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A METHODOLOGY FOR ASSESSING RESILIENCE OF THE HSR (HIGH SPEED RAIL) NETWORK AFFECTED BY DISRUPTIVE EVENT(S)

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ABSTRACT

This paper deals with modelling of resilience, i.e., vulnerability of the HSR (High Speed Rail) transport network affected by the system's internal and external disruptive events both acting either individually or together/ The former events can generally be sudden unpredictable failures of the network's components, i.e., particular facilities and equipment both on board the HS (High Speed) trolling stock and along the lines (power system, control-communications and signalling system, etc.). In addition, the specific events can be traffic incidents/accidents and industrial actions of the railway staff. The latter events can be natural disasters (for example earthquakes), bad weather (strong wind, heavy rain and snow falls, flooding, etc.) and terrorists; threats and attacks.

In all above-mentioned cases, the given impacts are of the intensity to deteriorate scheduled/planned transport services causing their cancellations or long delays, thus imposing additional direct costs on the main actors/stakeholders involved such as users-passengers and rail transport service providers.

In order to enable assessment of resilience, i.e., vulnerability of a given HSR network already being or is expected to be likely affected by given disruptive event(s), and estimate the overall costs of its impact, a convenient methodology consisting of the set of analytical models is developed with an explanation how it could be applied to the particular cases using the "what-if" scenario approach.
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KEY WORDS: HSR (High Speed Rail) network, resilience, i.e., vulnerability, disruptive event(s), costs, methodology

1 INTRODUCTION

In general, resilience of a physical object can be defined as its "ability to recoil or spring back into shape after bending, stretching, or being compressed" (http://complexworld.eu/wiki/Resilience_in_air_transport). In addition, it can be said that the resilience of a given technical system generally implies its ability to operate under changing

unexpected conditions without significant affection of its planned performances. As such, resilience can also reflect the vulnerability and/or robustness of the given system operating under disruptive conditions (Foster, 1993). Consequently, both concepts can be considered together as the resilience, i.e., vulnerability dealing with the response of the given system(s) to changes, particularly to those caused by different disruptive events. Under such conditions, it is often needed to identify acceptable levels of resilience, i.e., vulnerability and to maintain ability of the affected system to respond or resist to the impact(s) of disruptive event(s) (Nelson et al. 2007). This also raises a question of relevance of the level of resilience, i.e., vulnerability for the particular stakeholders/actors involved (Miller et al., 2010).

The above-mentioned concepts and definitions of resilience, i.e., vulnerability, can also be applied to the transport systems/networks. One of these is HSR (High Speed Rail) network consisting of nodes-stations/terminuses, links connecting them, supportive facilities and equipment (power and signalling system at nodes and along the links/lines) and rolling stock- HS trains - carrying out transport services between particular nodes/stations thus satisfying passenger demand during specified time.

Dealing with resilience, i.e., vulnerability of a HSR network(s) usually implies considering deterioration of the scheduled/planned transport services by the impacts of various internal- the system's and external disruptive events, which most often result in their cancellations and/or r delays (Ip and Wang, 2011).

The directly affected actors/stakeholders are users-passengers and operators of given HSR network, i.e. providers of transport infrastructure and services. They are all usually imposed additional costs associated with deteriorated services, as well as recovery actions in the aftermath.

In addition to this introductory section, the paper consists of four other sections. Section 2 describes the relevant characteristics of the HSR network and introduces the concept of resilience, i.e., vulnerability. Section 3 presents a methodology for assessing resilience, i.e., vulnerability, of a given HSR network(s) affected by a given disruptive event(s), and related costs imposed on particular main actors/stakeholders involved. Section 4 explains how the proposed methodology would be applied using the "what-if" scenario approach. The last section summarizes some conclusions.

2 RESILIENCE, I. E., VULNERABILITY OF THE HSR NETWORK AFFECTED BY DISRUPTIVE EVENT(S)

This section describes the components and operations of the HSR network(s), disruptive events that can affect it, and the concept of its resilience, i.e., vulnerability under given conditions.

2.1 Components and operations

The HSR network consists of fixed and mobile components. The fixed components are those of infrastructure and supportive facilities and equipment. The mobile ones are the rolling stock, i.e., HS (High Speed) trains. The infrastructure components include lines including stations and tracks connecting them. Each line is defined by the begin and end station/terminuses equipped by the several tracks/platforms for handling the HS trains. The number of these tracks/platforms depends on the intensity of arriving and departing transport services and the train's turnaround time. In addition, the intermediate stations are located along the lines enabling short stop of particular transport services in order to enable embarking and disembarking of users/passengers having there their origins and destinations

there. The number of tracks/platforms at these stations is usually two for passing HS trains and two for those stopping there.

Operations of HS trains along the line(s) is managed and controlled by the signalling system securing maintaining the minimum space interval between successive vehicles operating in the same direction equal to their minimum breaking distance. This distance in combination with the maximum operating speed defines the minimum time interval between successive vehicles/trains, and consequently the line's capacity. In turn this capacity, in addition to the volumes of expected passenger demand influences the transport service frequency on particular lines. The rolling stock, i.e., HS trains are electricity-powered vehicles.

The transport services along particular lines can be different. They usually distinguish regarding the number of stops and operating speed along given route, price, internal comfort and services, etc... The route is fined by the begin and end node/station of the particular transport services, and consequently origins and destinations of user/passenger flows, and the number of intermediate nodes/stations. .

The spatial configuration of the HSR networks is generally the country specific. Figure 1 shows examples for some European countries

Figure 1 Simplifies spatial configuration of HSR networks in particular European countries (Crozet,2013; http://www.johomaps.com/eu/europehighspeed.html)

As can be seen, the spatial configuration of HSR networks generally differ across particular countries having star (France), polygon (Germany), and line (Italy) shape. These configurations are vulnerable to particular disruptive events differently. For example, disruptive vent can affect the line network at certain station and/or link thus preventing the transport services between the stations on both sides of the location of its impact. At the polygon network, the particular liens can be similarly affected, but the remaining stay operational, At the star network, disruptive vent can prevent transport services throughout the entire network if for example takes place at the central station/terminus. As well, transport services on particular lines can also be affected similarly as at the line network. Duration of affection depends on the type of disruptive event, and intensity and duration of its impact, the number of transport services affected, and the recovery time.

2.2 Disruptive events, their impacts, and related costs

In general, disruptive events affecting a given HSR networks can be internal-the system's and external-out of the system-. The former events include non-predictable but catastrophic failures of particular network's components, traffic incidents/accidents, and industrial actions of the network's staff,

For example, there have been three severe HSR traffic incidents/accidents worldwide causing damages of the HSR network's components, passenger and staff fatalities and injuries and

temporal closures of the affected parts of the corresponding networks.. Table 1 gives the main characteristics of these accidents.

