} e^{-\alpha z_{i,j,l}}} \left(1 - r_{i,j,l}\right), \forall i,j; l \neq 1 \tag{8}$$

Where $z_{i,j,l}$ is the total logistics cost (TLC) of shipment from region *i* to region *j* via chain *l*, per ton. α' is the logit sensitivity parameter; α is the nested logit cost sensitivity parameter. Smaller values of this parameter make the system less sensitive to the cost signals, higher values of the parameter make the system to react strongly to the cost of a particular chain *l*.

The total logistics cost consists of two main components, transport costs and inventory holding costs, such as stock-related capital costs, storage costs, handling-in and handling-out costs (warehouse-related handling, such as offloading and loading of the inbound and outbound HGV vehicle, movement of the goods to and from storage in case they are physically stored at a distribution center or warehouse). In case of indirect shipment via a warehouse, the transport costs include the costs of shipment from producing region *i* to warehouse in region *k* and the cost of shipment from region *k* to the consumption region *j*. In case of direct shipment, transport cost consists only of the transport cost from *i* to *j*. The formal definition of TLC is given in (9) and (10)

$$z_{i,j,l} = \frac{d_{i,j}c^{vkm}}{L^{PC}} \qquad \text{if chain } l \text{ is direct } (l=1) \tag{9}$$

$$z_{i,j,l} = \frac{d_{i,k}c^{vkm}}{L^{PD}} + \frac{d_{k,j}c^{vkm}}{L^{DC}} + c^{w} + A_k$$
if chain *l* includes warehouse in region *k* $(l \neq 1)$ (10)

Where $d_{k,j}$ is the distance between centroids of the regions *k* and *j*

c^{vkm} is the cost of vehicle-kilometer. It is a constant in the model

L^{PC} L^{PD} L^{DC} are the HGV loads in ton for production to consumption leg (direct shipment), production to distribution leg, distribution to consumption leg respectively. HGV load variables are model calibration parameters

c^{w} is the cost per ton of warehouse or distribution center throughput. The inventory holding cost c^{w} is the same for all regions; it is a model calibration parameter

A_k is the attractiveness of region *k* for distribution or warehousing activities. The attractiveness parameter is similar to the inventory holding cost c^{w}, but takes different values for different regions. It is a model calibration parameter expressed in Euros per ton of distribution throughput. The A_k attractiveness parameter includes explicit costs, such as region specific labor and property costs, and implicit costs that are hard to structure, but those that influence decisions in a quantifiable way. In the calibration procedure we ensured that the sum of A_k terms is close to 0 such that the term c^{w} represents the average inventory holding cost for all regions. The regional attractiveness parameter plays an important role in the studies on logistics sprawl: introducing changes into regional attractiveness through, for instance, policy measures, will change attractiveness of the region(s) for the distribution activities. Such a change can be modeled through scenarios and can be grounded on the basis of local taxes, ground rents and other measures.

The gravity model described in section 3.1 uses the cost friction factor $c_{i,j}$ in the form of generalized logistics cost per ton shipped between production region *i* and consumption region *j*. There are n + 1 ways to ship goods from *i* to *j* in the described logistics chain model. The friction factor $c_{i,j}$ is computed (11) as the sum of total logistics cost $z_{i,j,l}$ of the chain *l* multiplied by the probability that this chain is used $r_{i,j,l}$. Equation (11) make the gravity and logistics chain models consistent in the terms of costs used.

