INCORPORATING LOGISTICS IN FREIGHT TRANSPORTATION MODELS: STATE OF THE ART AND RESEARCH OPPORTUNITIES

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ABSTRACT

When observing the freight transport system we see that changes in production, trade, inventories and transportation are all driven by logistics principles. At the same time, our freight models are not yet ready to predict the effects of the major changes that will take place in logistics systems in the future. In this paper we review the recent freight modelling literature and develop a research agenda for freight models, which incorporates two dimensions of logistics performance: service quality and costs. We discuss the main determinants that shape logistics networks according to these two dimensions and discuss alternatives for modelling changes in freight transport demand, using spatial equilibrium models, explicit choice models and hypernetwork models. Each of these categories has its own stream of research studies, that has largely developed in separation from each other and use a variety of modelling methods and data sources. We evaluate these approaches with respect to their possibilities to describe the integrated logistics networks of the future. We conclude the paper with a discussion of possible paths in freight modeling research towards integrating these two lines of thinking.

Keywords: freight transport modeling, logistics, supply chain management, spatial equilibrium modeling, hypernetworks

1. INTRODUCTION

The development of the economies all over the World is depending on the production and consumption of products and services. Both the supply and demand of products rely, among other aspects, on the accessibility of countries and regions. The relaxation of trade barriers since the Second World War has given a great stimulus to the development of World Trade (Rodrigue, 2006 a,b), but also the decrease of transport costs in real terms as well as the reduction of total logistics costs have contributed to this phenomenon in a significant way. The development of world trade is directly linked to the demand for international freight transport, maritime transport and air freight in particular. Although the share of transport costs in total logistic costs for expensive products is much less than for low value bulk products, also for these products considerable cost savings have been reached, both because of economies of scale and improved supply chain management. In the future, ongoing changes can be expected due to a further rationalization of supply chains and sustained international growth. In this paper we will describe each of these phenomena in more detail and with a systems perspective.

In order to obtain insight into the future development of freight flows, freight transportation demand models are needed. Traditionally these were organized around the principles of passenger transport modelling. Despite the fact that changes in freight transportation are all driven by logistics principles, most current freight models are not able to predict the effects of changes that will take place in logistics systems in the future (Tavasszy, 2008). Our main objective, therefore, is to develop a research agenda for freight demand modelling, incorporating the key dimensions of logistics performance.

The paper is organized as follows. First we discuss the service dimension of logistics service and its relationship with integrated logistic cost. This integrated logistic cost concept is an extension of the concept normally used in modelling international trade and freight transport, because it also takes into account the costs incurred due to unreliable demand and supply, the costs of passing boundaries (including administrative burdens) as well as the possibilities to create cost reductions through efficient logistics using economies of scale and hybrid networks. In the second part of this paper the utilization of this extended generalized cost concept in freight demand modelling is described in a conceptual way. We discuss alternatives for modelling using spatial equilibrium models, explicit choice models and hypernetwork models. We evaluate these approaches with respect to their possibilities to describe the integrated logistics networks of the future. We conclude the paper with a discussion of possible paths in freight modeling research towards integrating these two lines of thinking.

2. THE EVOLUTION OF LOGISTICS SERVICES

Service quality acts as a driver for changes in freight transport through the consumer-oriented evolution of logistics networks. Mass production systems that have evolved over centuries are being replaced by responsive systems that produce customized goods. Logistics and transport services support this development by new supply chain architectures. JIT systems were only a brief stage in the development of transportation-inventory systems -- in the future, logistics and transport will be much more tightly integrated with production systems. Complex trading networks have evolved primarily to exploit labour cost differences, regional production specialization, global product differentiation opportunities and availability of raw materials in particular countries. Their development has also been facilitated by major regulatory and technological trends. Trade liberalisation, particularly within trading blocks such as the EU and NAFTA, has removed constraints on cross-border movement and has reduced related ‘barrier costs’. Advances in telecommunications and information technology have given companies the means to manage the physical movement of products over long, often circuitous, routes. Many carriers have invested heavily in ‘track and trace’ systems to be able to establish the location of any consignment at any time, improving the visibility of the global supply chain to shippers and their customers (see HIDC, 1998). The way in which individual trends manifest themselves varies according to the geographical scale at which companies and markets are operating. In this section we explore two main drivers of these changes: mass individualization and globalization.

Mass individualisation

Since the middle of the previous century there has been an increase in product variety, up to the level of single product or service units being individualized and unique. Eventually, this will go hand in hand with an improvement of lead times to the extent that customized products have the same responsiveness as standardized products have now. How do these trends in logistics concepts translate into the spatial economy? What is the implication of long term changes in logistical structures upon economic growth and economic development at various spatial levels (local, regional, continental and global)? Figure 1 shows two main drivers for new service requirements for production and distribution systems.

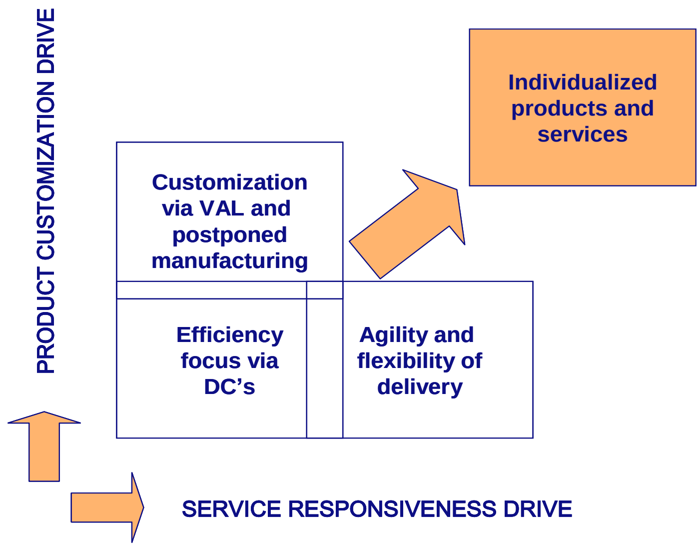


Figure 1. Drivers of change in logistics structures (adapted from Vermunt et al, 2000)

Expected changes in logistics structures

Logistics structures will vary according to the degree of customization and the degree of responsiveness required (see Vermunt et al, 2000 and Lee, 2001). In each of the four product segments denoted in the quadrants of figure 1, different chain configurations will be deployed to satisfy product and service demand. Typical variations between segments concern the move from European distribution, based on production to stock, towards production to order at a global scale, where delivery takes place directly or through cross-docking. Also new concepts like rapid fulfilment depots (for low demand but urgent products like spare parts) and flexible order production (allowing fast switching in batch size and end-product specifications) are being introduced to allow for better responsiveness. The more individualised products are the more these activities will be located closely to consumer markets. Centralized international distribution, introduced to reduce inventory and building on the decrease of trade barriers, is being supplemented by regional distribution centres, to create hybrid networks. Depending on the segmentation of demand in slow- and fastmovers, goods can move through different channels in parallel.

