Modelling the Cost Performance of a Given Logistics Network Operating Under Regular and Irregular Conditions

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This paper develops an analytical model for the assessment of the cost performance of a given logistics network operating under regular and irregular (disruptive) conditions. In addition, the paper aims to carry out a sensitivity analysis of this cost with respect to changes of the most influencing factors. In particular, this is expected to investigate the vulnerability of this network with respect to particular disruptive events. The logistics network under consideration consists of the manufacturers and retailers/consumers as the origin and destination nodes of the goods flow concerned, and the transport system (links and services) connecting them. The nodes are characterized by the goods' production and consumption rates, and the level of inventories, and related costs. The transport system is characterized by the transport mode that is exclusively used in the network, its frequency of service, the goods' delivery time (speed), and the related costs. Irregular conditions are characterized by the intensity of the impact and duration of the disruptive event, which, in the given case, is assumed to completely cut off the transport services in the network. The model uses inputs reflecting these characteristics. The output consists of the network's total and average cost per unit of goods, which is estimated depending on the type and delivery frequency of the transport mode that is exclusively used, and on the duration of the disruptive event. The model is applied to the generic hypothetical logistic network using data from the European logistics networks.

Keywords: logistics networks; cost performance; modelling; disruptions; reliability

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Notation

The basic notation used in developing the model:

i, j, k	are respectively the index of the given manufacturer, retailer/consumer, and items-goods; they range from 1 to M, N, K;
m_{ijk}, q_{jik}	are respectively the production and the consumption rate of the goods (k) at the manufacturer (i) and at the retailer/consumer (j) (quantity per unit of time);
h_{ijk}, h_{jik}	are respectively is the holding cost of the goods (k) at the manufacturer (i) and the retailer/consumer (j) (monetary units per unit of quantity per unit of time);
p_{jik}	is the value (price) of the unit of quantity of the goods (k) produced by the manufacturer (i) and consumed by the retailer/consumer (j) (monetary units per unit of quantity);
r_k	is the interest (discount) rate of the unit of the goods (k), implying that its value decreases over time (percent);
H_{ijk}, H_{jik}	are respectively the time interval between successive orders/deliveries of the goods (k) from manufacturer (i) to the retailer/consumer (j), respectively (time units);
τ_{ijk}	is the duration of a disruptive event affecting transport of the goods (k) between the manufacturer (i) and the retailer/consumer (j) (time units);
t_{ijk}	is the average delivery time of the goods (k) from the manufacturer (i) to the retailer/consumer (j) (time units);
T	is the period of time in which the cost of a given logistics network is considered (time units);
α_{ijk}	is the value of the time needed to transport the goods (k) between the manufacturer (i) and retailer/consumer (j)(monetary units per item per unit of time)[2].
d_{ijk}	is the transport distance for the goods (k) between the manufacturer (i) and the retailer/consumer (j) (units of length) (Figure 3a);
$v_{ijk}(*)$	is the average speed of transfer-transport of the goods (k) between the manufacturing plant (i) and the retailer/consumption plant (j) (units of length per unit of time);
W_{ijk}	is the anticipated delay while transporting the goods (k) between the manufacturer (i) and the retailer/consumer (j) (time units);
f_{ijk}^*	is the frequency of sending the goods (k) directly from the manufacturer (i) to the retailer/consumer (j);
d_{i1k}, d_{2jk}	are respectively the incoming and the outgoing distance of the goods (k) from the manufacturer (i) to the consolidation terminal T1 and from the deconsolidation terminal T2 to the consumer-retailer (j) (units of length) (Figure 3b);
$v_{i1k}(*), v_{2jk}(*)$	are respectively the average transport speed of the goods (k) along the consolidation/deconsolidation incoming and outgoing distances, di1k and d2jk (units of length per unit of time);
W_{i1k}, W_{2jk}	are respectively the anticipated delay of the goods (k) incoming at the consolidation terminal T1 from the manufacturer (i) and outgoing from the deconsolidation terminal T2 to the retailer/consumer (j)(time units);
τ_{i1k}, τ_{2jk}	are respectively the average time, which the goods (k) spend at the consolidation and the deconsolidation terminals T1 and T2 (time units);
$d_{12k}, v_{12k}(*)$	are respectively the distance and the average speed for the goods (k) sent between the terminals T1 and T2 (units of length, units of length per unit of time) (Figure 3b); ;
W_{12k}	is the anticipated delay of the goods (k) while being sent between the terminals T1 and T2 (time units);
f_{12k}	is the frequency of transport services between the terminals T1 and T2;

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[2]As in case of the inventories at both ends of the given chain, this value of time may depend on the value of the given item and the interest rate of capital reflecting the value of the item over time.

τ_k	is the average time, which the goods (k) spend at the consolidation/deconsolidation terminal T (time units) (Figure 3c)';
f_{i1k}, f_{1jk}	are respectively the incoming frequency from the manufacturer (i) and the outgoing frequency to the retailer/consumer (j) of the goods (k) at the terminal T;
p_{ijk}	is the price of transporting the unit of quantity of the goods (k) from the manufacturer (i) to the retailer/consumer- (j);
a_k	is the price (cost) per unit distance of the goods (k) (monetary units per unit of length);
b_k	is the price (cost) per unit of weight of the goods (k) (monetary units per unit of weight);
S_{ijk}	is the weight of a unit of the goods (k) sent from the manufacturer (i) to the retailer/consumer (j) (units of weight).

1.   Introduction

Logistics is usually defined as a set of the mutually interrelated organizational and operational activities concerned with handling particular goods from their origins to their destinations efficiently, effectively, and safely. The origins of particular goods are the manufacturing plants or the goods distributors. The destinations are either the manufacturing plants if the goods need finalization before being sent to the intermediate storage, or the end users, i.e. retailers and/or consumers. Figure 1 shows a simplified self-explanatory scheme of a given logistics network.
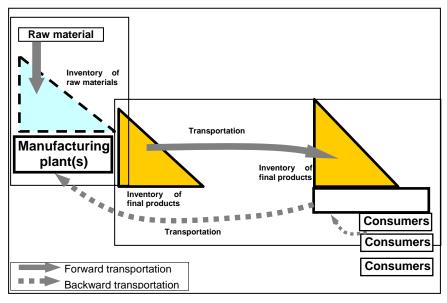

Figure 1. A simplified scheme of a given logistics network.