$$c_{i,j} = \sum_{l=1}^{n+1} r_{i,j,l}\, z_{i,j,l}, \forall i,j \tag{11}$$

The logistics chain model allows estimation of transport Origin-Destination OD table from the trade flow PC table. Let $f_{i,j}^{G}$ denote physical transport flow between regions *i* and *j* estimated by the chain model, measured in ton volumes. We distinguish between 3 types of transport flow, namely, $f_{i,j}^{G,PC}$ production-consumption flow: goods are loaded at production and delivered directly to consumption without intermediary stops at warehouses; $f_{i,j}^{G,PD}$ production-distribution flow: goods are loaded at production and delivered to intermediate stock or distribution locations; $f_{i,j}^{G,DC}$ distribution-consumption flow: goods are loaded at warehouses or distribution locations and delivered to consumption. Note that we use index *G* to indicate that the flow is estimated (generated) by the model; index *O* is used to show that the data is observed (based on transport survey).

$$f_{i,j}^{G,PC} = t_{i,j}\, r_{i,j,l\in direct\ shipment}, \forall i,j \tag{12}$$

$$f_{i,j}^{G,PD} = \sum_{k=1}^{n} (t_{i,k}\ \ r_{i,k,l\in DC\ in\ j}), \forall i,j \tag{13}$$

$$f_{i,j}^{G,DC} = \sum_{k=1}^{n} (t_{k,j}\ \ r_{i,k,l\in DC\ in\ i}), \forall i,j \tag{14}$$

$$f_{i,j}^{G} = f_{i,j}^{G,PC} + f_{i,j}^{G,PD} + f_{i,j}^{G,DC}, \forall i,j \tag{15}$$

4. Empirical application

The origins of the data used for the application are described in detail in (Davydenko 2011; Davydenko 2013). The input dataset is provided by the Dutch statistics bureau, Statistics Netherlands (CBS), and contains data for Heavy Goods Vehicle (HGV) movements in the Netherlands. The dataset is based on a survey sample and is aggregated to the annual volumes. It contains the following information

1. Year identifier of the flow
2. Loading region: Dutch NUTS3 region where the goods are loaded. The Netherlands is divided into 40 NUTS3 regions.
3. Loading location type, which can take one of the following 9 values: Production, Consumption, Sea Terminal, Rail Terminal, Airport, Inland Waterways Terminal, Entrepot, Distribution Facility or Warehouse, Other / Unknown.
4. Unloading region (similar to loading region)
5. Unloading location type (similar to loading location type)
6. Commodity transported according to the NSTR-2 commodity classification. NSTR-2 classification distinguishes 52 types of goods grouped into 10 chapters
7. Weight transported expressed as annual ton volume transported between the pair of loading and offloading regions, loaded and unloaded at the specified loading and offloading location types and of the specified commodity type

The uniqueness of the dataset used for the modeling purpose lies in that it provides data on loading and unloading location types. A loading-unloading location type pair specifies the purpose of the flow. For instance, goods loaded at production location type and unloaded at distribution location type represent PD (production-distribution) flow. Similarly, the regional production P_i and regional consumption C_j vectors have been constructed. P_i values are obtained as the sum of outgoing ton volumes from production location type in region i; C_j is the sum of incoming ton volumes into region j to the consumption and production (for further rework) location types. We consider some other location types as production: flows originating at the sea ports and terminals are also considered as production in the context of distribution modeling. On the consumption side, we treat production location as the consumption location because goods are used there for further rework (consumed for subsequent production)

A model calibration was performed minimizing the mean square error between observed interregional goods flow and estimated by the model goods flow (16). The observed interregional flow $f^{O}_{i,j}$ data come from the Dutch statistics bureau survey (see the list above on Data used). The calibration procedure finds such values of the model parameters that the mean square error between observed and generated by the model interregional flows is minimized.

$$\min \sqrt{\frac{1}{n}\frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{n}(f^{G}_{i,j} - f^{O}_{i,j})^2} \qquad (16)$$

The following variables were used as model calibration parameters: c^{w} (cost per ton of warehouse or distribution center ton throughput); vehicle loads for the three transport stages, L^{PC} L^{PD} L^{DC}; regional attractiveness A_k for the distribution or warehousing activities; logit sensitivity parameters α and α' in the chain model; gravity model sensitivity parameter β. The A_k can be interpreted as the centrality factor: distribution volumes in a region cannot be explained only by the costs of logistics chains, but there are other factors in play such as historical (legacy) industries, availability of labor and infrastructure, and other factors.