Table 1 Some characteristics of HSR fatal accidents
(http://en.wikipedia.org/wiki/Eschede_train_disaster;
http://en.wikipedia.org/wiki/Wenzhou_train_collision;
http://en.wikipedia.org/wiki/Santiago_de_Compostela_rail_disaster)

Country/System/ No of trains	Date	Cause	Passengers on board	Fatalities	Injuries
Germany/ICE/1	3/06/1998	Wheel disintegration	287	101	88
China/2	23/07/2011	Railway signal failure	1630	40	>210
Spain/Alvia/1	34/07/2013	Excessive speed on bend	222	>79	139

As can be seen, the main causes of the above-mentioned accidents were the internal failures of the HSR network components.

The latter events include the natural disasters (earthquakes, volcanic eruptions, tidal waves) usually heavily damaging and/or destroying the network's infrastructure and rolling stock, and variety of bad weather usually causing heavily compromising and/or completely blocking regular operations of the particular network's components (storm wind, heavy rain or snowfall, flooding, etc.).

The most illustrative example of the impacts of natural disasters was the Great East Japan Earthquake on March 11 2011 (Magnitude 9.0, the largest in the recorded history of Japan), whose impact severely damaged the concrete structures along the Tohoku Shinkansen HSR line, but not caused their collapse. At that time 27 Shinkansen HS trains on the line were affected, but without derailment and fatalities. The latest were avoided also by evacuation of users-passengers from the impact of the forthcoming tidal wave (tsunami). Anyway, the restoration of regular transport services was possible after 49 days (Seino, 2012; Shimamura and Keyaki, 2013).

The impacts of bad weather in terms of heavy storm and/or snowfalls have mainly affected the individual HSR services causing their derailment (for example TGV Atlantique on 2nd of January 2001) or operations at reduced maximum speed (for example on the storm wind-exposed segments of particular lines such as those in Scandinavia)
(Thomas, 2009; http://www.trainweb.org/tgvpages/tgvindex.html).

The specific external disruptive events are the terrorist threats and attacks. One of the illustrative example impacting the individual HSR service on the Marseille-Paris route was terrorist bombing causing five fatalities and 50 injuries (http://www.trainweb.org/tgvpages/tgvindex.html). The above=mentioned disruptive events and their impacts occur generally randomly in time and space. As such they may affect a given HSR network almost at any time and different spatial scale, the latter from local node/station/link/service to global single/several lines/services. In some cases, independently on time, spatial scale, and intensity of impact, different disruptive events may be interrelated and occurr simultaneously.

In addition, particular disruptive events and their impacts usually impose additional costs on particular actors/stakeholders involved. For users-passengers these can be the cost of

additional scheduled delays due to cancelled transport services if they manage to join still remaining services to be realized, the cost of non-realized trips otherwise, and the cost of delays of realized but delayed transport services. Transport operators are imposed the cost of cancelled and delayed transport services. They are also imposed the cost of recovery actions, (in some cases very substantive), which are not considered in the given context.

2.3 The concept of resilience, i.e. vulnerability

2.3.1 Definition and framework
Resilience, i.e., vulnerability of a given HSR network can be defined as its ability to stay operational safely at the specified level during the impact of a given disruptive event. This definition only considers actions aimed at mitigating impacts of disruptive vents and not the recovery actions aftermath. In addition, resilience, i.e., vulnerability of the given network can generally be considered as static and dynamic. The former refers to the network's ability to maintain its scheduled/planned operations during the impact of disruptive events. The latter implies the network's speed of recovering up to the desired (specified) operational level in the aftermath (Chen and Miller-Hooks, 2012, Janic, 2015; Rose, 2007). As well, the resilience, i.e., vulnerability of a HSR network can be considered in the short-, medium-, and long-term (Njoka and Raoult, 2009; TDM Encyclopedia, 2010).
The resilience, i.e., vulnerability of a given HSR network can be assessed at three layers as follows (Janic, 2015):

- The physical layer, which deals with the physical impacts on the network's infrastructure–odes-stations/terminuses, lines-tracks, rolling stock, and supporting facilities and equipment;
- The transport service layer, which mainly considers the impact on the scheduled/planned transport services between particular nodes/stations along particular lines; and
- The cognitive layer, which relates to the users'-passengers' confidence in the affected and subsequently recovered HSR transport services (Janic, 2015; Len at al., 2010).

2.2.3 Tactics and strategies for mitigating the consequences of disruptive vent(s)
In general, the main consequences of impacts of disruptive vents on a given HSR network are the costs of damages of infrastructure and transport services imposed on the above–mentioned main actors/stakeholders involved – the HSR network's operators, users=passengers, and sometimes the third parties. .
Therefore, in order to prevent and/or mitigate escalation of the above-mentioned costs the network components are constructed <u>and</u> designed to resist to the life-cycle wearing and tearing (with proper maintenance) and to the natural disasters (earthquakes, volcanic eruptions, tidal waves, extremely bad weather, etc.). In addition, the main tactics and strategies for mitigating the impacts of the above-mentioned and all other disruptive events on the scheduled/planes transport services include their cancellations and delaying.
The tactics and strategies for mitigating the costs of cancelled and delayed HSR transport services can be as follows (Cox, et al., 2011; Janic, 2015):

- <u>Conservation</u> implying maintaining operation of the network but with a reduced number of HSR transport services (i.e., mainly due their cancellation);
- <u>Production recapture</u> implying filling-in additionally the remaining transport services and scheduling additional ones after the end of disruptive event(s) in order to accommodate users/passengers from the previously cancelled services (only in case if the above-,mentioned components of the HSR network remained intact); and

- Management effectiveness referring to the strategies and tactics of restoring the affected infrastructure and transport services in the network after the end of disruptive event*s).

3 A METHODOLOFY FOR ASSESSING RESILIENCE, I. E.,VULNERABILITY OF AN AFFECTED HSR (HIGH SPEED RAIL) NETWORK

In particular, a methodology for assessing resilience, i.e., vulnerability of a given HSR network affected by a given disruptive event, and related costs for particular actors/stakeholders involved such as users-passengers and transport service providers represents a continuation of the methodology developed for an affected air transport network (Janic, 2015).

3.1 Some related research

The research on resilience, i.e., vulnerability of different systems have been under focus mainly over the past two decades and half, primarily due to affection of different systems usually by unpredictable disruptive vents. In this context, at the general level, the related research on general networks, network-based methods, and transport systems has been mentioned. As far as the networks are concerned, Henry and Ramirez-Marquez (2012) expressed resilience as the ratio of recovery to loss suffered by the system, implying that if the recovery is equal to the loss, then the system is fully resilient. Otherwise, without recovery, there is no resilience.