As can be seen, the inventories of raw materials as inputs for manufacturing of the given goods may exist at some manufacturing locations. The inventories of the final goods may exist at both the manufacturing and the retailers'/consumers' locations. Under the regular operating/market conditions, the inventories at both ends of the network generally decrease over time. They are renewed just before being completely or nearly completely exhausted. In that context, the logistics network links the processes of manufacturing, begin, end, and/or intermediate storage, transport, and the final distribution of the goods consumed. The network consists of the chains connecting either the individual pairs or the clusters of manufacturers and consumers of given goods. The main actors in the network are: i) the manufacturers and the retailers/consumers who are characterized, respectively, by their goods' manufacturing and consuming rates, and by their strategies of dealing with the goods' inventories; ii) the transport operators who enable physical transfer of goods between manufacturers and retailers/consumers; iii) the collectors and

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distributors of information on the progress of goods through the network (these often are usually goods' forwarders); and iv) the co-coordinators of organizational, physical, and communications activities between particular actors.

In terms of the geographical scale, the logistics networks can operate over local, national-state, continental, and/or intercontinental area(s). They can refer either to particular industries, such as the aircraft industry, the automotive industry, and the electronic industry, or to the clusters of different industries (firms) constituting and/or sharing common transport network(s) elements - infrastructure and services.

The performance of a given logistics network can be characterized as follows: the production and the consumption rate, and the level and the cost of inventories of the goods concerned at the manufacturers' and the retailers/consumers' locations; the quantity of goods in motion; the average speed (time), frequency of delivery, and the cost of transport; and the reliability of deliveries reflecting the vulnerability of a given network to different external and internal disruptions. In general, the above-mentioned performance synthesizes the overall cost performance of a given logistics network (Janic, 2004).

This paper develops an analytical model for estimating the cost performance of a given logistics network operating under regular and irregular (disruptive) conditions. The model is particularly intended to carry out a sensitivity analysis of this cost with respect to changes of the most influential parameters, such as the goods delivery frequency and the intensity of impact and duration of the disruptive event. This type of model could eventually contribute to providing some of the reasons, which explain the rather low market share of the inland non-road transport modes in particular European regions.

Apart from this introductory section, the paper consists of four sections. Section 2 describes some past current and future developments of particular logistics networks, mainly in Europe. Section three develops the analytical model for estimating the cost performance of a given logistics network under regular and irregular conditions, and Section 4 demonstrates an application of the model. The last section contains some conclusions.

2.   The logistics networks

2.1   *The past and current developments*

For a long time, the main interest of the majority of manufacturers and suppliers of particular goods has been their efficient, effective, and safe door-to-door delivery. The efficiency implies delivery at minimum costs. The effectiveness implies delivery in terms of respecting the specified date and time. Safety implies delivering goods without damage due to reasons specified in advance. The logistics networks which fulfil the above-mentioned requirements have gradually developer the following characteristics: i) a relatively dispersed concentration of the goods' manufacturing, storage, and consumption locations; ii) the use different configuration of transport networks for the goods' delivery; iii) an increase in the volume of direct deliveries with the nominated day and time; iv) a decrease in the size of shipments, and consequently an increase in the delivery frequencies; and v) an increase in the vehicles' utilization. These characteristics have then been supported by an increased use of Information/Communication Technologies (ICT), which have enabled customers to track and trace their shipments throughout a given logistics network(s) (chains) (Groothedde, 2005; Zografos and Regan, 2004). The main objective of such developments has been to reduce share of the logistics costs in the production costs of particular goods, which in turn has put the freight transport sector and particular transport modes under additional pressure to adequately respond to such requirements in terms

of flexibility, availability, quality, and cost[3]. Because of the generally increasing volumes of goods to be transported on distances up to about 500 km, a decreasing of the shipment size with a consequent increase in the frequency of goods' delivery and shorter lead time(s), in particularly the road freight transpiration has been shown to be the most capable of adequately responding, and consequently retaining the dominant market share in these markets in Europe. The increased application of the Just-in-Time manufacturing concept (JIT), which has generally diminished inventories and increased requirements in terms of the reliability of delivery time (as agreed) and flexibility (the time between the order and delivery), has also contributed to such development on the one hand; over the longer distances with ultimately lower volumes and less time- and frequency-sensitive goods' shipments, it is the railways, which have saved their market share. Nevertheless, in Europe, they have been losing market share overall. Figure 2 illustrates an example of development of the modal split in freight transport in the EU (European Union – EU 25) for the period 1995-2005 (EC, 2007).
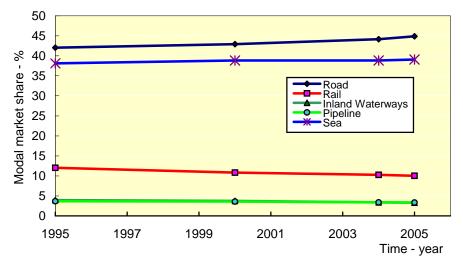

Figure 2. An example of modal split between different freight transport modes in European Union (EU-25) (t-km ton-kilometres) (Compiled from EC, 2007).

As can be seen, during the past decade, the road transport has slightly increased its market share in terms of the annual volumes of t-km (tone-kilometres) and consequently maintained its dominant market position during the observed period (42-44%). Sea transport has gained the second largest and slightly increasing market share during the observed period (38-39%). Rail transport has gradually lost its market share (from 12% to 10 %), and oil pipeline and inland waterways have also slightly lost their market shares (from 3.9% to 3.3% and from 3.7% to 3.4 %, respectively).

2.2   *Future trends*

Future trends will likely be based on even more increased requirements for reducing logistics costs. This will happen under conditions of further increase in volumes of goods on the generally decreasing delivery distances, changes in the structure of particular goods' categories, further diminishing of the shipment size, and even more increased users' needs for control over the services they receive (by more intensive use of ICT). In addition, the inventories at the manufacturers will be reduced further through shortening of the manufacturing cycle time. This

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[3]In Europe, the share of transport costs in the production of different commodities has been estimated as follows: retail products (0.7%), petroleum products (3.6-3.6), foodstuff (3.6-3.9), iron and steel (4.5-5), and building material (6.4-7.2) (Aberle, 2001).

will continue to drive the transition from PUSH systems driven by the supply of raw materials and final goods to PULL systems in which the actual demand for particular goods will trigger the upstream manufacturing processes in terms of time and quantities. This will also reduce the inventories at the retailers/consumers' locations. In addition, since the demand becomes known more precisely in advance, it will be increased by direct deliveries without the intermediate storage. Consequently, the inventories will be further shifted from the warehouses of the manufacturers and distribution centres to the rolling stock of particular transport modes. , The latter will have to respond appropriately. Thos in turn will increase the need for cooperation rather than competition either within the same or between different transport modes.