It should be noted that vehicle loads L^{PC} L^{PD} L^{DC} for the three transport stages can be seen as the proxy for transport costs on these transport stages. The model uses the constant vehicle-kilometer cost factor c^{vkm}; ton-kilometer costs are follow directly from the vehicle loads as L^{*} / c^{vkm}. Therefore, the model estimates vehicle loads and ton-kilometer costs at the same time. It should be further noticed that flows $f^{G}_{i,j}$ and $f^{O}_{i,j}$ in (16) are composite flows consisting of PC, PD and DC sub-flows (equations (12)-(15)). The model can be calibrated with respect to these constituting flows as well. As we discuss in the results section, an adjustment of the composition of the total flow $f_{i,j}$ can lead to a generally better model results.

We applied a single variable iterative optimization procedure. In each iteration step, the best value for each calibration variable is found. In the next iteration step, the variables are initiated with the best values from the previous step, while the search for the best value continues. The variable values stabilize after 4-6 iterations. Figure 2 presents calibration results carried out for all commodities grouped together, the observed data being for the period 2007-2009.

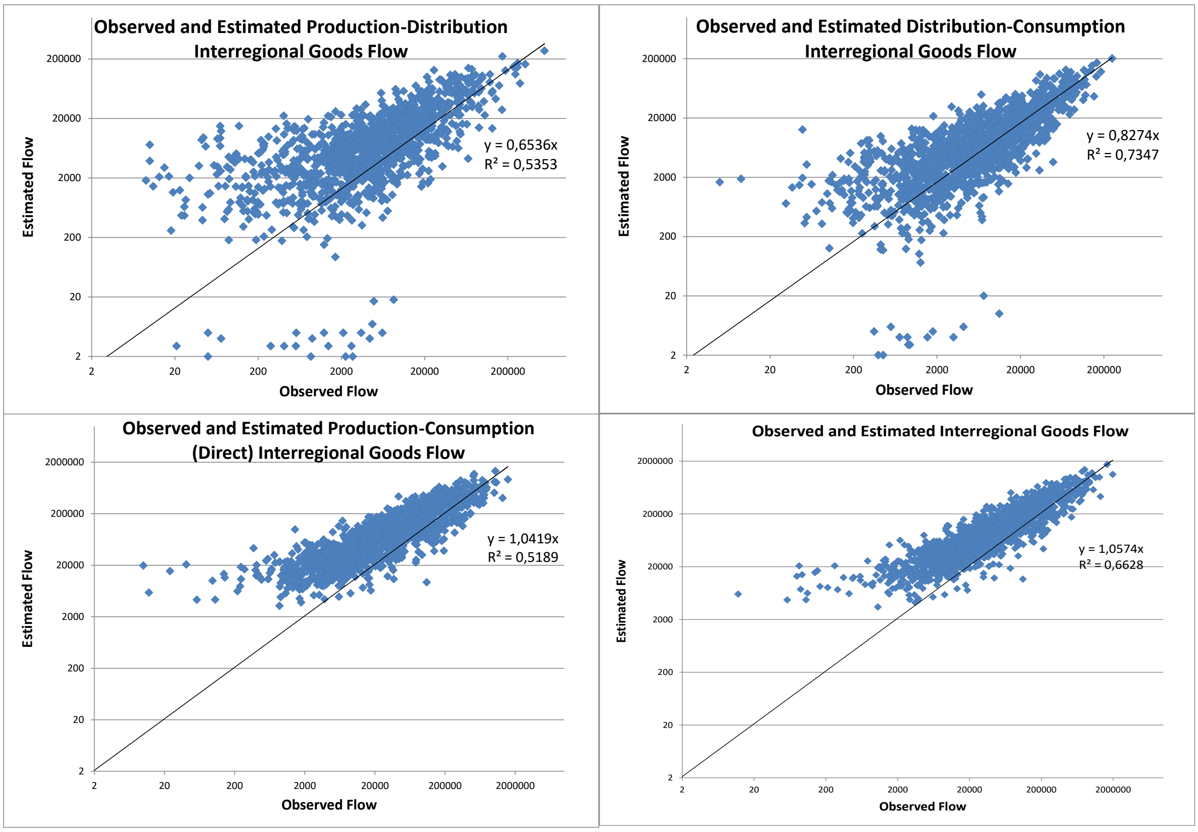

Figure 2. Comparison of estimated and observed flows in calibrated model

To demonstrate model performance at the regional level we also present an earlier published (Davydenko and Tavasszy, 2013) calibration result with respect to the annual regional warehouse throughput, Figure 3. The annual warehouse throughput is computed as the sum of all incoming and outgoing ton volumes through distribution facility per NUTS3 region. At this level the model shows an accurate (R^2 = 0,947) representation of the observed regional distribution volumes

