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RISK ANALYSIS AND EVALUATION FOR CRITICAL LOGISTICAL INFRASTRUCTURE

Abstract

Logistical infrastructure builds the backbone of an economy. Without an effective logistical infrastructure in place, the supply for both enterprises and consumers might not be met. But even a high-quality logistical infrastructure can be threatened by risks. Thus, it is important to identify, analyse, and evaluate risks for logistical infrastructure that might threaten logistical processes. Only if those risks are known and their impact estimated, decision makers can implement counteractive measures to reduce risks.

In this article, we develop a network-based approach that allows for the evaluation of risks and their consequences onto the logistical network. We will demonstrate the relevance of this approach by applying it to the logistics network of the central German state of Hesse. Even though transport data is extensively tracked and recorded nowadays, typical daily risks, like accidents on a motorway, and extraordinary risks, like a bridge at risk to collapse, terrorist attacks or climate-related catastrophes, are not systematically anticipated. Several studies unveiled recently that the overall impact for an economy of possible failures of single nodes and/or edges in a network are not calculated, and particularly critical edges are not identified in advance. We address this information gap by a method that helps to identify and quantify risks in a given network. To reach this objective, we define a mathematical optimization model that quantifies the current "risk-related costs" of the overall network and quantify the risk by investigating the change of the overall costs in the case a risk is realized.

Keywords: Logistics, risk, resilience, critical infrastructure

1. Introduction

Logistical infrastructure builds the backbone of an economy (Panasyuk et al., 2013). Without an effective logistical infrastructure in place, logistical processes are more difficult (i.e. might take longer and arrive late, might face quality problems, and might lead to higher cost), and demand for both enterprises and consumers might not be met. But even a high-quality logistical infrastructure can be threatened by risks.

One out of many examples is the blocking of the Suez Canal in 2004 by the broken-down tanker 'Tropic Brilliance'. The tanker experienced problems with the steering gear and grounded itself. At this location the Suez Canal was too narrow for other vessels to pass, so that the logistical infrastructure was blocked for any transportation processes. For 39 vessels already in the Suez Canal and another 113 ships waiting at the two entrances, this accident led to an unplanned delay of their transport chains of a few days (Ibrahim, 2004)[1]. The delay in return created even more problems for the supply chains the vessels were part of: Sony Corporation, for example, faced serious problems fulfilling customer demand for PlayStations in the UK (which was higher than normal due to Christmas sales), because the supply was stuck in the Suez Canal (Elliott, Theodoulou, 2004)[2]. In the end, Sony paid a high price to match demand, since as a result of the unintended situation in the Suez Canal; it chartered Russian Antonov AN-124 planes to ship PlayStations directly from China to the UK (Manners-Bell, 2014: 61-62). What can be derived from this example is how the (even temporary) blocking, or in general: unavailability, of logistical infrastructure can lead to tremendous negative effects on supply chains.

Thus, it is important to identify, analyse, and evaluate risks for logistical infrastructure that might threaten logistical processes. Only if those risks are known and their impact estimated, decision makers can plan and implement counteractive measures to reduce risks.

2. *Basics of risk management for logistical infrastructure*

2.1 *The importance of logistical infrastructure*

Logistics has always played a major role for economies. Examples show, that this has been true for projects on the regional or national level (such as for the building of the pyramids in Egypt) as well as for international trade such as between China and Europe using the Silk Road. Nowadays, the role of logistics is even bigger than before. In Germany, for example, the logistics sector is the 3rd biggest industry (behind the automotive industry and the retail sector), with an estimated total revenue of 240 billion EUR (Bundesvereinigung Logistik (BVL) e. V., 2016)[3].

Logistics might be defined as 'the process of strategically managing the procurement, movement, and storage of materials, parts and finished inventory (and the related information flows) through the organisation and its marketing channels in such a way that current and future probability are maximised though the cost-effective fulfilment of orders' (Christopher, 2011: 2). In our particular work we will have a more narrow understanding of the term "logistics" as the management and organization of all transportation processes of physical goods plus any necessary storage and handling processes. This includes freight logistics as well as public transportation and the transport of any personnel.

Additionally we can agree on the 6 'r' of logistics: Logistics ensures that the right product in the right quantity and the right quality is delivered at the right time to the right place or customer for the right cost (Jünemann, 1989: 18). To provide logistical services at a promised service level, certain prerequisites are necessary. One of the prerequisites is the logistical infrastructure.