Garbin and Shortle (2007) proposed measuring the network resilience as the percentage of network damage versus network performances under normal conditions. The performances of the network included demand, topology, capacity, and routing. Rosenkrantz et al. (2009) quantified resilience of the the given service-oriented networks means by node and link failures, consequently distinguishing between the network node and the network link resilience. In addition, the algorithm to determine the maximum tolerable node and link failures in the given network. Najjar and Gaudiot (1990) proposed network resilience and relative network resilience as two probabilistic measures of network fault tolerance in a multicomputer system.

The network-based methods have been particularly used for analysing the complex structure of large-scale systems/networks by quantifying the relative importance and mutual dependency of their nodes and links (Newman, 2004). These methods have been categorized into topology-based and flow-based methods (Ouyang, 2014). The latter methods can cover all resilience capacities, in contrast to topology-based methods which cover the specific capacity only. Both types of methods have shown to be particularly relevant in analysing air transport networks.

The research on the resilience, i.e., vulnerability of rail, road, and intermodal freight transport networks has been relatively exhaustive. This has included their definition and development of algorithms for optimizing the cost of recovery activities within the specified budget aftermath of the given disruptive events (Berdica, 2002; Chen and Miller Hooks, 2012).

Hughes and Healy (2014) developed a framework for a qualitative measurement of both technical and organisational dimensions of resilience including specific detailed measurement categories. The framework has enabled determination of the context of an initial assessment of resilience followed by its detailed assessment by measures combined to generate a range of resilience score.

Omer et al. (2013) identified three resilience metrics to measure the impact of hypothetical disruptions on the performance of a road-based transportation system: the travel time resilience, environmental resilience, and cost resilience.

In addition, Wang and Ip, (2009) and Ip and Wang (2011) defined the framework for evaluating the resilience, i.e., vulnerability of the logistics and rail freight transport networks, respectively. This enabled development of the optimization models and algorithms for allocation of the available resources guaranteeing security and quality of services in the logistics, and the optimal design of rail networks, based on their resilience, i.e., vulnerability. Gluchshenko & Foerster (2013) proposed a qualitative measure for resilience in air transportation based on recovery time. Janic (2015) has developed the methodology for estimating the resilience, i.e., vulnerability, friability, and related costs of an air transport network affected by the large scale disruptive vent(s). The methodology has been applied to the part of U.S. air transport network affected by hurricane Sandy. .

Evidently, it can be said that the research on resilience, i.e., vulnerability of HSR networks have been relatively scarce. The exception has been the work of Shimamura et al., (2013), who elaborated damages of concrete structures along the Tohoku Shinkansen line and the restoration after the impact of the above –mentioned 2011 Great Tohoku Earthquake (Japan). Consequently, the measures have been proposed to mitigate the impacts of the future similar earthquakes: viaduct reinforcement to resist to the strongest earthquakes, seismic early warning system to warn well in advance of the forthcoming earthquake, and anti-straying wheel guide mechanism to prevent derailing of HS trains during the earthquake. In addition, Jianhuai et al., (2013) have dealt with the attack vulnerability of Chinese HSRN (High Speed rail network) means by graph theory and complex network theory. It has been shown that the network has been very vulnerable subject to malicious attacks. The highest mutual node-based attacks can cause more damages than the largest degree node-based attacks. As well, In the research of Jaroszweski et al., (2014), the bed weather such as heavy rain. wind/storm, sand now/winter conditions has been identified as disruptive events for both conventional and JSR operations.

Anyway, the above-mentioned research has not explicitly dealt with developing a more generic methodology for estimating resilience, i.e., vulnerability of a given HSR network affected by some disruptive event(s).

Certainly, one of the strong reasons has been that the serious disruptions of the HSR networks with related consequences have been relatively rare compared to, for example, those of road and air transport networks, regarding the scale and volumes of their operations. Despite such facts, this work, continuing to the previous work of Janic (2015) intends to contribute to filling in this gap.

3.2 Objectives

Regarding the above-mentioned findings from the related research, the main objectives 0f this paper are to develop a methodology for estimating and predicting resilience, i.e., vulnerability, and cost of a given HSR network, which has been, currently is or will likely be under the risk of being affected by different types of the internal and/or external disruptive events. In this context, resilience implies resistance to diminishing the scheduled/planned level of operations, i.e., maintaining the specified operational level, during and just after the impact of given disruptive event. Alternatively, resilience reflects vulnerability as the scale of deterioration of scheduled/planned transport services of the affected HSR network under given *conditions,*. . In addition, the methodology should enable estimation of the costs due to the impact of given disruptive event for particular main actors/stakeholders involved such as users/passengers and transport service providers.

3.3 Assumptions

The methodology is based on the following assumptions:

- The HSR network consists of lines, each constrained by the begin and end station/terminus, the intermediate stations and double-tracks connecting them; such configuration enables performing transport services simultaneously in both directions along the line; the stations are considered as the nodes and the double tracks between them as bi-directional physical links of the network;
- Each station/node along particular lines of the network can be an origins and/or destinations (i.e., O-D) of user-passenger demand flows and related transport services carried out by the HS trains; consequently, these O=Ds, intermediate nodes/stations, and tracks/links between them define the routes where different types of transport services, each characterized by the number of intermediate stops and price are scheduled/planned;
- The passenger demand flows along routes of lines of a given HSR network are always fully satisfied by the scheduled/planned transport services of each type;
- Both internal-the system's and the external-out of the system disruptive events are of the stochastic nature in terms of time and location of occurrence, and the intensity of impact; therefore they are represented by the probabilities of occurrence at given intensity at the specified time; therefore, the probabilities of past events, which occurred, is equal to one; the probabilities of prospective events caries between zero and one, which can be estimated either from the past data or by "what-if" scenario approach; using "the past data" implies disruptive events with specified intensity of impacts are expected to likely occur in the future according to the similar pattern as used in the past; using the "scenario approach" implies predicting occurrence of disruptive events and their impact(s) with certain previously not experienced probabilities; in both cases, predicting can be useful for planning and implementing the preventive measures to mitigate the costs of damages during and after the end of impacts; in many cases, he external disruptive events can trigger occurrence of the internal-the system's ones, but not vice versa.
- The impacts of particular disruptive events affect the network's components and transport services over the specified time equal to duration of these events and the time of starting recovery actions;
- Disruptive events can, depending on the intensity and spatial scale of their impacts, affect different lines and components of the given HSR network individually and/or together;
- Disruptive events of given intensity of impacts usually require cancellation and/or delaying of the affected transport services as the mitigating actions; and
- The methodology for assessing and predicting resilience, i.e., vulnerability, *o*f a given HSR network is developed for a given type of disruptive event(s) occurred and lasting during the specified time; it also estimates the direct costs *imposed on* particular actors/stakeholders during the impact and not those of the recovery actions aftermath. .