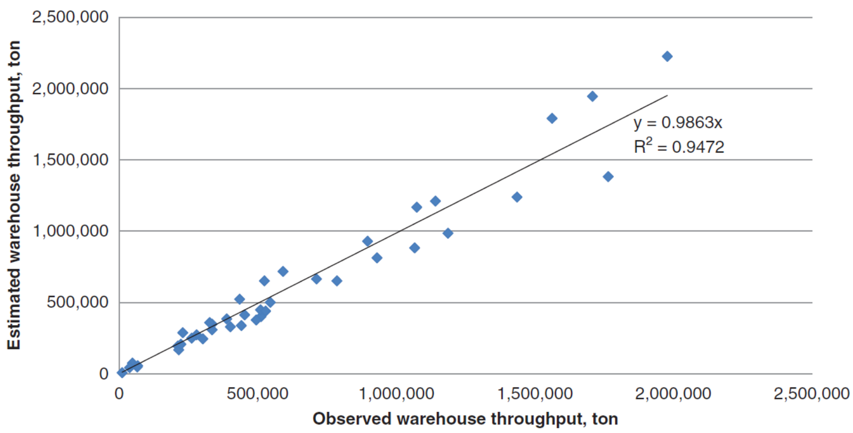

Figure 3. Comparison of estimated and observed warehouse flows per region

The model calibration has been performed according to equation (16), minimizing differences between observed and estimated flow. In the calibration, the following model parameters were estimated:

1. Transport costs and average transport loads for each of the three transport types, i.e. P2D,

P2C and D2C

2. Warehouse costs per ton of throughput
3. Model sensitivity parameters: gravity model sensitivity parameter (equation 1), top choice logit sensitivity parameter (equation 5) and nested logit sensitivity parameter (equation 8).
4. Regional distribution attractiveness parameters (equation 8) for each of the 40 regions.

In total, the model has 47 parameters. The observed and estimated flows have 40x40 = 1 600 relations. Taking into account the fact that the model was estimated on the OD flows, we conclude that it performs well with respect to estimation of the regional warehouse throughput.

In the next section, we describe the application of the model to assess the effect of cost changes on distribution structures, including the resulting regional activities and freight flows.

5. Sensitivity of distribution structures

5.1 Scenarios

The Netherlands is a relatively small country with a high population density of 404 people per km^2 (CBS 2013). The Randstad region of the Netherlands is a large urbanized area, comparable to areas such as greater Los Angeles. The Randstad region occupies approximately 20% of the total country's area and has a population density of 1170 person per km^2. The Ports of Rotterdam and Amsterdam and Schiphol Airport are located in the region. Figure 4 shows the map of the Netherlands with the Randstad region painted in the violet color and the rest of the country in green color.