Logistical infrastructure can be summarized as all facilities necessary to complete the logistical mission. Those facilities include production and distribution facilities as well as the transportation links between them (Closs, Thomson, 1992: 269). If we focus on the basic logistical processes such as transportation, warehousing, and handling, then those facilities can be classified into two types: On one hand, the logistical infrastructure consists of logistical nodes where goods are stored and handled. Those nodes can be any warehouse or transhipment point. On the other hand, there are logistical edges that are used for connecting logistical nodes. Those connecting edges are used for transportation processes. Possible additional so-called value-adding services are normally also carried out in the logistical nodes. We will, however, focus on the classical logistical processes such as transportation, handling, and storing.

The logistical infrastructure is a necessary prerequisite to provide logistical services. Without infrastructure, logistical services are not possible. However, the availability, capacity, and quality of the logistical infrastructure influence the performance of logistics. A good infrastructure enables smooth, fast, and efficient logistical processes, whereas a low level of the infrastructure hinders logistical performance. This becomes obvious when analysing the results of the World Bank that evaluated the logistical performance of 160 countries using the so-called 'international logistics performance indicator' (international LPI). The LPI consists of six components; and one of the components is infrastructure (Arvis et al., 2014: 7)[4]. The results of the analysis show that countries, that are ranked within the top 10 logistics performers (such as Germany as the overall number one on the list), also have a dense and high-quality infrastructure; on the other hand, countries within the bottom 10 (such as Somalia) also have an infrastructure far below average (Arvis et al., 2014: 34-37).

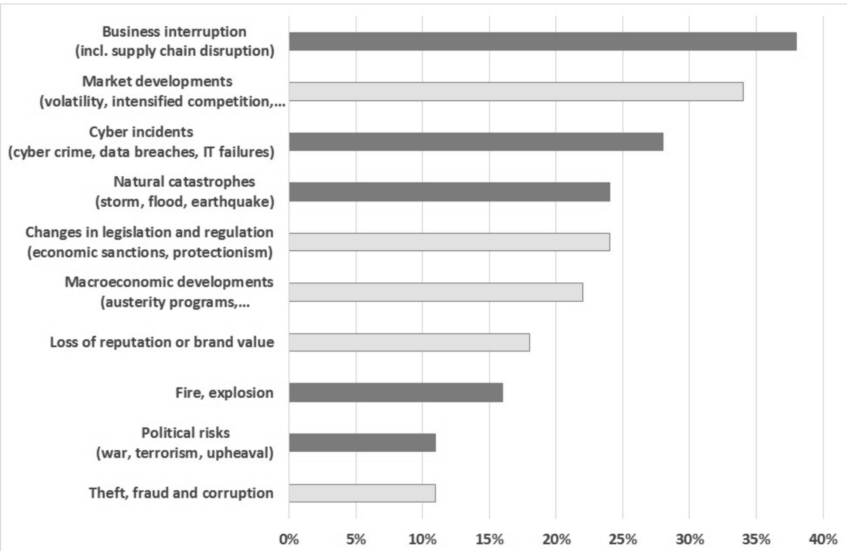
In 1996 President Bill Clinton first mentioned the term "Critical Infrastructure" in his Executive Order 13010, which ultimately resulted in the inauguration of the President's Commission on Critical Infrastructure Protection. The order defines a critical infrastructure: "Certain national infrastructures are so vital that their incapacity or destruction would have a debilitating impact on the defence or economic security of the United States." Applying that definition to the transportation infrastructure of a region, state, country or supranational network, a critical logistical infrastructure is a certain part of this network that its (temporarily) unavailability would have a highly negative impact on the possibility to supply certain nodes in the network properly. This negative impact can be either the complete cut-off of parts of the network or a substantial rise in operational costs.