There is one variable however that requires special attention and that is the level of reliability of the supply. Congestion, lack of adequate planning and sudden events (earthquakes, strikes) can have a strong impact on the reliability of supply chains and ask for resilience strategies (Sheffi, 2005). So not only demand segmentation influences logistics structures, also uncertainties in supply play an important role.

Through the use of hybrid networks a flexible way of quickly adapting from one supply source to another can be created as is clarified in Figure 2. The volatile part of the demand is supplied by a fast (and more expensive) network, while the stable part of demand is being delivered through the slow but cheap hub network that makes maximum use of economies of scale.

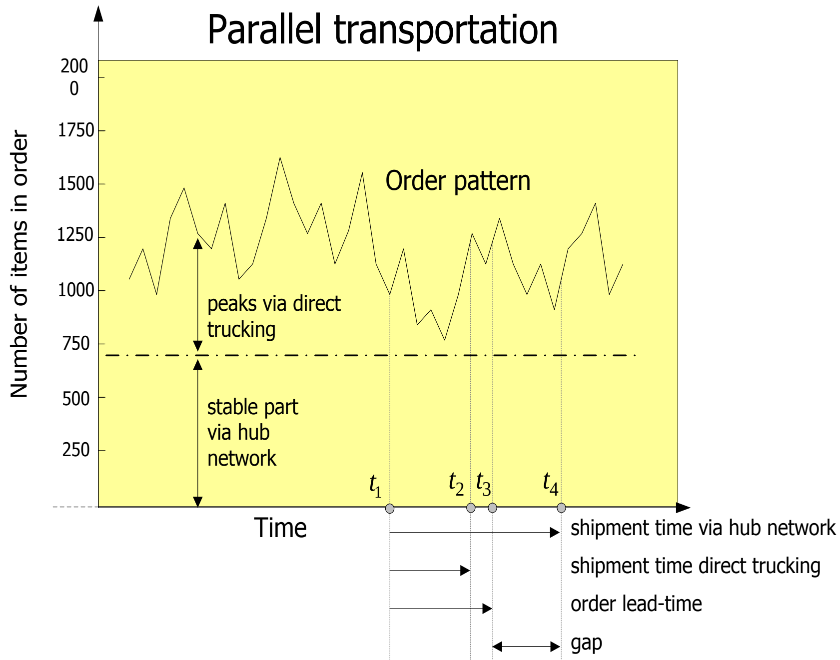


Figure 2. Being responsive by combining different networks (Groothedde, 2005)

Evolution of networks through time

These hybrid networks form the latest stage of evolution of firms' logistics capabilities, in their search for improved services and simultaneous cost reductions (see figure 3). The first wave of change took place in the 90's and involved the reduction of shipment sizes, an increase in frequencies and Just-In-Time transport, as a first sign of mass individualization. This wave of fragmentation was followed by a wave of internal rationalization of flows through the turn of the century. Firms are now seeking economies by collaboration across company boundaries and horizontal collaboration is seen as one of the transformational innovations which will change the logistics business landscape in the coming years (see e.g. Gartner, 2005 and Mason et al, 2007).

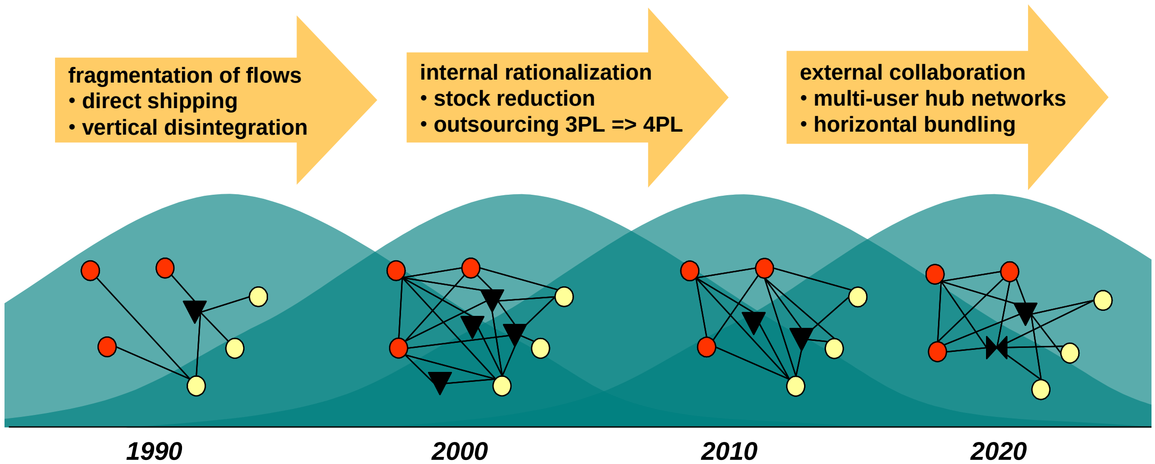


Figure 3. Evolution of logistics networks through time (source: own composition). The red dots (top, left) indicate suppliers, the yellow (right, bottom) indicate consumers, and the black figures warehouses (triangle) and cross-dock locations.

The description of these logistics structures requires a modelling of variables that are not part of a standard freight model, but essential to explain and explore the forming of supply chain configurations. These include

- Service variables such as order lead time, delivery frequency and shipment sizes
- Inventories and their spatial distribution (at production and sales sites, at intermediate depots and in the transportation pipeline) and volume
- Production variables such as batch size.

For freight models an important notion is that the spatial relations in trade are often not the same as transport relations, due to intermediate storage of goods (without being labelled for destination). In other words, as distribution structures are becoming more fragmented and assume more and more different shapes, the standard assumption in freight models that trade relations are the same as the origins and destination pairs for shipments, becomes less and less valid.

Globalization

Another important trend which has been driven in part by changes in logistics costs is globalization. The globalization of the world economy has emerged from a period with a high degree of protection and isolation towards the present state that is characterized mainly by free trade.