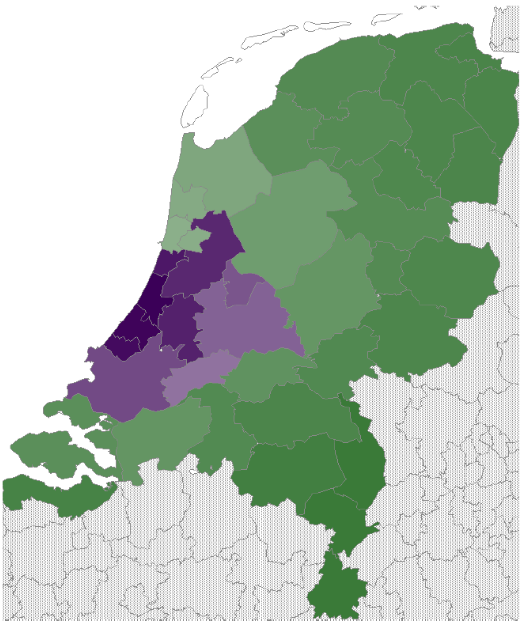

Figure 4. Randstad region (violet) of the Netherlands

The Randstad region plays an important role in logistics and distribution. It hosts about a third of the total Dutch logistics surface area of 35 million m^2 (NVM, 2021) for close to 2000 distribution centers. Besides the importance of the Randstad as point of gravity for national distribution it also has many warehouses with a continental gateway function. In the context of our case study, we speak of a centralization of logistics activities if the share of Randstad in total logistics activities increases, based on the measure of annual ton volumes of goods flowing through logistics facilities there. From a policy perspective, it can be considered desirable to predict or even influence the volume of distribution and warehousing industries in specific regions. The logistics chain model presented above provides a way to estimate the effects of various policy options and what-if scenarios. The variables in the model such as transport and warehousing costs, as well as regional attractiveness, reflect current reality in the Dutch distribution and warehousing industrial sector. Adjusting these parameters scenario-wise allows to gain an insight into the changes in distribution system that would be observed in reality if underlying factors change. As we are especially interested in the position of the Randstad area vis-a-vis the surrounding regions, we consider the following scenarios:

1. *Current situation*. It is the base scenario that is equal to the outcome of the calibrated model. All other scenarios are compared to the current situation scenario.
2. *Push towards centralization*. As a policy measure, a push towards centralization can be realized by an increase in attractiveness of the Randstad region or decrease in attractiveness of non-Randstad regions. In practice, it can be realized through local tax incentives, regulations on land prices and other measures. Given the estimated distribution costs C^W of 9,2 Euro per ton of throughput, an increase or decrease of regional attractiveness parameter A_k (equation 10) by 1 Euro represents a change in distribution costs by some 11%. Note that parameter A_k represents extra costs related to distribution in a region. Negative parameter values increase attractiveness of the region and positive values decrease attractiveness. Therefore, an increase in value of this parameter decreases attractiveness of the region *k*, and conversely, a decrease in value of the parameter increases attractiveness of the region *k* for the distribution activities.
    a. *Increase in attractiveness of the Randstad region*. This policy measure is realized by a reduction of A_k values by 1 Euro per ton unit of throughput, where index *k* belongs to the Randstad set of regions.
    b. *Decrease in attractiveness of the non-Randstad regions*. This policy measure is realized by an increase of A_k values by 1 Euro per ton unit of throughput, where index *k* belongs to the non-Randstad set of regions.
3. *Push towards decentralization*. Similarly to the scenario's 2a and 2b, the decentralization is realized by a change in the regional attractiveness parameter A_k (equation 10).
    a. *Decrease in attractiveness of the Randstad region.* Parameter A_k is increased by 1 Euro per ton of throughput for the regions belonging to Randstad.
    b. *Increase in attractiveness of the non-Randstad regions*. Parameter A_k is decreased by 1 Euro per ton of throughput for the regions belonging to the non-Randstad set of regions.
4. *Increased road transport costs*. A change in transport costs will have an effect on spatial organization of the logistics and distribution systems. Transport costs per ton-kilometer unit are decision variables in the model (equation 9 and 10) and are computed as the ratio $\frac{c^{vkm}}{L}$, where the nominator is a fixed constant of vehicle-kilometer Euro costs and the denominator is the vehicle load, which is estimated by the model for the three types of flow, namely L^{PD}, L^{CD}, and L^{DC}. For the scenario on increased transport costs, we consider two sub-scenario's.
    a. *Increase in transport costs and constant loads.* In this scenario, we consider an increase of vehicle-kilometer c^{vkm} cost by 10%. Vehicle loads L^{PD}, L^{CD}, and L^{DC} are left unchanged. This scenario does not take into account a possible reaction of the distribution systems with respect to vehicle loads. Hence, the ton-kilometer costs