2.2 Risks concerning the logistical infrastructure

The role and the importance of logistical infrastructure lead to the assumption, that possible threads to the infrastructure influence its availability and its quality. This, in return, has implications for the logistical performance. For example, the overturn of a vessel on an inland waterway might hinder any other vessel to pass this location until the vessel is recovered. The flow of goods might then be halted or rerouted. The rerouting, however, will lead to higher costs if other means of transportation have to be used. On the other hand, if the flow of goods is stopped, there might be cost due to out-of-stock situations. Furthermore, due to the high interconnectivity between different modes of transports or different logistical sub-infrastructures, every failure or blockade of one single edge can progress to a failure or blockade of whole parts of the network or, in the worst case, even to the halt of all logistical flows within the network. As an example one might consider a logistical infrastructure with a very centralized structure. If the central node in that network is the central airport as well as the central train station and the central port of the whole network, a total blockade of that very node could lead to a full halt of all logistics within the network not transported via the street network. This abstract-looking risk is not as abstract as it seems and might, for instance, be realized if Greater London is cut off from the power network for a certain period of time.

Logistical infrastructure can be threatened by a number of risks. Different approaches to risk classification, also focusing on logistics, are available (for example Heckmann et al., 2015: 122-127). To demonstrate the variety of risks that might influence availability and quality of the logistical infrastructure, we use the results of the latest study by Allianz[5] (Allianz SE/Allianz Global Corporate & Specialty SE (2016)).

Figure 1 Top business risks 2016



Source: Allianz SE/Allianz Global Corporate & Specialty SE (2016), p. 1

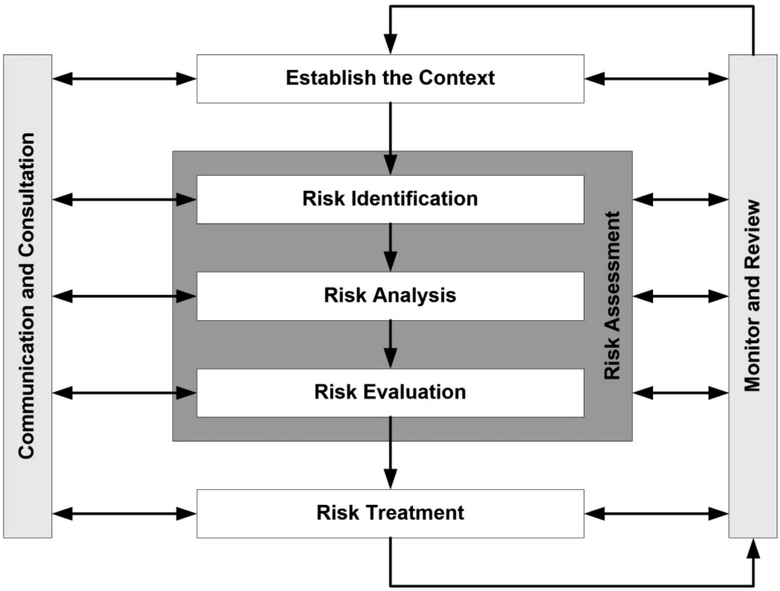
Figure 1 shows the top ten risks that might threaten businesses, as identified and ranked by Allianz. The dark blue bars reflect risks that have a connection to the logistical infrastructure, whereas the light blue bars have no link to the logistical infrastructure or the influence can be neglected. Business interruptions, including supply chain disruptions, are identified as the absolute top risks for businesses. However, one of the risks that have an increasing importance for business is cyber incidents. Due to changes in technology that lead to a wider digitalization of processes, the vulnerability of such processes increases (Zimmermann, 2004: 2). This is especially true for digitalized processes between two or more companies, as promised by Industry 4.0 approaches (Brettel et al., 2014). Natural catastrophes can have a major impact on logistical infrastructure. Examples for natural catastrophes are the Tōhoku earthquake and the following tsunami in 2011, which led to major damage to the critical infrastructure in Japan, and the eruption of the Icelandic volcano Eyjafjallajökull, which led to the closure of airspace and thus impacted air travel and air cargo all over Europe (Jones, Bolivar, 2011). The risk of natural disasters and geological catastrophes is getting higher every year as recent studies show (Munich Re, 2016)[6]. Another risk with increasing importance is the risk of a terror attack. One example is the bombings in Brussels in 2016, where two types of infrastructure (airport, underground) had been attacked by terrorists simultaneously; thus, those attacks affected the whole public transportation in Belgium.

2.3 Risk management

Risks are an immanent factor to all processes. Thus, it is not possible to fully exclude risk to establish certainty. To integrate risk in business and to be able to plan under risk, risk management offers an effective framework. Risk management can be defined as "the identification, assessment, and prioritization of risks followed by coordinated and economical application of resources to minimize, monitor, and control the probability and/or impact of unfortunate events." (Hubbard, 2009: 10)

Risk management can and should be seen as an iterative process chain. This risk management process is standardized by ISO 31000, which describes the different phases of risk management as depicted in Figure 2.