One of the main drivers behind this growth of international trade has been the differences in cost of producing the same type of product in different places of the world, which are due to difference in factor costs and availability of natural resources. Together with the cost of overcoming the distance one can determine whether it is more attractive to import the products from elsewhere and to carry the burden of transporting goods over large distances, or to avoid the costs involved in transporting these goods and produce them locally. Both the organization of production and transport economies of scale play an important role in the choice of production and sourcing solutions.

A well known example is the production of automobiles. In general one can say that the assembly of automobiles takes place not too far from the final customer, but some of the parts are produced by assembly plants that distribute their products to worldwide spread customers. The location of production plants normally is a long term investment decision, and thus the geographic spread of production patterns used to be rather stable over time. Nowadays, as a result of the economic crisis, the location of factories is re-evaluated and those that are not ideally located or do have a lack of governmental support are under the threat of being closed down. Assembly plants, however, are more footloose and their location can change, influenced by regulatory measures (subsidies, regulation on the share of local content), the relative importance of transport costs in the cost of final products, congestion and other capacity restrictions (Dicken, 2003). Sometimes, logistics reorganisation leads to new configurations in which scale economies are used more efficiently (ie the focused factory approach introduced by Unilever following the theory already developed in the early 70's by Skinner (1974)).

The developments described in this section summarize the main structural and geographical changes that we can expect in supply chains worldwide. In the next section we look into the behavioural drivers that determine these changes. We introduce the generalized logistics costs concept, describe some existing applications in freight modelling and propose some extensions, to allow an explanation of logistics phenomena described above.

3. THE GENERALIZED LOGISTICS COSTS CONCEPT

When we try to explain the worldwide flows of goods and trade patterns, the main explanatory variables are the GDP on both sides of the relation, the amount of population and potential customers, as well as the distance of the relation under research. However, when these main drivers are used to explain international trade in gravity type models, it appears that some structural over- and underestimating takes place, due to the fact that the regulatory frameworks and logistics organisation have a large impact on the possibilities to realize trade if the potential for that trade does exist.

Hausman et al (2004) have extended the traditional gravity type model with indicators that describe the attractiveness of establishing bilateral trade, given the volume of consumption and production on both sides of the relation and also given the distance to be covered to transport the products. These indicators involve the time indicators (also including hinterland transport to and from the main ports), costs (including product cost, transport (shipping) cost, and especially emphasize the effect of total cost of trade document procedures and border control cost and inventory cost) and indicators related to risk factors caused by as the complexity of customs documents and the frequency of services between ports). They have estimated a gravity model to test the relative importance of these variables and found that the indicators reflecting the logistics efficiency have an important explanatory power to explain the variations in international trade. Also they use this fact to stress the importance of logistic efficiency and the importance of avoiding cumbersome procedures that hamper reliable deliveries. Earlier, Hummels has performed an analysis that shows that each day of increased ocean transit time between two countries reduces the probability of trade by 1 percent (all goods) to 1.5 percent (manufactured products) (Hummels, 2001).

Starting from the results of Hummels and Hausman et al. the definition of logistics cost can be extended to achieve even more accuracy in the explanatory power of our freight transport models and SCGE models that describe word trade relations. The research implications are that the gravity model with a single generalized logistics cost function can be applied to determine trade flow between world regions. The model does not attempt to explain the interaction between trade and prices and volumes of production and consumption. This is the role of the LUTI (Land Use/Transport Interaction models) and SCGE (Spatial Computable General Equilibrium) models (see Oosterhaven et al, 2004 for a comparison of the two types of model). We return to this class of models later in the paper.

To extend the concept of Generalized Logistics Cost requires including variables that try to capture the effects of economies of scale and the impact of improved transparency, because it is recognized that these are important variables to include in the analysis (van Nunen et al, 2008). Also McCann (2004) has already indicated that reliability, transparency and frequency have an important impact on the necessary levels of safety stocks and should be included in the analysis. Other important cost components of a realistic integrated cost concept are:

1. pipeline costs (including inventory costs for products in the pipe line)
2. value density (***vd*** = ***V*** / ***Vol*** in m3), where ***V*** stands for value: for products with a higher value density inventory costs are more important than for other products
3. shipment size ***P*** : the higher the shipment size the lower the transport and handling cost per unit
4. frequency ***f*** : higher frequencies lead to lower waiting costs, and therefore more reliable lead times, lower safety stocks and also to network synergies
5. variance in demand, the higher this variance is, the higher is the demand for responsive and therefore expensive services that can meet this demand, or require to bear bigger amounts of stocks: if the demand is stable it can be can be forecasted accurately and goods can be shipped far before the actual demand is realized, while using a cheaper mode of transport.

The definition of Generalized Logistic Costs we propose that takes into account all of the drivers mentioned above for product i out of the set of all products, is:

$$C_i = I_i + H_i + T_i \text{ , } i = 1, \dots , I$$

$$I_i = I_i^{safety} + I_i^{pipeline}$$

$I_i^{safety} = f\,(\boldsymbol{f}, \boldsymbol{o}, \sigma^{demand}, \sigma^{supplyl})$

$\boldsymbol{f}$ = frequency
$\boldsymbol{o}$ = order size,
σ^{demand} = standard deviation of demand
σ^{supply} = standard deviation of supply

$I_i^{pipeline} = f\,(\boldsymbol{TT}, \boldsymbol{r}, \boldsymbol{V})$

$\boldsymbol{TT}$ = Transport time,
$\boldsymbol{r}$ = interest rate also reflecting the risk for obsolescence of unsold products,
$\boldsymbol{V}$ = value of goods transported

H_i = handling costs (depending on the packaging density ***pd***):
pd = # colli per m3)

T_i = transport costs = f (***d, P, f, vd, m, s, b***)
d = distance ,
P = shipment size

f = frequency = ***Vol*** / ***o*** , though reverse relationship, when frequency is a function of the order size, might also be true
vd = value density,
m = mode
s = speed (depending on the mode of transport)
b = reliability of the mode used:

We assume that rational supply chain managers try to minimize their logistic costs while maintaining a certain service level that is required for their customers. These service levels are very much correlated with the value density of the products involved (Christopher, 1992, Simchi-Levi et al, 2000) so the supply chain optimization problem can be reduced to a generalized cost minimization problem per product type. This optimization problem involves the choice of production and storage locations, the frequency of replenishment shipments, the choice of mode and the inventory policy used. In many cases the mode choice decision is not a free choice, and normal choice models that assume an extensive set of alternatives cannot be used. We propose to use generalized cost curves that take into account the most likely choice for mode of transport.