3.4 Structure of the methodology

3.4.1 General

The methodology consists of the models for estimating the resilience, i.e., vulnerability, and costs imposed on the HSR network affected by given disruptive event. The network consists of N lines, each containing N_k routes, where different types of the HSR transport services are scheduled/planned during the specified time *(τ)*. The simplified schemes of particular spatial configurations of HSR networks with lines, routes and types of transport services there for developing the methodology are shown in Figure 2 (a, b)

This time *(τ)* is defined from the moment of the occurrence of disruptive event until the moment of starting the recovery actions over the affected network and its components. . As

such it can be of different duration - from a few hours to one or several days, weeks, months, and even years. This however depends on the damages made to the HSR network
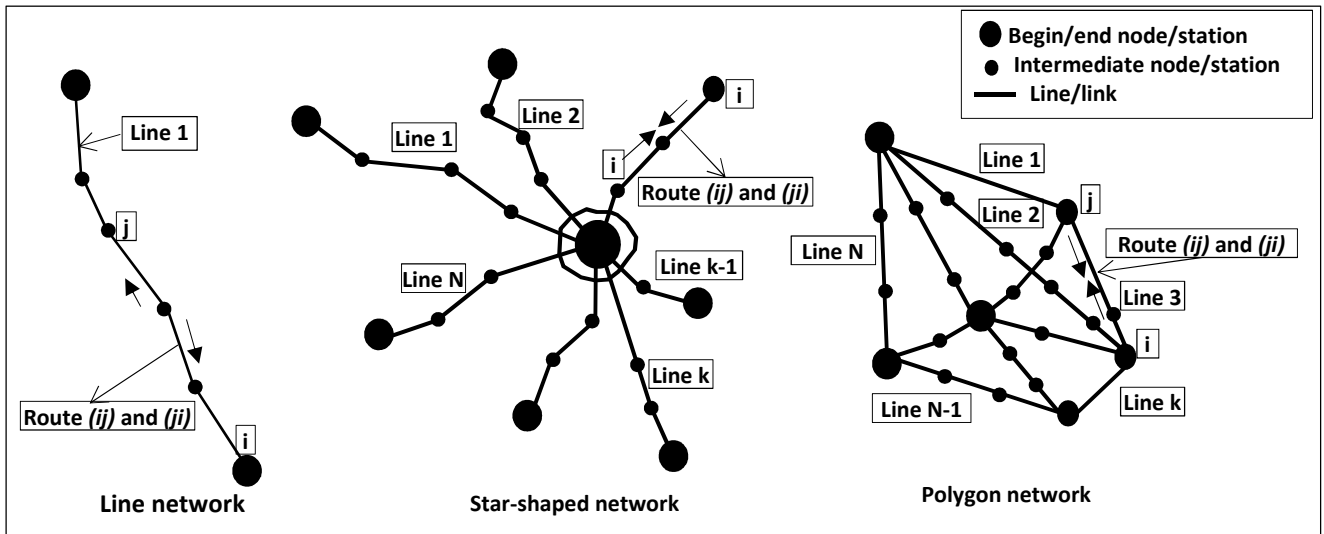
a) Spatial configurations
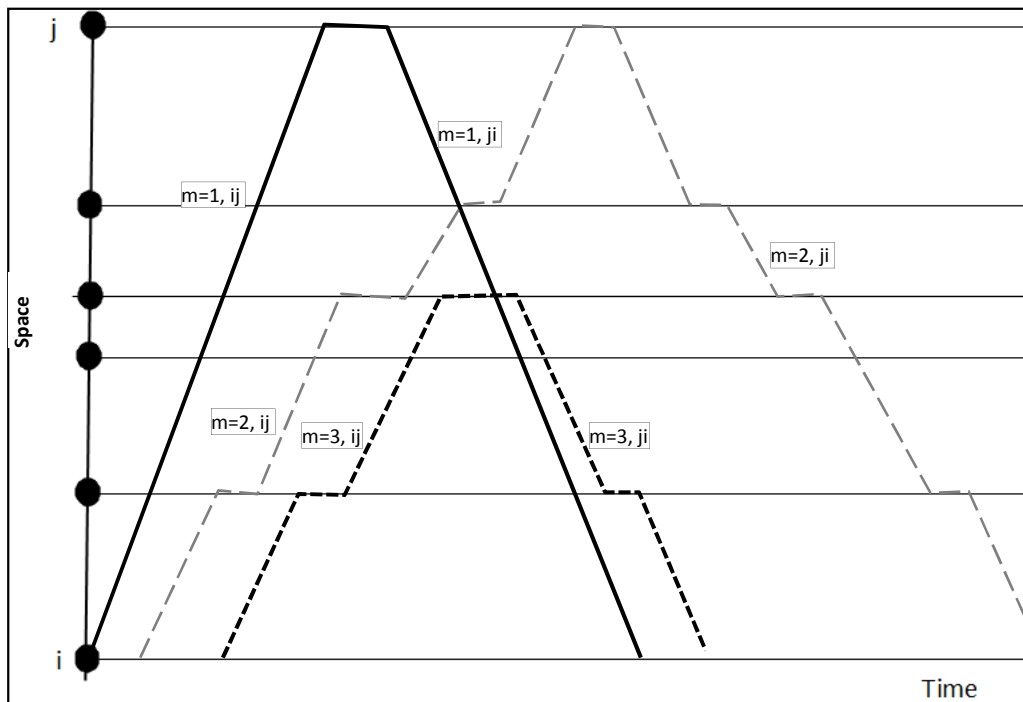
b) Scheduled/planned transport services

Figure 2 Scheme of the HSR network for the purpose of developing the methodology in given case

3.4.2 Model for estimating resilience, i.e., vulnerability

Specifically, the model for estimating the resilience, i.e., vulnerability of a given HSR network affected by the impact of a given disruptive event is based on the following assumptions:

- Resilience, i.e., vulnerability is considered only during the duration of impact of disruptive event;
- Direct routes with at least one scheduled/planned transport service of a given type connect the particular nodes/stations along particular lines of the network; if one node/station is closed by the impact, all departing and arriving transport services of all types to/from all other nodes/stations will be cancelled, i.e. the connections will be cut-off; the same happens if the link(s) between particular nodes/station is closed by the impact; and
- The number of transport services of all types scheduled/planned and actually realized on particular routes is used for measuring their relative importance, i.e., weight in the network during the impact of a disruptive event (the other measures not explicitly considered can be the number of passengers on-board of each of these services).