Figure 2 Risk management process



Source: Purdy (2010: 883)

The central steps in the risk management process are the risk assessment and, to actually handle the risk, the risk treatment. However, without a solid and effective risk assessment, risk treatment is not possible.

Risk assessment can be divided into three steps: The first step is to identify potential threats. It is actually the process of searching for known and unknown risks. In the second step, those risks that have been identified with the risk identification are now analysed. That is, "risk analysis is concerned with developing an understanding of each risk, its consequences, and the likelihood of those consequences." (Purdy, 2010: 884) The last step of the risk assessment is to evaluate and prioritize risks. This step is preparing risk treatment. However, often resources – staff, money, time, etc. – are limited, so that an efficient allocation of existing resources is necessary. Risk evaluation that aims to make a decision about the 'level' of risk is thus the foundation of risk treatment.

Applied to the context of logistical infrastructures, the first step reflects the identification of parts of the infrastructure that are more threatened by the potential realisation of any risk than others. This could be parts of the infrastructure that seem to be "attractive" to terrorists, as they are extremely vulnerable or critical to the infrastructure, or to those parts that are exposed to harsh geographic surroundings, for example by crossing earthquake infected or flood threatened regions. This phase of the risk management process is not further examined within this paper. Instead, we will focus on the second and the third step by presenting an approach that "puts a price tag" on a risk.

Although risks can only be reduced or avoided by applying the next phase of the risk management process (the 'risk treatment'), it is obvious that risk assessment plays a major role in risk management. Thus, this article focuses on risk assessment by proposing a model that helps to identify, analyse, and evaluate risks for the logistical infrastructure.

3. A network optimization approach

3.1 Basic idea

A multi-modal logistical infrastructure is used by a number of different actors at the same time. In reality those are, at least in some multi-modal sub-networks, logistical actors, private persons and public transport means. In contrast to a supply chain, where some regulating higher instance can coordinate the whole network, such a (partly) public network cannot be governed directly. In particular, this has an immense effect on the risk analysis and assessment of the infrastructure as a whole and all of its parts. To be able to receive a valid risk assessment the behaviour of all users of the network before and after the realisation of a risk has to be anticipated. The risk assessment, which means measuring the grade of the damage, can then be seen as the cost difference caused by the realisation of the risk. To quantify this, the whole network has to be valued as a whole twice, once before the risk realisation and once afterwards.

3.2 Assumptions

To enable an assessment of the network the following assumptions are made:

- The network has a finite number of well-defined points, called communities,
- For every community a net demand or net supply, given in transportation units (TU), is given,
- For every connection between two communities a capacity limit in TU per time unit is given,
- For every connection costs per TU are known.

Furthermore, we assume that the network is closed, which means that every TU, which is supplied in a community v inside the network, is demanded by, and transported to, any target community w inside the network. However, this assumption does not restrict the model in any way, as any non-closed network can easily be transformed into a closed network by introducing dummy communities that represent external supply or demand. Finally, we assume that all actors within the network act economically, maximizing their own profit. Explicitly this means that private uses of the network, like public transport means, that might also use a certain capacity on selected connections between communities, cannot be modelled. Implicitly such non-logistical users can be considered by lowering the capacity by the value of the mean of other usage before modelling the network.

3.3 Network definition

The logistical network of the observed region can be modelled as a graph $G = (V, E)$. Every vertex $v \in V$ then represents a community within the network and every edge $e = (v, w) \in E$ represents a single direct connection between two communities. Furthermore, let $b(v)$ be the net supply or demand of community $v \in V$ per time unit t. Supplying communities have a negative value, while demanding communities have a positive value. As we assume, as presented above, that the network is closed, the following equation holds:

$$\sum_{\forall v \in V} w(v) = 0$$

Finally, all edges have a non-negative capacity per time unit $u(e)$ and edge specific usage costs of $c(e)$.

3.4 Problem definition

Based on the above network, we can now formulate an optimization problem, which minimizes the overall costs of the network. This reflects, at least approximately and under the before-mentioned assumptions, the overall traffic amount within the network. In reality, users usually behave egoistically and are thus only interested in their own cost minimization and not in the minimization of the overall network costs. However, if the capacity on any highly prioritized part of the network is a scarce resource, even egoistically behaving actors will switch to the next best route. This way the probable real life traffic amount approximates, at least in a long term view, the calculated overall costs of the optimal solution.