are implicitly increased by 10%.

b. *Increase in transport costs and increase in production to distribution average load L^{PD}.* In this scenario, the vehicle-kilometer cost c^{vkm} in increased by 10%, as in the scenario 4a. However, this scenario assumes a possible reaction of the distribution to the increased transport costs through an increase in production to distribution loads L^{PD} of 5%. The vehicle loads related to transport to the customers (L^{PC} and L^{DC}) are assumed to remain the same, as we expect that delivery frequencies and hence batch sizes and loads would remain the same due to customer requirements and service agreements.. This implies that ton-kilometer transport costs are increased by 5% for the PD flows and by 10% for the PC and DC flows. This scenario reflects a probable reaction of the logistics and distribution systems to an increase in transport costs.

5.2 Scenario outcomes

To understand the different dimensions of the scenarios, the following outputs are considered:

1. Annual regional distribution volumes, expressed in ton of warehouse of distribution center throughput. These volumes are measured at the NUTS3 level: the Netherlands is divided into 40 regions of which 10 belong to Randstad. The changes in regional distribution volumes for Randstad and non-Randstad regions are presented.
2. Country level number of ton-kilometers and vehicle-kilometers. These are further split into three transport legs, namely from production to distribution (PD), from production to consumption (PC), and from distribution to consumption (DC). An interregional distance table, which shows distances between region centroids, is used to compute these parameters, conform equation 9 and 10, as the distances are also used for transport cost calculations.

Table 1 presents main scenario outcomes in % changes compared to the base case.

Table 1. Changes in distribution throughput and transport

	Distribution volume (ton)		Transport performance (tonkm)			
Scenario	Randstad	Non-Randstad	P-D	P-C	D-C	total
Centralization 2a	16,1%	-0,4%	4,6%	-0,6%	4,7%	0,1%
Centralization 2b	1,2%	-13,4%	-8,9%	1,2%	-8,8%	-0,2%
Decentralization 3a	-13,7%	0,6%	-3,7%	0,5%	-3,8%	-0,1%
Decentralization 3b	-0,9%	15,6%	10,4%	-1,4%	10,4%	0,3%
Increased transport costs 4a	-0,8%	-1,0%	-3,4%	-3,1%	-3,9%	-3,1%
Increased transport costs 4b	5,5%	6,2%	7,4%	-4,2%	2,1%	-3,4%