Lammers et al (2006) found that 95% of the transport mode choice is determined by the product characteristics and the 'as the crow flies' distance, that for most transport flows are given and cannot be influenced. In Figure 4 below the shipment sizes and transport costs of some modes of transport are visualized. From this picture it becomes clear that huge differences between the respective modes of transport exist, both in shipment size and in average transport charges.

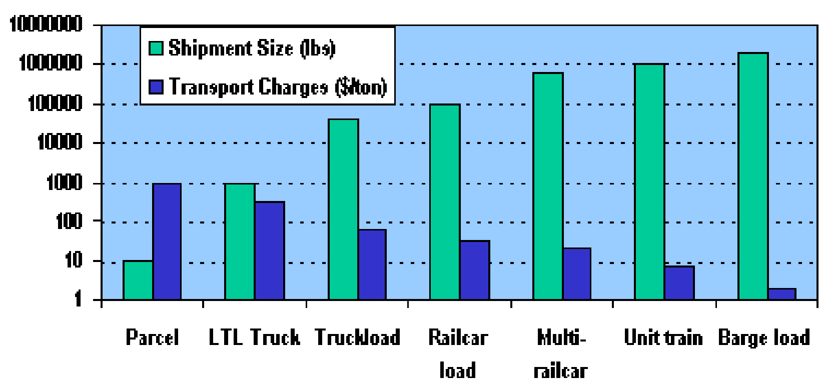


Figure 4. Differences in shipment size and transport charges for different modes of transport (source: Rodrigue 2006a)

Because of these large differences and the limited choice flexibility, it is possible, given a limited number of exogenous factors, to specify an a-modal or mode abstract generalized logistics cost function, such as the one visualized in Figure 5 below:

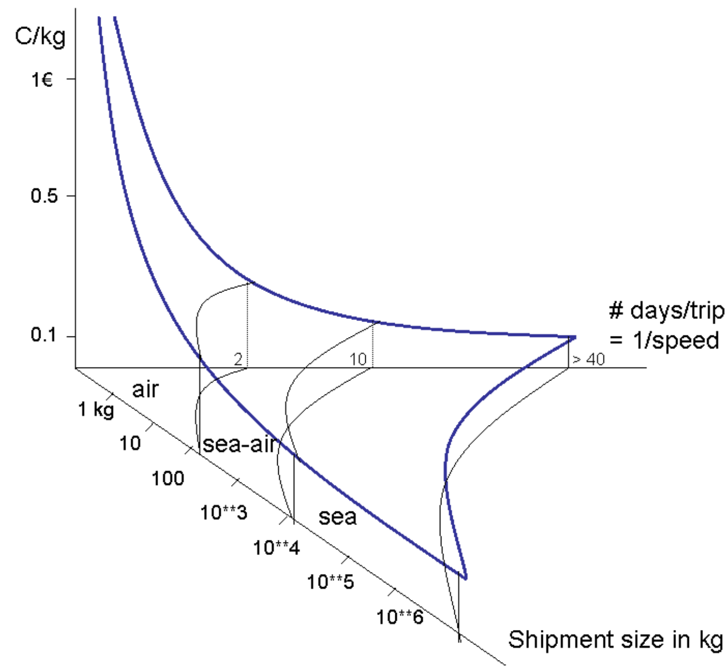


Figure 5. Transport cost per unit, as a function of speed (distance per time unit) and shipment size

This figure shows the areas for which the modes (air, road and sea transport) are dominant ones. By specifying the weight of the shipment and the required speed the mode choice and the transport cost per unit can be derived easily, if all modes are available. 100.000 tons of crude oil are transported by ship, a box of diamonds is shipped by air, unless the distance is less then 1000 km's, when road transport or express parcel transport will be used. There will be no discussions on the mode choice decision in these circumstances, at least in densely populated developed economies, where all abovementioned modes of transport are present and the speed requirements of the shipments do not restrict the choice options dominantly.

Besides shipment size and speed there are 2 other determining factors that really do have a strong influence on the modal choice and other logistic decisions, and that is the value density of the product and the level of demand uncertainty. When taking into account the value of the product and the volatility of demand also the effect of inventory costs via increased safety stocks and the effect of pipeline costs can be visualized, as is done in Figure 6.

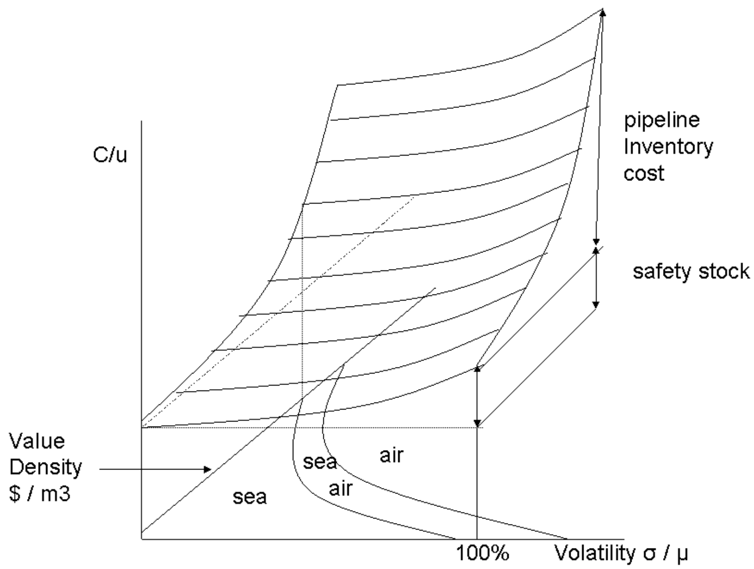


Figure 6. Logistics cost per unit as a function of value density (value per m3) and volatility (standard deviation of demand/ mean demand)

When the value density is low, pipeline costs (the inventory costs during transport) will be negligible. When the value density becomes larger, the pipeline cost becomes significant. For instance, in case of a shipment of 1 container with 1000 laptops (20 pallets of 50 laptops) with a production value of $500 per laptop, each container will have a pipeline cost of $5000 for a trip of 36 days and a capital cost of 10%. The average transport rate of this container from Asia to Europe is $ 1500, so the pipeline cost for this shipment will exceed the sea transport cost with a factor 3 and this integrated costs would be roughly the same when these products would have used the air mode (3kgs per laptop at 2$ per kg). So, although transport costs differ a lot per mode of transport; generalized costs show less variation, taking into account other logistic cost factors. When the volatility is high, retailers and distributors do need safety stocks in order to avoid empty shelves if the demand for a product is higher then the stock and the demand during the reorder period. Safety stocks can be avoided for a great deal if fast and reliable transport options exist that can guarantee the delivery of products within the customer service requirements. So, trade offs exist between inventory costs and transport costs and the Generalized cost concept should take these trade offs into account.