The model consists of the following components:

i) The node's/station's relative importance/weight

The relative importance, i.e. weight, of a given node/station *(i)* on the line *(k)* can be estimated as follows:

$$w_{k/i}(\tau) = \frac{F_{k/i}(\tau)}{\sum\limits_{i=1}^{N_k} F_{k/i}(\tau)} \qquad (1a)$$

Similarly, the relative importance/weight of the node/station *(i)* in the entire HSR network can be estimated as follows:

$$w_i(\tau) = \frac{F_{k/i}(\tau)}{\sum\limits_{k=1}^{N} \sum\limits_{i=1}^{N_k} F_{k/i}(\tau)} \qquad (1b)$$

where

$F_{k/i}(\tau)$ is the number of departing and arriving transport services at the node/station (i) on the line *(k)* during time *(τ)*;

The transport services $F_{k/i}(\tau)$ in Eq. 1 (a, b) can be determined as follows:

$$F_{k/i}(\tau) = \sum\limits_{\substack{j=1 \\ j \neq i}}^{N_k} \sum\limits_{m=1}^{M_{k/ij}} \left[f_{k/ij/m}(\tau) + f_{l/ij/m}(\tau) \right] \qquad (1c)$$

where

$f_{l/ij/mi}(\tau), f_{il/ji/m}(\tau)$ is the number of scheduled/planned transport services. i.e., the service frequency, of type *(m)* on the route *(ij)* and *(ji)*, respectively, of line *(k)* during time *(τ)*.

The service frequency $f_{l/ij/mi}(\tau)$ and $f_{il/ji/m}(\tau)$ in Eq. 1c can be determined as follows: $f_{l/ij/mi}(\tau) = \tau / h_{k/ij/m}(\tau)$ and $f_{l/ji/mi}(\tau) = \tau / h_{k/ji/m}(\tau)$, where $h_{k/ij/m}(\tau)$ and $h_{k/ji/m}(\tau)$ are the average time intervals between successive transport services of type *(m)* scheduled/planned on the route *(ij)* and *(ji)*, respectively, during time *(τ)*.

ii) The line's relative importance/weight

The relative importance, i.e. weight, of the line *(k)* of a given HSR network containing *N* lines can be estimated as follows:

$$w_k(\tau) = \frac{F_k(\tau)}{\sum_{k=1}^{N} F_k(\tau)} \tag{2a}$$

where

$F_k(\tau)$ is the total number of transport services carried out along the line *(k)* during time *(τ)*.

The transport services $F_k(\tau)$ in Eq. 2a can be determined as follows:

$$F_k(\tau) = \sum_{i=1}^{N_k} \sum_{\substack{j=1 \\ j \neq i}}^{N_k} \sum_{m=1}^{M_{k/ij}} \left[F_{k/ij/m}(\tau) + F_{l/ji/m}(\tau) \right] \tag{2b}$$

where

$F_{k/ij/m}(\tau), F_{ik/ji/m}(\tau)$ is the number of actually realized transport services of type *(m)* on the route *(ij)* and *(ji)*, respectively, of the line *(k)* during the time *(τ)*

The transport services $F_{ik/ji/m}(\tau)$ and $F_{ik/ji/m}(\tau)$ in Eq 2 b can be determined as follows:

$$F_{k/ij/m}(\tau) = \left| \sum_{r=1}^{f_{k/ij/m}(\tau)} [1 - p_{k/ij/m/r}(\tau)] \right| \text{ and } F_{k/ii/m}(\tau) = \left| \sum_{r=1}^{f_{k/ji/m}(\tau)} [1 - p_{k/ji/m/r}(\tau)] \right| \tag{2c}$$

where

$f_{k/ij/m}(\tau), f_{k/ji/m}(\tau)$ is the frequency of transport services of type *(m)* scheduled/planned on the route *(ij)* and *(ji)*, respectively, of the line *(k)* during the time *(τ)*; and

$p_{k/ij/m/r}(\tau),$
$p_{k/ji/m/r}(\tau)$ is the probability of of cancellation of the *(r)*-th transport service of type *(m)* scheduled/planned on the route *(ij)* and *(ji)*, respectively, of the line *(k)* during the time *(τ)* due to the occurrence and the intensity of given disruptive vent,

The other symbols are analogous to those in the previous Eqs.

The probabilities $p_{k/ij/m}/r(\tau)$ and $p_{k/ji/m}/r(\tau)$ in Eq. 2c are equal to the product of the probabilities of two events: that the disruptive event occurs and that the intensity of its impact causes cancellation of the affected transport service. Then, from Eq. 2c follows that the

number of cancelled transport services is determined as: $F^*_{k/ij/m}(\tau) = \left| \sum_{j=r=1}^{f_{k/ij/m}(\tau)} p_{k/ij/m/r}(\tau) \right|$ and

$F^*_{k/ii/m}(\tau) = \left| \sum_{j=r=1}^{f_{k/ji/m}(\tau)} p_{k/ji/m/r}(\tau) \right|$. The rest of transport services can be on time or delayed, but realized anyway (in all cases they are considered as integers).

Equation 1(a, b) indicates that the relative importance/weight of a given node/station increases with increasing of the share of its departing and arriving transport services in their totals at a;; nodes/stations of a given line(s) and those of the entire HSR network, respectively, all during the specified period of time and under given conditions. .

Similarly, Eq. 2a indicates that the relative importance/weight of the given line increases with increasing of the share of its transport services in their total of the entire network, during the given period of time under given conditions, . In addition, Eqs. 1 and 2 indicate that both departing and arriving transport services at particular node(s)/station(s), i.e., those carried out in both direction along the particular route(s) are taken into account in determining their weights, respectively. As mentioned above, the transport services along particular routes are scheduled to satisfy the expected passenger demand under given conditions. In this context, their number at both nodes/stations and routes is always lower or at most equal to the corresponding capacities. These are usually expressed by the maximum number of services (i.e., HS trains), which can be accommodated there during the given period of time under conditions of constant demand for service.

.iii) The node's/station's self-excluding importance/weight

The self-excluding importance, i.e. weight, of the node/station *(i)* on the line *(k)* with N_k routes of a given HSR network implies that its other connected nodes/stations do not include it. Thus it can be estimated as follows:

$$u_{k/i}(\tau) = \frac{F_{k/i}(\tau)}{\sum_{i=1}^{N_k} F_{k/i}(\tau) - F_{k/i}(\tau)} \qquad (3a)$$

where all symbols are as in the previous Eqs.