The regional distribution volumes can be influenced by the distribution throughput costs. Scenario 2a shows that a decrease of distribution-related costs by 1 Euro per ton of throughput, which represents some 11% of the distribution cost, leads to an increase of Randstad distribution volumes by 16,1%, while taking only some 0,4% of the volumes of the non-Randstad regions. A more attractive distribution in the Randstad region leads in this scenario to a shift from direct shipments to shipments via distribution in Randstad. Scenario 2b, where the costs of non-Randstad distribution are increased by the same amount leads to a decrease of non-Randstad volumes by 13,4% and some spillover effect to the Randstad regions and increased number of direct shipments. Similarly, an increase in the costs of distribution in Randstad (Scenario 3a) leads to a decrease of 13,7% of the volumes and spillover to non-Randstad regions of 0,6%. Scenario 3b shows an increase of non-Randstad volumes by 15,6% in case if distribution there becomes cheaper. Overall, this points out to a relatively high sensitivity of logistics activities in regions to the throughput costs: a cost change of some 11% (i.e. as a result of facility throughput cost rise from 9,2 Euro per ton to 10,2 Euro per ton) leads to a corresponding change in the regional distribution volumes of -13,4% in the affected regions, implying price elasticity of logistics activities of more than -1.

Three observations can be made considering scenarios 2 and 3. First is that regional distribution volumes can be influenced by the costs of the distribution throughput. The system shows a substantial elasticity in this respect: a change of distribution costs of 11% results in volume changes in the range of 13-16%. Second is that spillover effect to other regions is relatively small, between 2,3% (Scenario 2a) and 8,9% (Scenario 2b). The main volume changes are happening in those regions where distribution costs are adjusted. Third, scenarios 2 and 3 have only a small effect (-0,2% to 0,3%) on the total number of ton-kilometers and vehicle-kilometers, however, constituting flows via logistics facilities (PD and DC flows) are influenced much more substantially, between -8,8% and 10,4%.

The transport costs increase of Scenario 4 leads to substantially smaller transport volumes, showing implied negative transport cost elasticity in the range of -0,335 and -0,292. The model shows that under assumption of constant vehicle loads (Scenario 4a), an increased transport costs leads to slightly smaller distribution volumes for Randstad and non-Randstad regions. This phenomenon is explained by the fact that some chains via distribution centers are more expensive than direct ones in the model equation (10). The transport price increase makes these chains via distribution facilities relatively more expensive. However, if it is assumed that logistics systems react to higher transport costs with bigger loads going to the distribution centers (Scenario 4b), the system reacts with an increase in distribution volumes of around 6%. It can also be observed that non-Randstad regions show a somewhat stronger link between transport costs and distribution volumes.

5.3 Discussion

Our first general observation relates to the sensitivity of indirect distribution to distribution cost changes. The cost elasticity implied lies in the range of -1,2 to -1,5. Distribution center volumes are therefore found to be very responsive to local factors such as land rents, labor costs and also interest. There are no comparable figures in the literature that we could confront these numbers with and comparisons with new cases would therefore be interesting. This result can be useful for spatial planners to estimate expected regional changes in distribution activities as it explains how local activities could respond to local cost changes.

It is also surprising to note that, despite the clear symmetry in the input values for the scenarios, this symmetry does not reappear in the resulting flows – be it in relation to the directionality of the cost change (comparing e.g. scenario 2a with 3a), as well as spatially (e.g. 2a vs 3b). If we look at this asymmetry more closely, the net result of fluctuations in costs over time would be a slight but significant movement of activities towards the urban center. One possible interpretation of this phenomenon is the effect of sunk costs or economies of scale present in the system. Research into the historical dynamics of changes in spatial flow patterns in relation to cost changes could provide an additional empirical basis for this finding.

A change in transport costs also leads to an effect on the total distribution volumes. Companies flee into inventory by increasing their transport at the cost of inventory, or the reverse, depending on the direction of the cost incentive. The effect on distribution volumes depends on the reaction of the logistics systems: if it leads to bigger production-distribution loads, then the regional distribution volumes also increase. The volumes outside of the Randstad region in this case increase faster than in Randstad, therefore, increased transport costs lead to the spread of distribution centers outside of Randstad. The system reacts to the higher overall transport costs with a smaller volume of transport. Both ton-kilometer and vehicle kilometer measures show road transport cost elasticity of around -0,3. This is a new finding for own elasticities of road transport flows for cost changes, as an addition to current knowledge of own elasticities based on mode choice and possibly of spatial interaction in freight transport (de Jong et al, 2010). In the literature, overall transport elasticities of road volumes (tonkm) to costs were found to lie around -1, without considering the effect of changes in distribution structures as discussed here. The inclusion of this effect is not trivial, however – it cannot be just added to the existing numbers as they are not independent. As companies flee into inventory, total cost increases will be mitigated and the propagation of the cost impact into other decisions, such as the mode of transport, will be much reduced. Follow-up research, which studies these models together, could shed more light on this important issue for policy makers.