Another possible criticism is the fact that the model does not consider any differentiation between different goods, which means in real life that demand for any good of type A, say candles, can be met by supplying the node with any good B, say water, as long as the amount of TU of the demand equals the amount of the supply. To take different type of goods in account, or the fact that a company X cannot or will not meet the demand of company Y, different networks can be set up for each and every type of goods and/or company. To get an overall result a first, prioritized, network model can then be solved and the resulting amount of traffic on every single edge can then be deducted from the overall capacity of this particular edge.

The resulting optimization problem is known as the Minimum Cost Flow Problem or Minimal Cost Flow Problem in literature and can be modelled as a linear program as follows:

$$\min \sum_{e \in E} c(e) * f(e)$$

$$\sum_{e \in N^+(v)} f(e) - \sum_{e \in N^-(v)} f(e) = b(v) \qquad \forall v \in V$$

$$0 \le f(e) \le u(e) \qquad \forall e \in E$$

Here, $f(e)$, for all $e \in E$, are the decision variables of the model. Further, $N^+(v)$ describes the set of all positive neighbours of each $v \in V$ and analogously $N^-(v)$ denotes the set of all negative neighbours of $v \in V$.

The objective function minimizes the overall costs of the network. The first constraint guarantees that the solution does really represent a flow within the network that meets all demands and supplies. The second constraint takes the capacity restrictions of the single edges into account.

3.5 Solutions of the problem

The above formulated model can be solved in polynomial time, for example with the minimum mean cycle cancelling algorithm of Goldberg and Tarjan (Goldberg, Tarjan, 1989). The result of the optimization is, other than a complete display of all traffic amounts, an objective value, which represents the minimal costs of the overall network. This can be interpreted as the quantitative assessment of the overall network. If a risk is realized the network can be adjusted to the new situation by simply deleting the destructed edge(s) and/or vertex or vertices. Let $\breve{G} = (\breve{V}, \breve{E})$ be the resulting sub-network with $\breve{E} \subset E$ and $\breve{V} \subset V$. Now, the solution space of the Minimum Cost Flow Problem on $\breve{G}$ is a sub-space of the solution space of the Minimum Cost Flow Problem on G. In particular it holds for the solution value that:

$$\Delta MCFP := MCFP(\breve{G}) - MCFP(G) \ge 0$$

This difference of the objective values can be interpreted as the costs of the realization of the risk. With the help of this "risk costs" and the common probability of a risk realization $P(\breve{V}, \breve{E})$ on all edges and/or vertices the risk can be assessed as

$$Risk(\breve{V}, \breve{E}) = P(\breve{V}, \breve{E}) * \Delta MCFP$$

3.6 Limitations of the current approach

In this section, we critically look at the above model and examine its strengths and weaknesses by listing different risk scenarios where the model will be useful and others where the model could theoretically be applied, but would not lead to any satisfying results. Theoretically, the model can be applied to the "intact network" and an erratic network in any case, as long as the risk realization can be identified as the total crash of at least one edge or one node of the network. However, as the network, in which the destroyed edge(s) and/or node(s) are deleted, is only optimized once, it cannot reflect any slowly adopting process. Instead the optimal solution of the initial network and the optimal solution of the erratic network are calculated and compared. However, in real life settings a network will slowly adapt to the new situation after the realization of a risk and the erratic edge(s) and/or node(s) will be avoided in non-optimal ways shortly after the risk is realized. Therefore, the model is most useful and closest to the reality for any applications where edge(s) and/or node(s) are destroyed for a longer period of time. In this case the new optimal solution for the erratic network can be achieved in real life by guiding the traffic accordingly on all parts of the network.