Similarly, the self-excluding weight of the node/station *(i)* of the HSR network containing *N* lines each with N_k routes can be estimated as follows:

$$u_i(\tau) = \frac{F_{k/i}(\tau)}{\sum_{k=1}^{N} \sum_{i=1}^{N_k} F_{k/i}(\tau) - F_{k/i}(\tau)} - \qquad (3b)$$

where all symbols are as in the previous Eqs.

Equations 3a and 3b indicate that the self-excluding weight of a given node/station increases more than proportionally with increasing of the share of its weight in the total weight of the given line and entire network, respectively, under given conditions.

iv) The line's self-excluding importance/weight

Similarly as in case of nodes/stations, the self-excluding weight of a given line of a given HSR network can be estimated as follows:

$$u_k(\tau) = \frac{F_k(\tau)}{\sum\limits_{k=1}^{N} F_k(\tau) - F_k(\tau)} - \tag{3c}$$

where all symbols are a in the previous Eqs.

Equation 3c indicates that the self-excluding weight of the given line increases more than proportionally with increasing of its share in the total weight of the HSR network, under given conditions.

v) The node's/station's resilience, i.e., vulnerability

The resilience, i.e., vulnerability, of the node/station *(i)* on the line *(k)* can be estimated as the sum of the product of all self-excluding importance/weights except the one for the node/station *(i)* and the number or proportion of transport services actually carried out as follows:

$$R_{k/i}(\tau) = \sum_{j=1; j \neq i}^{N_k} u_{k/j}(\tau) \sum_{m=1}^{M_{k/ij}} \left[F_{k/ij/m}(\tau) + F_{k/ij/m}(\tau) \right] \tag{4a}$$

Similarly, the resilience, i.e. vulnerability of the node/station *(i)* of the entire HSR network can be estimated as follows:

$$R_i(\tau) = \sum_{k=1}^{N} \sum_{j=1; j \neq i}^{N_k} u_{k/j}(\tau) \sum_{m=1}^{M_{k/ij}} \left[F_{k/ij/m}(\tau) + F_{k/ij/m}(\tau) \right] \tag{4b}$$

where all symbols are as in the previous Eqs.

Consequently, Equation 4 (a, b) indicates that the resilience, i.e., vulnerability, of a given node/station at the level of it belongs and the level of entire HSR network is proportional to the sum of the product of the corresponding self-excluding weight(s) and the number of actually realized transport services to and from other connected nodes/stations under given conditions. In addition, it increases with increasing of the number of sustained, i.e. actually realized transport services. .

vi) The line's resilience, i.e., vulnerability

The resilience, i.e., vulnerability of the given line *(k)* of the HSR network can be estimated as follows:

$$R_k(\tau) = \sum_{k=1}^{N} u_k(\tau) \sum_{i=1}^{N_k} \sum_{j-1; j \neq i}^{N_k} \sum_{m=1}^{M_{k/ij}} \left[F_{k/ij/m}(\tau) + F_{k/ij/m}(\tau) \right] \tag{4c}$$

where all symbols are as in the previous Equations.

vii) The HSR network's resilience, i.e., vulnerability

The resilience of the HSR network consisting of N each with N_k nodes/stations lines can be estimated as the sum of the resilience of each individual node/station or line, based on Eq. 1a and 4a, and 2a and 4c, respectively, as follows:

$$R(N,\tau) = \sum_{k=1}^{N} \sum_{i=1}^{N_k} w_{k/i}(\tau) R_{k/i}(\tau) \qquad (5a)$$

or

$$R(N,\tau) = \sum_{k=1}^{N} w_k(\tau) R_k(\tau) \qquad (5b)$$

where all symbols are as in the previous Eqs.

Equation 5(a. b) indicates that the resilience, i.e., vulnerability of the HSR network is proportional to the sum of the weighted resilience, i.e., vulnerability of each station/node or the line belonging to it.

Alternatively to Eq. 5(a, b), the resilience. i.e., vulnerability, of the HSR network consisting of N lines, each with N_k routes can be measured by an indicator based on the inherent network properties and the set of actions for mitigating costs and maintaining the required safety level of operations. The mitigating actions include delaying, rerouting and/or cancelling affected transport services. In such cases, this indicator can be defined as a proportion or the ratio between the on-time and/or between the actually realized on-time and delayed, and the total number of scheduled/planned transport services during time *(τ)*. The indicator of the network's resilience, i.e., vulnerability, can be specified as follows (Chen and Miller-Hooks, 2012):

$$R(N,\tau) = \frac{\displaystyle\sum_{k=1}^{N} \sum_{\substack{i,j=1 \\ j \neq i}}^{N_k} \sum_{m=1}^{M_{k/ij}} \left[F_{k/ij/m}(\tau) + F_{k/ji/m}(\tau) \right]}{\displaystyle\sum_{k=1}^{N} \sum_{\substack{i,j=1 \\ j \neq i}}^{N_k} \sum_{m=1}^{M_{k/ij}} \left[f_{ik/ij/m}(\tau) + f_{k/ji/m}(\tau) \right]} \qquad (6)$$

where all symbols are as in the previous Eqs. Eq. 6 indicates that the resilience, i.e., vulnerability, of the given HSR network increases in line with the actually realized and scheduled/planned transport services at all its stations, lines, and routes during the given period of time under given (disruptive) conditions.

Step-by-step algorithm for estimating the resilience, i.e., vulnerability of given HSR network

<u>STEP 1</u>	Calculate the weight and self-excluding weight of each node/station or line of the given HSR network by Eq. 1, 2, and 3, respectively;
<u>STEP 2</u>	Calculate the resilience of each node/station and line of the HSR network by Eq. 4;
<u>STEP 3</u>	Calculate the resilience of the entire HSR network by Eq. 5 or 6; and
<u>STEP 4</u>	Repeat <u>STEPS</u> 1, 2, and 3, as necessary, if the conditions/impact, configuration and service performance of the network, and specified time, change.