In addition to these volume effects, the spatial re-distribution effects identified may result in much higher changes in freight traffic at a local level, i.e. relatively small spatial re-distributions at the macro level may result in significant changes in the flow at the micro level (i.e. the level of road infrastructure). One can already observe this pattern with the orders of magnitude difference between system-level impacts (order of 0,1) and subsystem impact (order of 1 for segments of the chain and order of 10 for Randstad/non-Randstad). These shifts cannot be observed if these segments are not modelled explicitly and it underlines the importance of addressing distribution structures in freight transport models. We argue that this specific result, reached from a regional economic modeling perspective, is of particular relevance for the study of logistics sprawl. Also, it can provide important inputs to investment plans and cost-benefit analyses of infrastructure projects. With this new type of model, tools are available that allow regional authorities to anticipate on the effects of future changes in transport costs. Both increases in transport costs (due to e.g. carbon pricing and congestion) as well as reductions (due to vehicle automation) are conceivable and will influence the volumes and locations of logistics activities. The model allows to make a first estimate of these impacts on regions.

6. Conclusions

Understanding possible future patterns of distribution facilities is important for effective regional policies concerning spatial development, social policy, transport and infrastructure investments as well as for the environmental consequences in these densely populated areas. Our study demonstrates that a logistics chain model based on an aggregate logit choice model can be applied, in an empirically valid way, to explore possible future directions of logistics sprawl. We apply the model to study the impact of regional and transport policies, to find that the distribution activities are elastic to local changes: a 1% decrease in costs will lead to a >1% increase in activities. Despite the fact that transport flows are inelastic to transport costs (between -1 and 0), the elasticity is in the same order of magnitude as existing cost elasticity values for road freight transport. This implies that the effect is significant, in comparison to the other known responses to cost change, through e.g. mode shift.

It should be noted that the logistics chain model presented in this paper is a macro model, limiting its applications to the questions at the regional level. Specific situation and specific locations is taken into account explicitly, with an impact at the aggregated regional level. Traffic congestion on specific infrastructure links, differentiation in stock policies of various product groups and other detailed inputs need to be taken into account at the aggregate level. This suggests a need for additional steps in freight modelling research, including the incorporation of higher resolution spatial and commodity flow data into the modelling. Vehicle telematics data, automated surveying and data collection methods present a rich opportunity to for further research. In addition, the fact that the Randstad region is a polycentric region presents a further research opportunity to study the sprawl with a higher level of spatial granularity. Likewise, the logistics chain model can be extended with environmental functionality resulting in estimations on various airborne emissions of transport, related to scenario outcomes.

The reality of fast innovation in the logistics sector, specifically related to last mile deliveries, such as instant deliveries to the customers, evening hour deliveries and omni-channel distribution all provide inspirational cases for further research and model development. The model presented here allows assessment of these developments through the change in transport costs, as for instance, speedier deliveries would result in smaller shipment sizes, and hence, higher ton-kilometer transport costs. The ton-kilometer cost of DC flows is a model parameter and can be adjusted accordingly to assess the effect of the sector's innovations on the spatial organization of logistics facilities. However, as other factors, like information availability, reliability and flexibility, are playing an increasingly important role, the service components of these models should be strengthened. Encouraged by appearance of new data sources and operational data of logistics operators, we see new research opportunities in enriching the model capabilities further in these directions.

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