Thus it can be concluded, that by taking into account a few important product and demand characteristics, a large variation in generalized logistics cost can be explained already quite well.

4. INCORPORATING LOGISTICS IN FREIGHT MODELS

4.1 State of the art

The classical transport modelling framework consists of four modelling steps: trip production, trip distribution, mode choice and route choice. This structure has been in use for both passenger and freight models for decades. Freight models have undergone different improvements. Most of these improvements have been within the individual steps, not changing the structure of models. Instead of providing a review here of the evolution of freight models in general[1], we focus on those improvements that have changed the structure of modelling, to take into account changes in logistics services and logistics costs. Figure 7 shows the main three lines of re-structuring initiatives that we can trace in the literature; these include 2 lines of integration of partial models of the 4-step framework and one concerning the introduction of supply chains as structuring elements for freight flows. Below we describe these developments and explore an extension of this line towards further integration of sub-models.

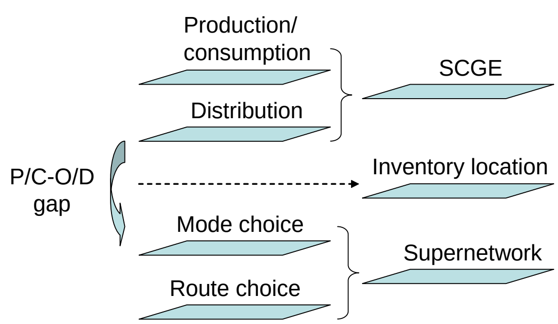


Figure 7. Alternative configurations for an integrative freight model

Integration of the production, consumption and trade

The development of international trade is influenced by differences in factor costs in the respective regions as well as by the barriers to trade, both regulatory and generated through the distance between these regions (see Figure 8). From this picture it becomes clear that neoclassical equilibrium theory can also be applied here. The only extension with this theory is that, instead of distance and transportation costs being used as

[1] See e.g. WSP (2002), de Jong (2004), Tavasszy (2008) for earlier reviews

measures of resistance between regions, one now introduces the concept of total logistics costs. These costs do not only reflect transportation related elements but all relevant logistic costs which also include storage, handling and inventory costs. In a situation where travel costs decrease and differences in factor costs remain high, one can expect globalisation to proceed. If production cost differences diminish, while at the same time transport cost would increase, the reverse would be likely.

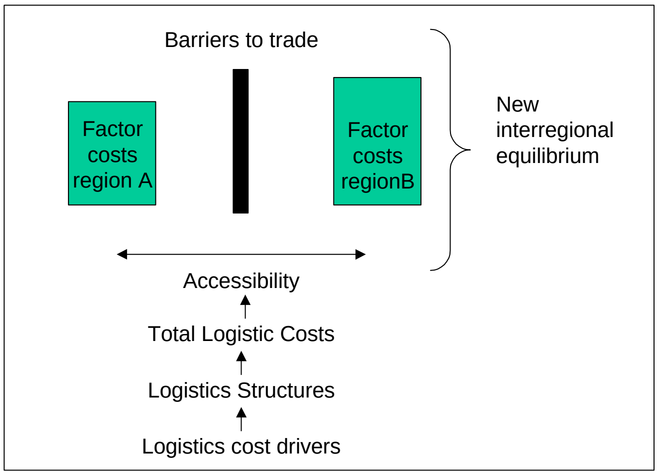
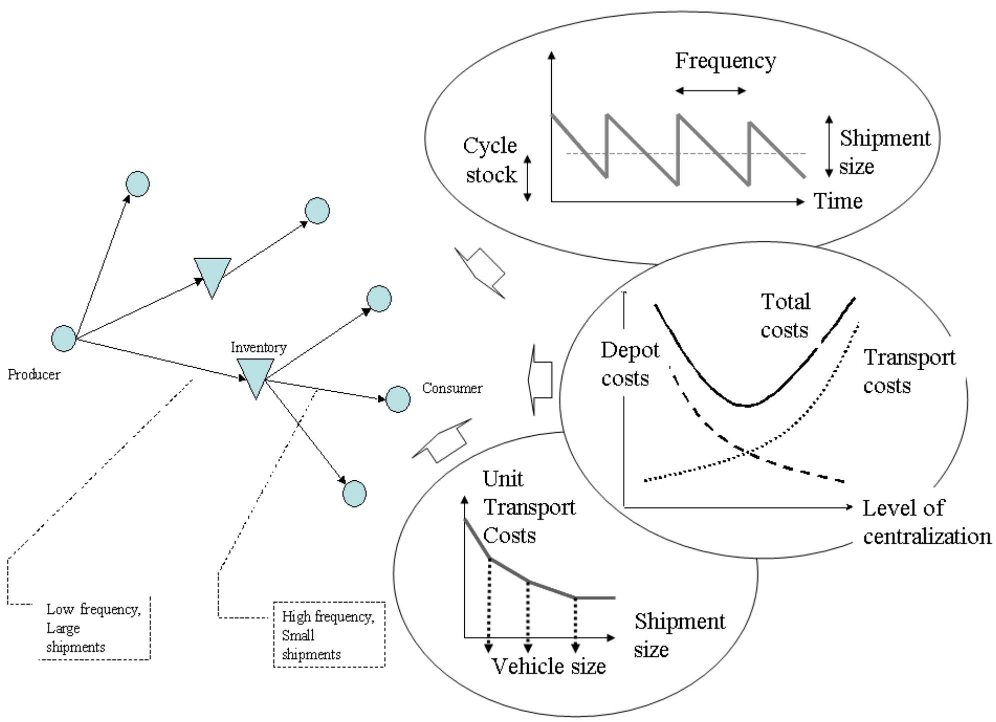


Figure 8. Relationship between logistics and the spatial economy

Currently the SCGE class of models is the main tool for estimation of transport-related and financial-economic impacts. Bröcker (1998) uses SCGE models as models for long term policy evaluation, overcoming the perception that the general equilibrium models cannot be made operational. Prior to the advent of the SCGE models in the 90's spatial price equilibrium models (Harker and Friesz, 1985) and gravity models (Chisholm & O'Sullivan, 1972) were the main methods by which trade was modelled. In Europe there are SCGE models covering the whole EU, as well as Dutch, Italian, Norwegian models. Among the models mentioned, the Harker model, extended with a freight network, is perhaps the most comprehensive to date in its attempt to integrate different levels of our framework in one equilibrium formulation. Despite the importance of factors like barriers and factor costs, accessibility remains the key linking pin between logistics and the spatial economy. Hence the concept of total logistic costs should be applied as accessibility measure, in order to be able to describe spatial restructuring effects of logistics trends. Until now, this practice has not been adapted in SCGE models[2].