2.3   The problem of vulnerability-reliability

The dynamism of a particular logistics network can be defined by the average speed of moving goods through the network. This speed is influenced by the production and consumption rates of goods and by distance, and dependent particularly on the frequency and speed of transport services. Consequently, those logistics networks with a higher speed of moving goods could be considered as more dynamic than the others. (Blumenfeld et al., 1985; Daganzo, 1984, 1999). In addition to these advantages, a disadvantage of these logistics networks implicitly assumed to carry goods of a higher time-sensitivity is their higher vulnerability to both internal and external disruptions. This implies that these disruptions can affect a one or more network components to deteriorate in terms of the regularity and punctuality of supplying raw materials, thus affecting the manufacturing and the consumption rate(s), the frequency and speed of transport services, etc. In general, disruptions with a rather modest impact and a shorter duration mainly cause particular transport operations and processes to slow down, and consequently to the creation of higher inventory "buffers" at both ends of the given logistics network (Qi et al., 2004). Disruptions with a severe impact and longer duration usually mean the major transport axes are cut off and consequently the affected transport services have to be cancelled. In some cases, alternative, very often less convenient, routes and transport modes in terms of the goods' transit times and costs can be used (EC, 2002, 2007; Zografos and Regan, 2004). Consequently, in the former case of mild disruptions, the quality of transport services deteriorates, which in turn causes the overall inventory costs to rise at both manufacturers and retailers/consumers (McCann, 2001). In the latter case, the volume of goods in transportation decreases due to cancellation of particular transport services, which causes decrease in the planned utilization of the allocated transport vehicles/fleet(s) on the one hand, and diminishing of the overall utilization of the related infrastructure due to the cancelled services, on the other (McCann, 2001). As well, the goods' production rate at both the manufacturers and further upstream at the suppliers of raw material for these goods in the PULL concept may be also affected (Thomas and Griffin, 1996).

Overall, the scale and scope of the affect of a given logistics network by a given disruptive event depends on: i) the networks' characteristics in terms of its size, type, the volume of goods, and the spatial coverage (regional, interregional); ii) the goods' service time, delivery frequency, and inherent sensitivity; iii) the intensity, scale and duration of the given disruptive event; and iv) the availability of the alternatives to temporarily take over the affected goods' flows .

2.4   The objectives of the paper

Regarding the above-mentioned current and future characteristics of a given logistics network, the main objectives of this paper are as follows:

- Developing a convenient analytical model for the assessment of the cost performance, i.e. the total and average cost, of a given logistics network operating under planned-regular and unplanned-irregular (disruptive) conditions;

- Carrying out a sensitivity analysis of these costs with respect to changes of the most influential parameters; in the given context, these are assumed to be the configuration and type of the transport network and transport mode, the frequency of goods' deliveries between the manufacturers and the retailers/suppliers, and the intensity of impact and duration of the disruptive event; and

- Providing some among the explanations for why particular non-road inland freight transport modes (railways, inland waterways, pipelines) have been losing their market shares in some European regions despite being stimulated by national and international (EU) policies.

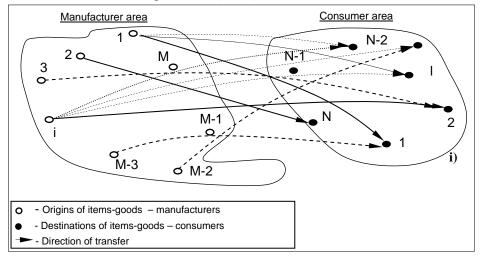## 3.   A Model of the cost performance of a given logistics network

3.1   State of the art of modelling

Extensive research has been carried out the different operational and economic performance of the logistics networks. This particularly refers to the investigation of optimizing the coordination of the supply chains, defined as the management of material and information flows between the vendors, manufacturing and assembly plants, and distribution centres. The focus has been on categories of operational coordination such as Bayer-Vendor, Production-Distribution, and Inventory-Distribution. The achievement in optimizing the cost of such co-ordination has been overviewed by Thomas and Griffin (1996). In addition, there has been some research concerned the choice of transport mode within the given logistics chains. The main criteria have been the costs of the entire chain (network) consisting of the production, storage, and shipping costs (Benjamin, 1990). In that context, the goods' delivery time has been shown to be of the great importance for both shippers and receivers, thus reflecting the potential benefits from transport investments. Nevertheless, the importance of time has always been dependent on the perception of the particular actors involved (Allen et al., 1985; Wigan et al., 2000 Note: Year is inconsistent with the referencelist).
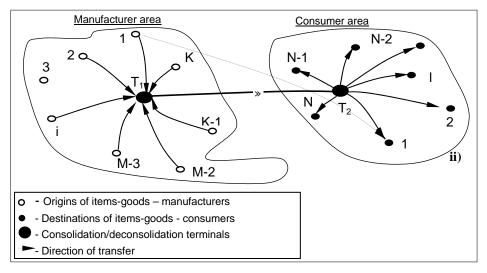
This paper mainly uses the ideas and elements of the analytical modelling of logistics systems (networks) developed by Blumenfeld et al. (1985), Campbell (1990; 1992), Daganzo (1984; 1999), Daganzo and Newell (1985), Hall, (1987; 1993), Janic et al. (1999) and McCann (2000). In particular, as a start, the simplistic analytical models dealing with handling, inventory, and transportation costs of complex logistics operations that deliver a bulk of goods as freight shipments from the manufacturers to the retailers/consumers either directly or via consolidating terminals developed by Daganzo (1984, 1999) are used. In these models, detailed data on the particular operations and the associated costs have been replaced by their summaries enabling the use of simple analytical models instead of complex, mainly computer-supported numerical structures. In addition, some research has also been carried out on the impacts of disruptions of the production and the consumption processes on the network cost performance (Dejax, 1991; Qi et al, 2004). Since this paper mainly focuses on the assessment of the cost performance of a given logistics network operating under regular (planned) and irregular (disruptive) conditions, it should be considered simultaneously as a complement and the added value to the above-mentioned research topics. In particular, to the author's knowledge, modelling of the cost performance of a given logistics network that operate under the irregular (disruptive) conditions and a comparison of these costs to the costs of the same network while operating under the regular (planned) conditions represent an innovative approach in the given context.