4. Conclusion and future extensions

The future extensions focus on two areas: On the one hand, the limitations of the current approach need to be eliminated so that the model reflects real-world business processes better, and the acceptance is increased. The most natural extension addresses the slow adaption to a crash of parts of the network by choosing the following approach:

With the above described model the optimal solution, which stores the traffic usage on each edge as the flow, can be determined for the pre-crash network and the post-crash network. As a part of that solution of the pre-crash network the actual flows on all edges of the network, including the edges crashing and those neighbouring crashing edges, are known. Assuming a crash on a subset of edges the position of all logistical transportations is implicitly given by the flow on each edge. For the sake of simplicity, the positions of currently flowing transport units can be assumed to be at a node within the network. This could be done, for instance, by assigning half of the flow on each edge to its start node and half of the flow to its end node. In the event of a crash, in this way we assign all transport units that are within the network to a node in the network. By doing that, and deleting the crashed edge(s) and/or node(s), we gain a new network with manipulated node weights (= demands/supplies), called $\tilde{G}$. Optimizing this net network in the very same way as described above gives an optimal value that reflects an optimal behaviour of all parties in an event of a crash. All transport units that will be transported at any later points can then be assumed to be transported in the (new) optimal way through the after-crash network. This way we receive 3 different optimal values of the same problem on different networks: $MCFP(G)$, $MCFP(\breve{G})$ and $MCFP(\tilde{G})$. Furthermore, we assume that the time for the crashed edge(s) and/or node(s) to recover is known as T_{rec} and the fraction of a time unit when the crash occurred is known as $0 \leq t_{crash} \leq 1$. The costs of the crash can then be calculated as:

$$\tilde{\Delta} MCFP = \frac{MCFP(\breve{G}) * T_{rec} - MCFP(\tilde{G}) * (1 - t_{crash})}{T_{rec} + (1 - t_{crash})} - MCFP(G)$$

This extension allows us to consider a two-step optimization of the network towards the new, worse, situation. However, it does not yet consider a "smooth" adaptation process of the whole network nor does it tackle all the remaining gaps between real life applications and the mathematical model above.

Consequently, further extensions include

- a time horizon, which allows the model to adapt slowly to a new situation and differentiate the costs of a risk depending on the time the subnetwork is defunct;
- a pre-processing which derives the needed data from existing data on logistical network;
- the consideration of recovering costs and the effects recovering works might have on the logistical network;
- a differentiation between different actors and different goods in a way that forbids fulfilling a demand of a certain good of a certain supplier by any other good or any other supplier;
- mathematical relations between the current usage grade and the usage costs to reflect that using a "busy street" might be "slower" than using an "empty" street.

On the other hand, future extensions will focus on establishing a better provision of data. So far, the data situation has not been optimal. For decision making within the risk management process, better, i.e. more detailed data is necessary.

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ANALIZA I PROCJENA RIZIKA ZA KLJUČNU LOGISTIČKU INFRASTRUKTURU

Sažetak

Logistička infrastruktura predstavlja okosnicu gospodarstva. Bez postavljene učinkovite logističke infrastrukture, opskrba možda ne bi bila moguća, kako poduzeća tako i potrošača. Međutim, čak i visokokvalitetna logistička infrastruktura može biti izložena riziku. Stoga je važno definirati, analizirati i procijeniti rizik za logističku infrastrukturu koji bi mogao ugroziti logističke procese. Donositelji odluka mogu provesti protumjere za smanjenje rizika samo ako su ti rizici poznati i ako je izvršena procjena njihovoga učinka.

U ovome ćemo članku izraditi pristup na temelju mreže koji će omogućiti procjenu rizika i njihovih posljedica na logističku mrežu. Pokazat ćemo relevantnost ovoga pristupa tako što ćemo ga primijeniti na središnju njemačku saveznu pokrajinu Hessen. Iako se danas podatci o transportu detaljno prate i bilježe, tipični dnevni rizici, poput prometnih nesreća na autoputu te izvanredni rizici, poput mosta kojemu prijeti urušavanje, terorističkih napada ili katastrofe vezane uz klimu, nisu sustavno predviđeni. Nekoliko je studija nedavno otkrilo da ukupni učinak mogućega zatajenja jednoga čvorišta i/ili rubne točke na mreži nisu izračunati, a osobito nisu unaprijed određene ključne rubne točke. Mi se bavimo ovim nedostatkom informacija pomoću metode koja pomaže pri prepoznavanju i kvantificiranju rizika u određenoj mreži. Kako bismo postigli ovaj cilj, definiramo model matematičke optimizacije koji kvantificira sadašnje „troškove vezane uz rizik" cijele mreže te kvantificiramo rizik istražujući promjenu ukupnih troškova u slučaju da se rizik ostvari.

Ključne riječi: logistika, rizik, otpornost, ključna infrastruktura