Inventory Choice

The output of the freight economy linkages models is materialized in the form of interregional freight flows. However, these flows do not in itself form a sufficient basis for the estimation of the actual path and infrastructure claim that these flows cause. The class of logistics behaviour models solves this problem by modelling actual goods flow between the trading regions, including intermediary transhipments and stock points. The output of logistics models is in the form of Origin-Destination matrices (O/D matrix), which take into account intermediary flows between the stock or transhipment points. Logistics models can also generate information on mode and vehicle type used, as the choice for inventory location will be closely related to the choice of shipment sizes and modes of transport within the different legs of the chain. An abstract mode approach, as suggested earlier in our paper, can also be applied here.



[2] See Tavasszy & Ruijgrok (2003) for a more detailed exploration how changes in total logistic costs follow from changes in spatial structures of logistics activities.

Figure 9. Key elements of the intermediate inventory choice modelling problem: endpoint and pipeline inventories (A), spatial logistics trade-offs (B) and economies of scale in transport (C)

There have been a number of experimental initiatives worldwide to develop spatial logistics models. The Los Angeles County freight model includes a comprehensive, innovative, multimodal modelling framework to support freight transportation decision making in Los Angeles County (Fisher, 2005). The modelling approach combines freight modelling techniques: logistics chain modelling and tour-based truck modelling. The SMILE model has been constructed in order to enhance understanding of the developments and policy options regarding freight transport in the Netherlands. The model developed in 1990s in the Netherlands and was the first aggregate freight transport model, which accounts for routing of flows through distribution centres. It explicitly takes into account logistics developments and translates logistics tendencies, such as centralization of warehouses, higher frequencies and consolidation into freight demand characteristics (Tavasszy, 1998). The SMILE model extends 4-layer classical freight modelling framework with an extra logistics layer. The decision to use intermediate inventories in SMILE was constructed as a discrete choice model, disregarding mode and route choice but following a mode abstract approach and employing transport cost curves where costs vary by shipment size.

The GOODTRIP model has been developed at Delft University in the Netherlands. The GOODTRIP model estimates goods flows, urban freight traffic and its impacts (Boerkamps, 1999). Based on consumer demand, the GOODTRIP model calculates the volume per goods type in m^3 in every spatial zone. The goods attraction constraint calculation starts with consumers and ends at the producers or at the city borders. Next, the goods flows of each goods type are combined by using groupage probabilities. The model not only builds a distribution O/D matrix, but also produces vehicle tours, thus spinning into the realm of the freight trips and networks class of models. The tours per mode are assigned to corresponding infrastructure networks, resulting in network loads, per mode on each network. The modelling process is sequential; there are no feedbacks to previous phases in the process.

The SLAM model (Spatial Logistics Appended Module) evaluates the impacts of changes in the logistic and transport systems within the whole Europe on the spatial patterns of freight transport flows (Tavasszy, 2001). The model takes into account changes in distribution structure, i.e. the number and location of intermediate warehouses for the distribution of goods. This model spawned the SCENES model, which has been incorporated into the EU modelling suite TRANSTOOLS.

Apart from the state-of-the-art models, there is an ongoing research in the field of logistics behaviour models. Burmeister (2000) looks at Just In Time (JIT) production environments with complex logistic systems and intensive use of technologies such as information and communication. Such complex systems are believed to replace the traditional manufacturing practices in future. The article identifies "4 worlds" which have distinct organization of transport and production. The JIT concept has been tested for each of the four worlds. One of the ideas the article is that transport serves as production coordination means and the synchronisation of both processes is essential.

In the United Kingdom work has been done on the EUNET 2.0 model, which is an integrated regional economic and logistics freight transport model, Jin (2005). It has been designed using SCGE and SCENES modelling principles and serves the purpose of forecasting future levels of goods transport demand as a function of economic transactions and freight logistics. The model represents logistic movements and integrates this representation in a Spatial Input-Output (SIO) Model, while explicitly treating logistic stages (echelons) and associated transport costs. The model reaches trip and network modelling levels, taking into account different modalities and vehicle sizes.

Groothedde et al (2005) have elaborated quantification of economies of scale in logistics networks. Consolidation of logistics networks allows more efficient and more frequent shipping by concentrating large flows onto relatively few links between hubs. The authors propose a formulation of total logistics costs in a logistics network, which takes into account density of the flow and location of inventories. The paper showed on an application example in the Netherlands that collaborative consolidation of flow between key points (hubs) provides substantial advantages for collaborating parties.

Maurer (2008) develops a model framework that combines a firm level, supply chain optimization model with a national model framework. The micro level model is used to establish inventory locations and volumes within the UK for an entire industry. These data are used to translate an interregional trade table into an interregional table for transport movements.

Mode choice, assignment and supernetworks

The freight trips and network models normally treat mode split and, simultaneously or subsequently, assigning vehicle trips to the transport network using route choice models. Modal choice models have evolved through the incorporation of logistics variables like shipment size and form of contract (own account or hire/reward). Most recently, Combes (2010), developed a model at firm level for the simultaneous mode/shipment size for simultaneous use of two transport modes, using a production function for transport services. Arunotayanun and Polak (2007) show that contract forms have a significant influence on the choice of mode. Both sources build on the French ECHO shipper survey.