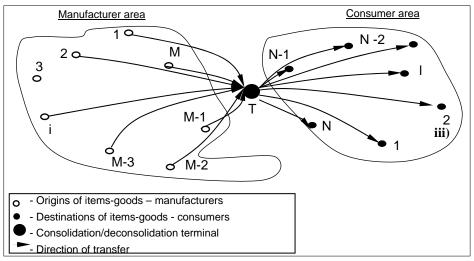## 3.2   *The network configurations*

A model of the cost performance of a given logistics network includes the following: a sub-model of the inventory cost of goods at the manufacturers' and at the retailers/consumers' location(s), a sub-model of the cost of time of goods during transportation, and a sub-model of the transport cost. In that context, the transport networks of different spatial configurations can be used either exclusively or in different combinations (mixtures) to connect particular manufacturers and retailers/consumers of the goods. The former cases appear convenient for the analysis, modelling, and a comparison of different network configurations in the given context. The latter cases frequently exist in practice. Figure 3 (a, b, c) shows a simplified scheme of these particular exclusive network configurations (a, b, c).

a) Direct connections

b) Connections via two consolidation/deconsolidation terminals

c) Connection via single common consolidation/deconsolidation terminal

Figure 3. A simplified scheme of three transport network configurations serving a given logistics network

As can be seen, the manufacturers (white circles denoted by index *(i)*) are clustered in the "manufacturer area". The retailers/consumers (black circles denoted by index *(j)*) are clustered in the "consumer area". These both represent the network nodes where the goods' flows originate and destine, respectively. The arrows indicate the direction of movement of these goods (Janic, 2007).

In addition, the particular configurations of the transport networks in Figure 3 are as follows:

i)   Configuration with direct connections of particular pair(s) of manufacturers and retailers/consumers (Figure 3a);

ii)   Configuration with indirect connections of particular pairs of manufacturers and retailers/consumers including one consolidation and one de-consolidation of the goods concerned at the different locations (terminals) (Figure 3b); and

iii)   Configuration with indirect connection of particular pairs of manufacturers and retailers/consumers, including one consolidation/deconsolidation of the goods concerned at the same location (terminal) (Figure 3c).

One or a few operators of the same or different transport modes might be involved in the above-mentioned connections as follows:

• The configuration with direct connections implies that the road transport operators provide direct door-to-door connections between particular manufacturers and retailers/consumers. In the past, and still at the present, the railways also provide such connections along tracks called industrial tracks that is between the manufacturers and the doors of retailers/consumers (Figure 3a);

• The configuration with one consolidation and one deconsolidation of goods at different – distant – locations (terminals) requires using at least two different transport modes. Usually, the road transport operators transfer goods from the door(s) of manufacturers to the consolidation terminal T_1 and then from the deconsolidation terminal T_2 to the door(s) of consumers-retailers (Figure 3b). Any transport mode - road, rail, inland waterway, or air – can be used to operate between terminal T_1 and terminal T_2. If rail is used as the main mode, the goods consolidated (packed) into the standardized units – containers, swap-bodies and semi-trailers – will require transhipment (sometimes combined with

short-time storage) at the rail/road terminal(s) T_1 and T_2. If maritime transport is used as the main mode, the terminals T_1 and T_2 will be located in their ports. In that case, the goods packed in the maritime containers are collected from and distributed to these port terminals by road, rail, or both. If air transport operates as the main mode, which is the practice of express freight delivery operators such as FEDEX and DHL, terminal T_1 and terminal T_2 are the cargo terminals at the goods origin and destination airports, respectively. The goods are consolidated in boxes of the small size and weight (letters and small limited-weight packages) collected within the "manufacturer" (i.e. the "sender") area and distributed within the "consumer" (i.e. the "receiver") area by road (Figure 3b).

- The configuration with one consolidation/deconsolidation of goods at the same location (terminal) usually requires the use of only one transport mode. It can exclusively be either road or rail. If it is rail, the goods (loading units) are loaded onto flat wagons at the doors of particular manufacturers; these wagons are assembled into trains and then dispatched to terminal T, which is usually the rail-shunting yard. There, the incoming trains are decomposed and the outgoing trains reassembled and sent to the "consumer" area(s). After decomposing these trains, the rail wagons are distributed to particular consumers-retailers along the industrial tracks. Otherwise, road transport can be used at both ends of the network. If air transport is used, the ultimate "manufacturers" and the ultimate "consumers" of goods are the cargo terminals at local-regional airports. Terminal T enables the exchange of goods as shipments between incoming and outgoing aircraft/flights before they proceed towards their final destination(s). In any case, road transport is used for the collection and distribution of goods shipments from and to, respectively, the real "manufacturers/consumers-retailers", and from and to regional airports (Figure 3c).

These configurations of logistics networks can be identified for the specific purposes of their analysis and modelling. In practice, particular manufacturers and retailers/consumer are usually connected by different types of mixed networks. For example, this can often be the road networks consisting of elements of the above-mentioned configurations (a) and (c) (see Figure 3a and 3c).

3.3   Assumptions

The model of the cost performance of a given logistics network: is based on the following assumptions:

- The number of manufacturers and consumers of given goods is known. The same manufacturer can produce these goods for different consumers; the same consumer can receive goods from different manufacturers. This assumption closely reflects the real situation, since the number of both manufacturers and retailers/consumers of given goods in a given region is countable. In addition, most of them both use different clients in order to provide the required quantities of goods on the hand, and to reduce, for example, the higher prices of goods, on the other;

- Goods are consolidated into compact forms in terms of size and weight, i.e. into compact boxes, palletized and/or containerized shipments; consequently, they are countable rather than expressed in the units of weight or volume. On the one hand, this implies that the intermodal transport operating by different transport modes can be used in a given logistics network. On the other hand, regarding the overall rate of the containerized goods, the quantities of goods in the given network are limited compared with the total quantities transported in the market;

- The production and consumption rates of given goods at particular manufacturers and consumers-retailers, respectively, are constant. This seems to be realistic under conditions of relatively stable demand for these goods at given prices during a given period of time.