3.4.3 The model for estimating the number affected transport services

In general, the time of occurrence and the intensity of impact of most disruptive events is actually exactly unpredictable. Therefore, it can be important to estimate the number of HSR transport services (trains) simultaneously operating in the given network during the specified

time, when the disruptive event(s) can happen with certain probability. This number is estimated as follows:

$$F_k(\tau) = \sum_{i=1}^{N_k} \sum_{\substack{j=1 \\ j \neq i}}^{N_k} \sum_{m=1}^{M_{k/ij}} \left\{ \begin{array}{l} F_{k/ij/m}(\tau) * [\dfrac{d_{k/ij/m}}{v_{k/ij/m}} + q_{k/ij/m}(\tau) * D_{k/ij/m}(\tau)] + \\[3mm] + F_{k/ji/m}(\tau) * [\dfrac{d_{k/ji/m}}{v_{k/ji/m}} + q_{k/ji/m}(\tau) * D_{k/ji/m}(\tau)] \end{array} \right\} \tag{7}$$

where

$d_{k/ij/m}, d_{k/ji/m}$ is the length of route *(ij)* and *(ji)*, respectively, of the line *(k)*, where the transport service of type *(m)* is scheduled/planned;

$v_{k/ij/m}, v_{k/ji/m}$ is the operating speed of the transport service of type *(m)* along the route *(ij)* and *(ji)*, respectively, of the line *(k)*;

$q_{k/ij/m}(\tau), q_{k/ji/m}(\tau)$ is the probability of delaying transport service of type *(m)* on the route *(ij)* and *(ji)*, respectively, of the line (k), during time *(τ)*; and

$D_{k/ij/m}(\tau), D_{kjijm}(\tau)$ is the average delay of transport services of type (m) on the route *(ij)* and *(ji)*, respectively, of the line (k) during time *(τ)*.

The delays $D_{k/ij/m}(\tau)$ and $D_{kjijm}(\tau)$ in Eq. 7 can be imposed on particular transport services with certain probabilities $q_{k/ij/m}(\tau)$, and $q_{k/ji/m}(\tau)$. These are the product of the probabilities of two events: that the given disruptive event occur, and that its intensity of impact causes delays of the affected HS transport services. For example, these can be extremely bad weather such as strong cross or head wind sudden heavy rain, intensive snowfalls, etc., usually compromising operation speed of HS trains along segments of the entire routes. In case of wind, the above-mentioned delays can be estimated as follows:

$$D_{k/ij/m}(\tau) = \Delta d_{k/ij/m} \left[\frac{1}{v_{k/ij/m} - w_{k/ij/m}(\tau)} - \frac{1}{v_{k/ij/m}} \right] \tag{8a}$$

and

$$D_{k/ji/m}(\tau) = \Delta d_{k/ji/m} \left[\frac{1}{v_{k/ji/m} - w_{k/ji/m}(\tau)} - \frac{1}{v_{k/ji/m}} \right] \tag{8b}$$

where

$\Delta d_{k/ij/m}(\tau), \Delta d_{k/ji/m}(\tau)$ is the average distance along the route *(ij)* and *(ji)*, respectively, of the line *(k)* where the scheduled/planned operating speed of the transport services of type *(m)* is affected/reduced, during time *(τ)*

$w_{k/ij/m}(\tau), w_{k/ji/m}(\tau)$ is the average head or cross wind affecting the scheduled/planned speed of transport service of type *(m)* on the route *(ij)* and *(ji)*, respectively, of the line *(k)* during time *(τ)*.

The other symbols are as in the previous Eqs.

3.4.4 The model for estimating the direct costs of affected transport services

The costs of the HSR network consisting of *N* lines affected by the given disruptive event can be estimated as the sum of i) the cost of increased schedule delays for users-passengers due to additional waiting for transport services, which will be realized; ii) the costs of users-passengers of the non-realized trips due to cancelled transport services, iii) the cost of delays of affected but realized transport services imposed on both users-passengers on board and transport operators; and iv) the cost of cancelled transport services imposed on transport operators (this is actually a loss of profit as the difference between revenues and costs of cancelled services assumed to be at least zero profitable). Under such conditions, the total above-mentioned costs can be estimated as follows:

$$
C(N,\tau) = \sum_{k=1}^{N} \sum_{j,j=1/\,j\equiv i}^{N_k} \sum_{m=1}^{M_{k/ij}} \left\{
\begin{array}{l}
\alpha_{k/ij/m}(\tau)*SD_{k/ij/m/ji}(\tau) + \alpha_{k/ji/m}(\tau)*SD_{k/ji/m/ji}(\tau) + \\[4pt]
+\max \beta_{k/ij/m}(\tau) \left\{ \begin{array}{l} 0; F^*_{k/ij/m}(\tau)*\lambda_{k/ij/m}(\tau)*n_{k/ij/m}(\tau) - \\ -F_{k/ij/m}(\tau)*[1-\lambda_{k/ij/m}(\tau)]*n_{k/ij/m}(\tau) \end{array} \right\} + \\[4pt]
+\max \beta_{k/iji/m}(\tau) \left\{ \begin{array}{l} 0; F^*_{k/ji/m}(\tau)*\lambda_{k/ji/m}(\tau)*n_{k/ji/m}(\tau) - \\ -F_{k/ji/m}(\tau)*[1-\lambda_{k/ji/m}(\tau)]*n_{k/ji/m}(\tau) \end{array} \right\} + \\[4pt]
+F_{k/ij/m}(\tau)*q_{k/ij/m}(\tau)*D_{k/ij/m}(\tau)*\gamma_{k/ij/m}(\tau)*\varphi_{k/ij/m}(\tau) + \\[4pt]
+F_{k/ji/m}(\tau)*q_{k/ji/m}(\tau)*D_{k/ji/m}(\tau)*\gamma_{k/ji/m}(\tau)*\varphi_{k/ji/m}(\tau) - \\[4pt]
+c_{k/ij/m}(\tau)*F^*_{k/ij/m}(\tau) + c_{k/ji/m}(\tau)*F^*_{k/ji/m}(\tau)
\end{array}
\right\} \qquad (9)
$$

where

$SD_{k/ij/m}(\tau),\ SD_{k/ji/m}(\tau)$	Is the additional schedule delay for passengers due to cancellation of transport services of type *(m)* on the routes *(ij)* and *(ji)*, respectively, of the line *(k)* during the time *(τ)*;
$\alpha_{k/ij/m}(\tau),\ \alpha_{k/ji/m}(\tau)$	is the average unit cost of passenger time waiting due to cancellation of transport services of type *(m)* on the routes *(ij)* and *(ji)* respectively of the line *(k)* during time *(τ)*;
$\beta_{k/ij/m}(\tau),\ \beta_{k/ji/m}(\tau)$	is the cost of non-realized trip of a passenger due to cancelled transport services of type *(m)* on the route *(ij)* and *(ji)*, respectively, of line *(k)* during time *(τ)*;
$\gamma_{k/ij/m}(\tau),\ \gamma_{kjijm}(\tau)$	is the average cost of unit delay of transport service of type *(m)* realized on the route *(ij)* and *(ji)*, respectively, of the line *(k)*, during time *(τ)* (this cost include the average unit time cost of both transport operator and passengers on-board)*;
$\varphi_{k/ij/m}(\tau),\ \varphi_{kjijm}(\tau)$	is the delay multiplier of transport service of type (m) on the route *(ij)* and *(ji)*, respectively, of the line *(k)* during time *(τ)*;
$c_{k/ij/m}(\tau),\ c_{k/ji/m}(\tau)$	is the average cost of cancellation of the transport service of type *(m)* on the routes *(ij)* and *(ji)*, respectively, of the line *(k)* during time *(τ)*
$n_{k/ij/m}(\tau),\ n_{k/ji/m}(\tau)$	is the number of seats per service type *(m)* on the route *(ij)* and *(ji)*, respectively, of the line *(k)*, during time *(τ)*; and
$\lambda_{k/ij/m}(\tau),\ \lambda_{k/ji/m}(\tau)$	is the average load factor per service type *(m)* on the route *(ij)* and *(ji)*, respectively, of the line *(k)* during time *(τ)*.