Two further models of transport service choice, that employ a form of logistics cost formulation, come from Liedtke (2005) and de Jong et al (2007). Both use micro level simulation of transport logistics choices. Liedtke (2005) develops an agent based microsimulation model for freight transport in Germany using a total logistics costs formulation for transport and trade decisions. The background of de Jong's research lies in a micro-economic model of mode choice with endogenous shipment sizes (Abdelwahab, 1998). De Jong applies this approach within a multimodal network model, which allows more flexibility in the choice of mode in terms of multimodal transport chains. Based on this work, a logistics simulation model with deterministic cost minimisation has been constructed for both Norway and Sweden. An interesting opportunity lies in the combination of this model with the recent work of Combes (2010). Once suitable aggregation mechanisms have been found, applications of this model would become possible in the area of hybrid networks, as described earlier in the paper.

Recent work of Wang and Holguín-Veras (2009) and Holguín-Veras (2008) has considered enhanced formulations to model commercial tours and vehicle empty trips at the aggregate level. The aggregate tour model starts from a micro level formulation, enumerating promising tours and calculates the most likely aggregate flow patterns using a maximum entropy formulation.

Another direction of innovation lies in the simultaneous treatment of modal split and network assignment in so-called supernetworks. These models and allow transhipment between modes of transport and different means of transport by mode (e.g. various truck types or LTL-FTL trips). Examples can be found in various descriptive national freight models in Europe (Beuthe (2001), Swahn (2001), Williams (2002), De Jong (2007)). Recently, such models also have applied for the prediction of changes in intercontinental, multi-modal transport chains (Tavasszy et al, 2007 and Pattanamekar et al, 2009).

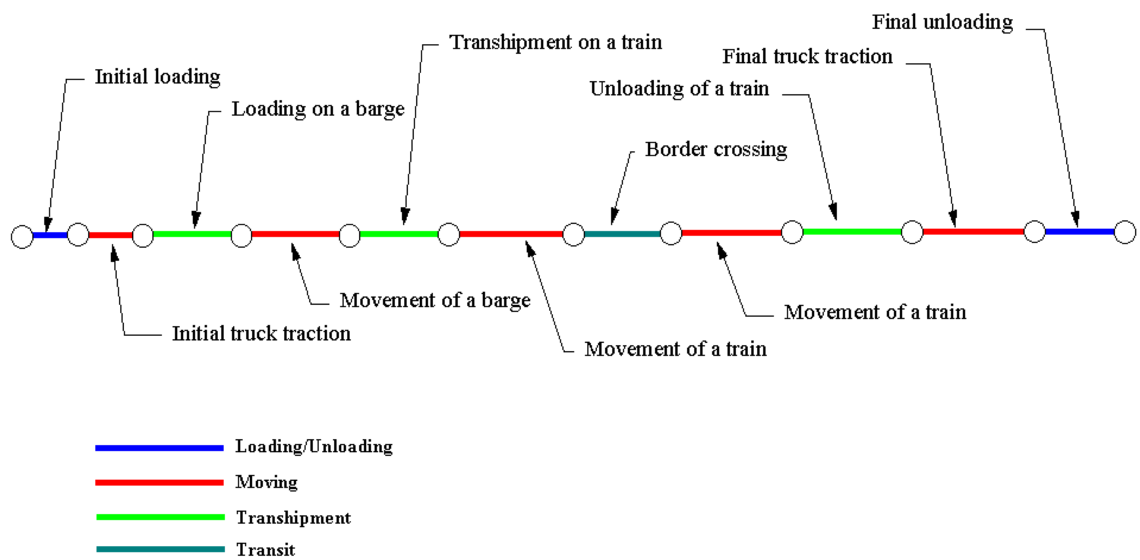


Figure 10. Illustration of the network architecture of the European multimodal network choice model NODUS (www.fucam.ac.be)

4.2 Research opportunities

Freight models have to a great extent evolved separately along the lines of our framework presented above, with very few integrative attempts. As Liedtke et al (2009) point out, a risk of the traditional multi-step transportation modelling framework is the mismatch between the functional behaviour of the different sub-models making construction of comprehensive choice models problematic. Our objective in this section is to sketch a model in which functional behaviour is aligned between sub-models, by reaching consistency in demand volumes and costs of services between the different layers of the model framework. Consistency in costs is reached by applying the generalized costs concept as described earlier in the paper. Consistency in demand volumes at different levels is reached by equilibrating the flows in the different layers.

The basic architecture for an integrative model that complements the classical 4 step modelling approach is one with a separate choice model for intermediate inventories, as described in the previous section. The approach of using logsums to aggregate costs over choice alternatives is already standard practice in discrete choice models for passenger transport. The SCENES and SAMGODS freight models provide specifications using sequential discrete choice models and logsum approaches for consistency in costs, including an inventory model. The logistics choices and cost formulations were not as wide in scope, however, as described in this paper. Shipment sizes were exogenous, supply chain choice sets were limited to national and continental distribution centres and costs of unreliability were not included.

Models of spatial interaction
Ideally, models of spatially separated product markets should show prices and quantities that are consistent within and between regions. Although this is the case for SCGE models, accessibility is usually still represented by distance or transport costs alone, sometimes supplemented by trade barrier effects. The definition of accessibility in trade models can successfully be extended to include logistics variables, as Hausman et al (2004) show. In their model, however, logistics costs are exogenous. Linkages with models that explain changes in logistics costs as a function of network choices and supply chain design could increase the scope of applications of the model because of existing economies of scale. While the Hausman model deals with trade and assumes regional freight demand to be constant, the next step would be to include generalized logistics costs in SCGE models, or another model type in which regional freight demand is endogenous.

Choices concerning the location of intermediate inventories could potentially be integrated in models of spatial interaction as well. Applying the O/D estimation approach presented in Pattanamekar et al (2009), chains of movements can be synthesized starting from observations of individual origin-destination movements (as available in transport statistics) and thus reproducing a table of trade between regions of production and consumption.

One result of using generalized logistics costs is the natural inclusion of the choice of shipment size. To reflect the reality of decision making at firm level, models of supply chain choice, mode choice and routing should be in harmony from this perspective. For example, inventory optimization models should take into account synchronization between production and shipping schedules in a way that inventories are considered at those locations that determine the eventual route of the shipment. Finally, as many of these cost and service functions are non-linear or discontinuous, ideally, (dis)economies of scale need to be considered. Note that this presents additional difficulties for aggregate models, as (unlike in passenger transport networks) some of this non-linearity and discontinuity appears at the individual firm level, rather than at the collective level.