- The technological, operational, and economic characteristics of particular transport mode(s) operating within a given logistics network in terms of type and capacity of transport means, frequency of services, speed, and the corresponding handling and operational costs, are given. This sounds reasonable with the transport prices offered to the given manufacturers and the retailers/consumers reflect the total costs of particular transport operators;

- Disruptive event(s) affect a given logistics network by compromising the planned time and punctuality of delivery of goods, either by slowing down the operations and processes in the network or by completely cutting off the transport services between particular manufacturers and retailers/consumers. The type, intensity, and duration of the impact of a given disruptive event are known. In general, disruptive events can be of different type, intensity of impact, duration, and time of occurrence. Since they are usually unpredictable, their impact and related consequences are unavoidable and the consequences are also unpredictable. Therefore, assuming them as quite certain in the model enables the estimation of their impacts using "what-if" reasoning.

3.4   *The model structure - regular operations*

The model of a given logistics network operating under regular conditions consists of the following components: i) the characteristics of a given logistics network; ii) a sub-model of the inventory cost of the goods at the manufacturer(s); iii) a sub-model of the inventory cost at the goods at the retailer(s)/consumer(s); iv) a sub-model of the taken to transport the goods; v) a sub-model of the transport time and transport frequency; and iv) a sub-model of the transport costs.

3.4.1   *The characteristics of a given logistics network*

The values of the variables M, N, K, specified at the beginning of the paper, combined with the distances between particular manufacturers and retailers/consumers of a given logistics network can be used, respectively, as indicators of its size, coverage, and the diversity of goods concerned. The holding cost of the goods (k), hijk and hjik, comprises the inventory and the warehousing cost. The former of these costs mainly depends on the value (price) of a single unit of good (k), pijk and the interest rate rk. The latter depends on the size of a given quantity of goods (k), i.e. the required space for its storage, packaging, the required air conditioning, etc. The times between the successive orders/deliveries of the goods (k), Hijk and Hjik, respectively, depend on the requirements of the retailers/consumers and the manufacturers' and the transport operators' capabilities to fulfil these requirements. In the contemporary logistics networks, this interval is becoming shorter, i.e. there are more frequent orders/deliveries of the smaller quantities of given goods.

3.4.2   *The inventory cost at the manufacturers*

The frequency of orders/deliveries of the goods *(k)* from the manufacturer *(i)* to the retailer/consumer *(j)* during the period *T* can be estimated as (Daganzo, 1999):
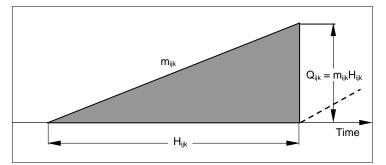
$$f_{ijk} = T / H_{ijk} \tag{1}$$

The frequency of transport services can be equal to or lower than the frequency of orders/deliveries f_{ijk} in equation (1). This implies diversity of the capabilities of particular transport modes to appropriately respond to the requirements. In addition, the variable *T* indicates the period of time for which the cost performance of a given network is estimated. It can be a day, week, month, or year.

The total quantity of goods *(k)* manufactured between the two successive orders/deliveries, i.e. during the interval H_{ijk} can be determined based on the equation (1) as:

$$Q_{ijk} = m_{ijk}H_{ijk} = m_{ijk}(T / f_{ijk})$$ (2)

The inventory cost of goods Q_{ijk} can be determined, on the base of equations (1) and (2), and Figure 4, as follows:

Figure 4. A scheme of the inventories of goods (k) at the manufacturer (i) before being sent to the consumer (j)

$$c_{ijk} = (1/2)Q_{ijk}H_{ijk}h_{ijk} = (1/2)m_{ijk}\left(T / f_{ijk}\right)^2 h_{ijk}$$ (3)
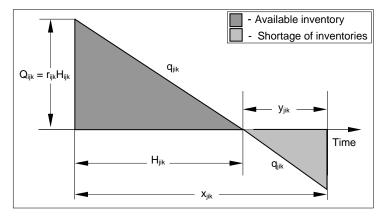
The total inventory cost of goods *(k)* at the manufacturer *(i)* before being sent to the retailer/consumer *(j)* during the period *T* can be determined based on the equation (3) as follows:

$$C_{ijk} = f_{ijk}c_{ijk} = (1/2)m_{ijk}(T^2 / f_{ijk})h_{ijk}$$ (4)

Equations (2)-(4) imply that the frequency fijk is always positive. If referring to the frequency of services of particular transport modes, it will ultimately be out of the direct control of the users-manufacturers and retailers/consumers, thus enabling them a choice of the most convenient transport alternative (see Figure 2).

3.4.3 *The inventory cost at the consumers*

The time interval between the successive arrivals of particular orders of the goods *(k)* at the retailer/consumer *(j)* should be approximately the same as their inter-departure interval(s) from the manufacturer *(i)*, i.e. $H_{ijk} = H_{jik}$. The quantity of goods $Q_{ijk} = m_{ijk}H_{ijk}$ is consumed at the constant rate q_{jik} before ($m_{ijk} < q_{ijk}$), exactly at the time ($m_{ijk} = q_{ijk}$), or after receiving the next order ($m_{ijk} > q_{jik}$). Figure 5 shows the case when $m_{ijk} < q_{ijk}$ with two components of the inventory cost: one to the cost of the inventories held by consumers, and the other to the cost of the shortage of inventories due to rather to quick consumption.

Figure 5. A scheme of the inventories of goods (k) at the consumer (j) after arrived from the manufacturer (i)

If the deliveries are always on time, i.e. without significant deviation from the schedule, the total cost of the consumed inventories can be estimated as:

$$_1c_{jik} = (1/2)x_{jik}m_{ijk}H_{ijk}h_{jik} = (1/2)\left(\frac{m_{ijk}T}{f_{ijk}}\right)^2\left(\frac{1}{q_{jik}}\right)h_{jik} \tag{5a}$$

Similarly, the total cost of the shortage of inventories can be determined as:

$$_2c_{jik} = (1/2)y_{jiki}(y_{jik}q_{jik})p_{jik} = (1/2)\left[\left(\frac{T}{f_{ijk}}\right)\left(1-\frac{m_{ijk}}{q_{jik}}\right)\right]^2 q_{jik}p_{jik} \tag{5b}$$

Combining equations (5a) and (5b) gives the total inventory cost of the goods *(k)*, which have arrived from the manufacturer *(i)* at the retailer/consumer *(j)*. Then, the total inventory cost at the retailer/consumer *(j)* for the period *T* can be estimated as:

$$C_{jik} = f_{ijk}(_1c_{jik} + _2c_{jik}) = (1/2)\left(\frac{T^2}{f_{ijk}}\right)\left(\frac{m_{ijk}^2}{q_{jik}}h_{jik} + (q_{jik} - m_{ijk})p_{jik}\right) \tag{5c}$$

In the equation (5), the frequencies of delivery of goods are again positive and influenced by the similar factors as in the case of inventories at the manufacturer(s).

3.4.4   *The cost of the time taken to transport the goods*

The cost of the time taken to transport the goods *(k)* between the manufacturer *(i)* and the retailer/consumer *(j)* over the period *T* can be determined as:

$$_tC_{ijk} = (m_{ijk}T)t_{ijk}\alpha_{ijk} \tag{6}$$

3.4.5   *The transport time and the transport frequencies*

The transport time t_{ijk} and the transport frequency f_{ijk} in equations (1)-(6) mainly depend on the type of transport network serving the manufacturer *(i)* and the consumer *(j)*, and the transport modes involved. Referring to Figure 3 is Section 3, they can be determined as follows:

i)   *Direct transportation*

- Transport time

The transport time consists of a single component excluding the anticipated delay as follows:

$$t_{ijk} = d_{ijk}/v_{ijk}(d_{ijk}) + W_{ijk} \tag{7a}$$

The time t_{ijk} is actually the stochastic variable with a given probability density function characterized by its mean and standard deviation. The mean mainly depends on the distance and the average speed. The standard deviation mainly depends on the traffic conditions and the other speed-affecting factors along the route, including disruptive events of a relatively milder impact. The standard deviation of t_{ijk} compromises the on-time arrival of given goods at the retailer/consumer *(j)*. In order to prevent the shortage of inventories, this retailer/ consumer should maintain the protective inventories at additional cost[4].

- Transport frequency

The frequency of sending goods *(k)* from the manufacturer *(i)* to the retailer/consumer *(j)* can be determined as follows:

$$f_{ijk} \equiv f_{ijk}^{*} \tag{7b}$$

In this case, the road transport is presumably used because of its inherent flexibility and ability to respond to the retailers/consumers' and the manufactures' requirements at any time (Figure 3a).

ii) *The transport with consolidation/deconsolidation at two different locations*

- Transport time

The transport time consists of five components excluding the anticipated delay(s) as follows:

$$t_{ijk} = d_{i1k}/v_{i1k}(d_{i1k}) + W_{i1k} + \tau_{i1k} + d_{12k}/v_{12k}(d_{12k}) + W_{12k} + \tau_{2jk} + d_{2jk}/v_{2jk}(d_{2jk}) + W_{2jk} \tag{8a}$$

The time t_{ijk} can also be considered as a stochastic variable, composed of the five stochastic components (excluding the anticipated delays). Each component has its probability distribution with the main parameters-mean and standard deviation. Intuitively, one can conclude that this integrated average time might be longer than is the case for direct connections. Certainly, it will have a greater standard deviation consisted of the sum of the standard deviations of the five components (stochastic variables). This may imply the higher transport inventory cost as well as a higher cost of the protective inventories at the retailers/consumers (Winston, 1994).

- Transport frequency

The frequency of sending goods *(k)* from the manufacturer *(i)* to the retailer/consumer *(j)* can be determined as follows:

$$f_{ijk} \equiv f_{12k} \tag{8b}$$

The frequency f_{12} in equation (8b) is usually determined by the schedule of transport modes involved - rail, inland waterways, or air (Figure 3b). Thus, since many manufacturers and consumers are served at the same time, this frequency is likely to be differently efficient and effective regarding their specific requirements.

iii) *The transport with consolidation/deconsolidation at a common location*

- Transport time

The transport time consists of three components excluding the anticipated delays as follows:

$$t_{ijk} = d_{i1k}/v_{i1k}(d_{i1k}) + W_{i1k} + \tau_{1k} + W_{1jk} + d_{2jk}/v_{1jk}(d_{2jk}) \tag{9a}$$

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[4] If the time t_{ijk} is considered as a stochastic variable with a normal (Gauss) probability distribution, mean $\overline{t_{ijk}}$ and standard deviation $\sigma_{t_{ijk}}$, and if the acceptable risk of a shortage of the goods *(k)* at the consumption plant *(j)* is β_{jk}, the cost of the protective inventories per delivery will be of the order: $(1/2)q_{jik}h_{jik}\left(\sigma_{t_{ijk}}\Phi^{-1}(1-\beta_{jk})\right)^{2}$ (Φ^{1} is the inverse of Laplace function (Winston, 1994)) and should be added to the cost in equation (5c).

The time tijk in the equation (9b) can be considered similarly as in case ii) as a stochastic variable composed of three other stochastic variables with a known probability distribution, mean and standard deviation. Intuitively, one can conclude that the standard deviation of the resulting time might be shorter than in case ii) but longer than in case i). It again requires protective inventories at the retailer/consumer (j), which impose additional inventory cost.

- Transport frequency

The frequency of delivering goods *(k)* between the manufacturer *(i)* and the retailer/consumer *(j)* can be determined as:

$$f_{ijk} \equiv \min(f_{i1k}; f_{k1j}) \tag{9b}$$

The frequency f_{ijk} in the equation (9b) may again serve a single or a cluster of geographically very close manufacturers and consumers, which again makes it different in terms of convenience for their specific requirements (Figure 3c).