Integrating logistics considerations into transport choices using network models
Inventory decisions can be modelled as part of a hypernetwork choice problem, where different layers of the network represent segments of the chain upstream and downstream from distribution centres. Hypernetworks are a generalization of the

transport network concept into choice alternatives that go beyond transport activities. In our case, the generalization involves the holding of intermediate inventories. The route choice model can be implemented out using deterministic or probabilistic network choice methods. Figure 11 illustrates a bi-level hypernetwork with 2 routes: direct shipping (route I, below) and indirect shipping (route II, on top). The top layer network in the figure has high shipment sizes, and the goods have to switch to the lower layer network with small shipments via a connecting link between the two layers, indicating storage in a DC (indicated by triangles between the network layers). Note that this differs from the supernetwork approaches for transport mode choice. In these approaches the choice for inventory location is not included or the alternative routes constitute only transport service related network choices and not, like in this case, the choice of supply chain configuration.

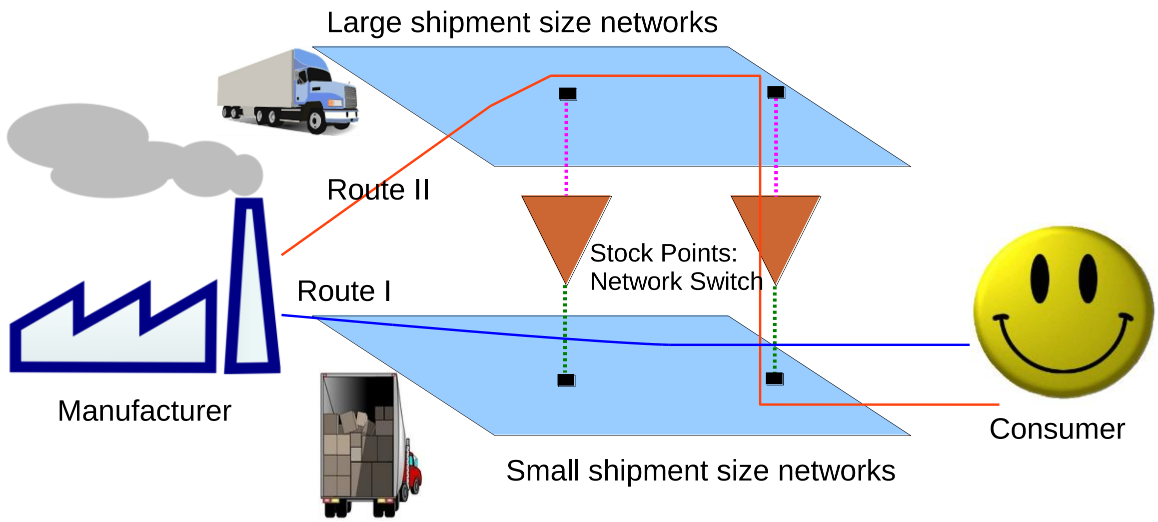


Figure 11. A hypernetwork model for inventory location choice

Note also that in order to account for the enormous variation in commodity segments, a probabilistic choice model, allowing the simultaneous use of different alternatives, will be needed. Where supply chain structures interact with routing and mode choice, models need to be developed such as SMILE that describe the choice of vehicle type (including light goods vehicles) and the choice of transshipment terminals (see also the NODUS and SAMGODS models). An important extension of routing models is the aggregate representation of roundtrips (Wang and Holguin Veras, 2008). The inclusion of inventory costs in itself can also be relevant to increase the accuracy of mode choice models, even if inventory locations are not the subject of choice (de Jong, 2007).

The modelling work of Nagurney (2002) already represents an important step in this direction. She proposed a novel multilevel network framework that allows capturing distinct flows, in particular, logistical, informational, and financial flows within the same network system, while retaining the spatial nature of the network decision-makers. The authors interlink three networks that facilitate movements of goods from producers to consumers: logistical, informational and financial networks. Calculation of prices belongs to the financial networks and is done dynamically using input from logistical and informational networks.

A specific point in the above sections concerns the multitude of possible supply chain architectures. More complex forms of supply chains, where different manufacturing systems interact with inventory configurations (e.g. "built to order" connected to a rapid fulfilment depot instead of supply chains driven by "built to stock" manufacturing) are a further expansion of these hypernetwork type models.

Note that freight model databases need to be extended in terms of the structural elements of logistics activities. Data are needed on the various logistics infrastructures (size, location of inventories, terminals), the quality of logistics services (speed, reliability) and the costs of services. Also the demand for logistics structures and services needs to be monitored. Finally, data that characterizes logistical requirements (i.e. behavioural preferences) of shippers and carriers is needed. These data can be obtained through estimation of behavioural models, but will also require some form of observation of (intended or realized) logistics choice behaviour. Shipper surveys are an excellent tool to gather this type of data and were the basis of the latest advances in modelling. Note that new initiatives described above with a strong empirical component were only possible because of the availability of shipper surveys, in particular in France and Sweden. In most cases, however, shipper surveys are not available or do not present sufficient detail. Here, aggregate models for the behaviour of populations can be searched, rooted in physics (e.g. using the entropy maximization approach as applied in Wang et al, 2009), that take into account logistics considerations and can be estimated on aggregate data.

5. CONCLUDING REMARKS

Freight models have progressed beyond the 4 step framework in several ways. Both in the area of spatial interaction models, inventory choice and logistical choice models, as well as network models improvements in modelling techniques, and improvements in model structure and explaining variables have been introduced that have led to a better description of each of these different layers of freight modelling.

These model innovations have been developed rather independently, and although each improvement can be justified on its own account, they all are lacking a framework in which the specific characteristics of freight flows are taking into account consistently. This means that they have to reflect the fact that there is always direct linkage between freight flows and the way the world and regional economies develop, but also there needs to be a link with the development of logistics organization and they should be sensitive to quality and price differences in the available modes and infrastructure. Presently this consistency is mostly lacking, leading to model constructions that can potentially be inconsistent, and do not describe equilibrium processes between demand and supply adequately.

In this paper we have described a number of avenues that could be developed to streamline the modelling concepts in a consistent way, in order to account for system attributes and preferences that are determined by logistics considerations. In Figure 7 these different avenues have been sketched. All modelling frameworks rely on a consistent and unifying Generalized Cost concept. Such a concept is necessary to make a consistent calculation of the way geographic distances are evaluated on the different levels of the modelling framework, but also it is necessary to use a consistent framework in finding market equilibriums that in many cases reflect scale economies and thus need a consistent modelling framework.

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