3.4.6   The transport cost

The transport cost implies the cost of the physical movement of the goods *(k)* from the manufacturer *(i)* to the retailer/consumer *(j)*. This cost has two aspects: i) that of the manufacturer, and that of the retailer/consumer, in which case the price paid for service is relevant; and ii) that of the transport operators, in which case their operational cost is relevant. In the given case, the former aspect is considered. Consequently, the total transport cost of the service frequencies f_{ijk}, each carrying the quantity Q_{ijk} of the goods *(k)*, during the period *T* can be estimated as follows:

$$C_{ijk}^{t} = f_{ijk} Q_{ijk} P_{ikl} \tag{10a}$$

In equation (10a), the price P_{ijk} mainly depends on the distance and size, i.e. the weight or the volume, of the order/delivery, and thus can be expressed as:

$$P_{ijk} = a_k d_{ijk} + b_k Q_{ijk} = a_k d_{ijk} + b_k \left(\frac{m_{ijk} T}{f_{ijk}} \right) = a_k d_{ijk} + b_k \left(\frac{m_{ijk} T S_{ijk}}{f_{ijk}} \right) \tag{10b}$$

In many cases, the price P_{ijk} may include the cost of handling the goods, which refer to operations such as loading, unloading, and eventually transhipment between different transport modes at the consolidation /deconsolidation terminals.

3.5   The model structure – irregular operations

Various internal and/or external disruptive events may affect the given logistics network. In the given context, for the chain *(ijk)* this scenario implies cutting-off connections and consequently the transportation of the goods *(k)* from the manufacturer *(i)* to retailer/consumer *(j)* for a certain period of time φ_{ijk}. Under such circumstances the number of cancelled orders and the number of delivered orders $f_{ijk/c}$ and F_{ijk}, respectively, can be determined as follows:

$$f_{ijk/c} = (\varphi_{ijk} / H_{ijk}) \equiv (\varphi_{ijk} f_{ijk}) / T \tag{11a}$$

$$F_{ijk} = f_{ijk} - f_{ijk/c} = f_{ijk} - \varphi_{ijk} f_{ijk} / T = f_{ijk} \left(1 - \frac{\varphi_{ijk}}{T} \right) \tag{11b}$$

In equation (11b), if $\varphi_{ijk} = T$, the network will be completely blocked for any delivery during the entire period *T*. Consequently, the inventories of goods *(k)* at the manufacturer *(i)* will increase to the level $m_{ijk}T$. Otherwise, the retailer/consumer *(j)* will have to keep protective inventories of

about $q_{ijk}T$ in order to compensate the shortage of goods *(k)* during the network breakdown. When $\varphi_{ijk} < T$, the impact of compromised frequency on the cost of the given logistics network can be estimated by replacing the variable f_{ijk} in the equations (2) – (10) with the variable F_{ijk} in the equation (11b).

3.6   The total and the average cost of the given logistics network

The total cost of the given logistics network can be determined from equations (2)-(11) as follows:

$$C_T = \sum_{ijk} (C_{ijk} + C_{jik} +_t C_{ijk} + C_{ijk}^t)$$

(12a)

The total quantity of goods handled by the network during the period *T* can be determined as:

$$Q_T = \sum_{ijk} m_{ijk} T$$

(12b)

Dividing the total cost (12a) by the total quantity of goods (12b) gives the average cost per unit of goods. This might be of interest for comparing the different network configurations, which handle different quantities of the various goods using different transport modes operating under either regular or irregular (disruptive) conditions.

4.   An application of the model

4.1   Description of inputs

The model is applied to a logistics network, which consists of M = 70 manufacturers and N = 70 retailers/consumers. They are clustered in the "manufacturer" and the "consumption" area, respectively, at an average door-to-door distance of d = 900 km. They exchange goods with each other, which makes 4900 possible interactions. In Europe, this may refer to the areas between the Benelux countries (Belgium, the Netherlands, and Luxembourg) and the North Italy and/or the South of France. The goods are consolidated into pallets. The number to be sent between the two regions during the period T = 1 year amounts to 30 million. If they are uniformly distributed, this will give an average flow of 6122 pallets/year between each manufacturer and each retailer/consumer. The average weight of a pallet amounts to 0.75 tones and its value p = 1500 €/pallet. The interest rate of goods on each pallet is r = 6.5%. Consequently, the average value of time of a pallet is estimated to be α = pr = 1500 x 0.65 = 92.5 €/pallet-year. The average holding cost of a pallet at the inventories at each manufacturer and each retailer/consumer is assumed to be h = 5€/day. The standard deviation of the arrival of pallets at the retailers/consumers is assumed to be: σ = 4 and σ = 12 hours per delivery, independently of the order/delivery frequency. The acceptable risk of the shortage of goods at each consumer-retailer is assumed to be β = 0.05.

Two networks in terms of their spatial configurations are assumed to exclusively serve the manufacturers and the retailers/consumers: i) the direct transport network operated by the road transport mode (Figure 3a); and ii) the intermodal rail/road transport network with one consolidation and one deconsolidation of goods, i.e. transhipments, at two intermodal terminals (Figure 3b). In case ii), the pallets are additionally consolidated into the containers, swap-bodies, and semi-trailers. At the road transport, the average speed of moving pallets through the network is assumed to be: v1 = v2 = 45 km/h. For intermodal transport, this average speed is assumed to be: v1 = v2 = 30 km/h along a road haulage distance of d1 = d2 = 50 km at both ends of the network, and v12 = 30 km/h along a rail haul distance of d12 = 800 km (EC, 2001a, b; 2002). These speeds also include the time taken to pass through the two intermodal terminals. The vehicle carrying capacity is 28 pallets/truck and 1015 pallets/train.

The average transport cost of a pallet between any pair of manufacturers and consumers-retailers is assumed to be: P = 28.64€/pallet in road transport network and P = 30.17€/pallet in the intermodal transport network (Groothedde, 2005; Janic, 2007). The impact of the disruptive event causes cancellation of transport services during the time of its durationφ.

4.2   Analysis of the results

The calculations with the model are carried out in order to investigate the sensitivity of the network cost performance to changes of the type of transport network (mode) used, the goods' order/delivery frequency, and the intensity of the impact and duration of the disruptive event. The other inputs are considered as parameters and implicitly independent of each other. This particularly relates to the overall quantity of goods in the network, which may generally depend on price of the goods', the quantities carried out by different transport modes, which may depend on the level of their competition and the related transport prices, the transport cost, which may change with the quantity of the transported goods, etc. The results are shown in Figures 6 and 7.

Figure 6 shows the dependence of the average cost per item/pallet on the frequency of orders/delivery between tan average pair of manufacturers and retailers/consumers.
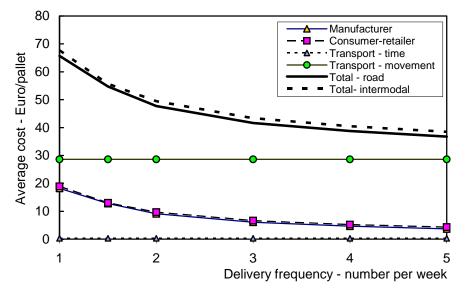

Figure 6. Dependence of the average cost per pallet on the order/delivery frequencies in a given example

As can be seen, if road transport is used, the average inventory cost per pallet at both manufacturers and consumers-retailers decreases more than proportionally to frequency of orders/deliveries. The transport, inventory, and moving costs remain constant. Consequently, the total average cost per pallet decreases more than proportionally too with the frequency of orders/deliveries, respectively. In addition, the average inventory cost at the consumer-retailer is a bit higher because of maintaining the protective inventories. Under the assumption that the intermodal transport performs similarly to road transport in terms of the capacity and frequency of carrying out orders/deliveries according to the requirements, its cost will be higher than the cost of the road transport mainly because of the higher transport costs and the higher protective inventory cost at the consumers-retailers. The above-mentioned generic dependability explains why both manufacturers and retailers/consumers tend to make more frequent orders/deliveries, which apply to either the PUSH or the PULL concept - they push inventories from their stocks into the transport system. The more frequent (smaller) orders/deliveries require the deployment of a larger number of vehicles. The road transport mode is often capable of fulfilling such requirements, which may explain its, although slight, growth in terms of catchment of the market

share, in Europe. Intermodal transport usually responds by running the daily trains (i.e. up to five trains per week per operator). This, if combined with the limits of capacity of each train, constrains the operator's flexibility to appropriately respond and consequently capture a higher market share(s). For example, when train capacity amounts to one thousand pallets per train, intermodal transport will be able to count on about 250 thousand pallets per year, which is about 0.83 % of the total of 30 million pallets in the given example. If more rail transport operators provided capacity equivalent to ten trains per week, the market share of intermodal transport would increase to about 8.3%. This reasoning is sensible only if the higher prices of the intermodal transport would be acceptable for particular users – the manufacturers and the retailers/consumers.

Figure 7 shows that the average cost per pallet will increase more than proportionally to the duration of the disruption of a given logistics network.
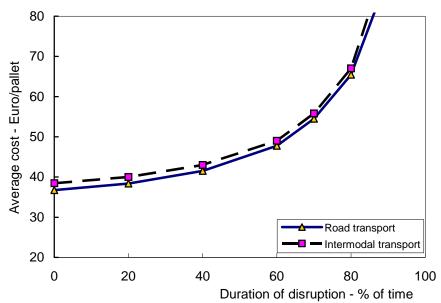

Figure 7. Dependence on the average cost per pallet on the duration of the disruption of the logistics network in a given example

In the given scenario, the disruption is assumed to completely cut off the transport links between manufacturers and retailers/consumers for a given period of time. Its duration is varied as a parameter in relative terms. Under such circumstances combined with the lack of the alternative routes, the particular transport services/deliveries will not be carried out, thus causing loss of revenues but also reduced cost for the affected transport operators. In addition, the inventories and the related costs at manufacturers, and the shortage of goods and related cost at retailers/consumers will increase. Consequently, the total average cost per unit of the transported quantity of goods will increase more than proportionally by the duration of such a disruptive event concerned. Again, this cost is slightly higher for intermodal than for road transport.

In addition, it should be noticed that road transport seems to be less vulnerable to any kind of the disruptive events than intermodal transport. For example, if road transport is used, the disruption, if it is not on a large spatial scale, might affect only individual pairs of the manufacturers and the retailers/consumers. However, if intermodal transport is used, the disruption of one of the terminals and/or of the rail line might ultimately affect almost all manufacturers and all retailers/consumers connected to them. This might consequently increase the total cost of disruption of the intermodal transport network by several times compared with the corresponding cost of using the equivalent road transport network, the fact which would

regarding this inherent vulnerability, appear not to favour the use of intermodal transport network.

5.   Conclusions

This paper has developed an analytical model for estimating the cost performance of a given logistics network operating under planned-regular and unplanned–irregular (disruptive) conditions. The network costs have included the inventory cost of the given goods at the manufacturers' and the retailers/consumers' locations, the cost of the time taken to transport the goods, and the cost of their transportation between the manufacturers and the retailers/consumers.

The model was applied to a simplified logistics network using data from Europe. The aim was to carry out a sensitivity analysis of this cost with respect to changes of the most influential parameters, which in this case were the delivery frequency of goods and the duration of the disruptive event tat was assumed to completely cut off connections between the manufacturers and the retailers/consumers. The other variables were also considered as parameters. In the sensitivity analysis, the logistic network has been exclusively served by either the road or the intermodal rail/road transport mode.

The results obtained showed that, under the regular operating conditions, the average network cost per unit of quantity of goods consolidated into pallet(s) decreased more than proportionally as the order/delivery frequency increased independently of the transport mode used. In particular, the inventory cost of goods at the manufacturers and at the retailers/consumers decreased, while the cost of the time taken to transport the goods and the cost of transportation itself remained constant. This happened because of pushing the inventories from the stocks of manufacturers and the stocks of retailers/consumers into the transport system. In that context, the road transport was shown to be slightly cheaper than its road/rail intermodal counterpart.

Disruption of the given logistics network prevented the delivery of the goods and consequently increased the average cost per unit of the transported goods – the pallet - more than proportionally to the duration of it. This cost was again slightly higher for intermodal than for road transport for the entire duration of the disruptive event.

The model and the results also showed that if road transport was exclusively used, the impact of particular disruptions might very likely remain relatively limited to the particular manufacturers and retailers/consumers-. However, if intermodal transport was used, the impact of these disruptions affecting any of the intermodal terminals and/or the rail line(s) connecting them might affect many more manufacturers and retailers/consumer connected to it (them) and consequently causes a substantial increase in the total inventory costs. This again might act against more intensive use of rail/road intermodal transport in the given context.

Further research might be focused on the additional refinement of the proposed model by alleviating its present limits, including modifying its existing structure by taking into account the mutual dependability between particular variables. This may include considering more realistically the quantity of goods (i.e. demand) - price relationship, diverse goods of different quantities and requirements for transportation, the modal competition, and the external cost of particular transport modes serving the same logistics network. Last but not least, more realistic scenarios of the impact of disruptive events, in terms of a spatial scale, intensity of impact, and duration could be considered too.

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