The other symbols are analogous to those in the previous Eqs.

In Eq. 9, it is assumed that the passengers from cancelled transport services first fill in empty seats of the services to be realized. If their number is greater, then the number of empty seats on the services to be realized, some of them will not realize their trips and consequently suffer corresponding cost. In addition, delays can be imposed on the realized transport services either at departure or while being on-route due to many causes. Then, they can propagate through the HS trains' daily itineraries, which is taken into account by the delay multipliers.

The additional passenger schedule delays $SD_{k/ij/m}(\tau)$ and $SD_{k/ji/m}(\tau)$ in Eq.9 can be estimated as follows:

$$SD_{k/ij/m}(\tau) = \frac{1}{2}\tau * Q_{k/ij/m}(\tau)\left[\frac{1}{F_{k/ij/m}(\tau)} - \frac{1}{f_{k/ij/m}(\tau)}\right] \tag{10a}$$

and

$$SD_{k/ji/m}(\tau) = \frac{1}{2}\tau * Q_{k/ji/m}(\tau)\left[\frac{1}{F_{k/ji/m}(\tau)} - \frac{1}{f_{k/ji/m}(\tau)}\right] \tag{10b}$$

where

$Q_{k/ij/m}(\tau)$, $Q_{k/ji/m}(\tau)$ is the passenger demand flows, i.e., the number of passengers on the routes *(ij)* and *(ji)*, respectively, of the line *(k)*, requesting and getting the service type *(m)* during time *(τ)*.

The other symbols are as in the previous Eqs.

When the above-mentioned passenger demand is expected to be satisfied by the scheduled/planned transport services, the following conditions are fulfilled:

$$Q_{k/ij/m}(\tau) = f_{k/ij/m}(\tau) * \lambda_{k/ij/m}(\tau) * n_{k/ij/m}(\tau) \tag{11a}$$

and

$$Q_{k/ji/m}(\tau) = f_{k/ji/m}(\tau) * \lambda_{k/ji/m}(\tau) * n_{k/ji/m}(\tau) \tag{11b}$$

where all symbols are as in the previous Eqs.

4 HOW THE METHODOLOGY WOULD BE APPLIED

As mentioned above, the application of the proposed methodology has been described as a process rather than using the particular case study.

4.1 Inputs

The models contained in the methodology for assessing resilience, i.e., vulnerability and related costs of a given HSR network affected by given disruptive events use the following inputs:

i) Configuration of the network
Configuration of the given HSR network is represented by the following inputs:

- Number of nodes (-)
- Number of lines (-)
- Number of routes per line (-)
- Number of different types of transport services per route of given lines (-);
- Length of routes along given lines (km)
- Scheduled/planned operating speed of different types of transport services along routes of given lines (km/h); and
- Speed of cross or headwind affecting given types of transport services along routes of given lines (km/h).

ii) Characteristics of transport services on routes of given lines
Characteristics of transport services in the given HSR network are represented by the following inputs:

- Specified time (hour, day, week, month, year, or few years);
- Scheduled/planned frequency of transport services of given types (departures/period of time);
- Average seat capacity and load factor per given types of transport services (seats/departure; -);
- Number of users/passengers requesting given types of transport services (passengers/specified time);
- Delay multiplier for given types of transport services (-);
- Probabilities of cancellation of each transport service of given types (between 0.0 and 1.0); and
- Probabilities of delaying given types of transport services (between 0.0 and 1.0).

iii) Costs on routes of given lines
Costs of transport services imposed by disruptive vent(s) on the actors/stakeholders of given HSR network are represented by the following inputs:

- Average cost per unit of delay of particular types of transport services (€/min/service);
- Average cost per cancelled transport services of given type (€/service);
- Average cost of passenger time due to extended schedule delays from cancelled transport services of given type (€/min/passenger); and
- Average cost of non-realized passenger trips due to cancelling transport services of given types (€/passenger-trip).

4.2 Results

Using the above-mentioned inputs in the corresponding models, the resilience, i.e., vulnerability of the given HSR transport network based on the resilience, i.e., vulnerability of

its nodes or routes, and related costs for particular actors/stakeholders can be estimated in two ways: i) a priory, i.e., predictive when disruptive vent is still expected to occur; and ii) a posterior, when the disruptive event has already occurred.

In both cases, the corresponding above-mentioned inputs for the selected lines, their routes, and services can be used. In particular, the sensitivity analysis of resilience, i.e., vulnerability of the network can be carried out respecting to changes of the following inputs:

The size and content of the already or prospectively affected part of the network by given disruptive events characterized by the number of lines, routes, and types of transport services scheduled/planned during the specified time.

Probabilities of cancelling and/or delaying particular scheduled/planned transport services in the already or prospectively affected part of the network; and

Speed/time of propagating of the given disruptive events across the network implying changes of size and related content of its affected part over time (this mainly depends on type of disruptive events).

In this case it is reasonable to expect that if the size of the affected [art of the network and the probabilities of cancelations and delayed transport services increase the resilience, i.e., vulnerability of the given network will decrease, and reach its minimum when the corresponding probabilities are equal to one. In the former case, when these probabilities are less than one, the resilience, i.e., vulnerability of the network has predictive character, if disruptive events occur simultaneously in the forthcoming specified time, cancellations of some and delays of other remaining transport services are likely to expect. In the latter case, the disruptive event(s) has already occurred and caused cancellation or delaying of all affected transport services. In this case the disruptive events causing cancellation and delays exclude each other. .

With propagation of the disruptive events across the network the number of nodes/stations, lines, routes, and services to be prospectively or been already affected changes- some new are coming under impact some others have been relieved - thus influencing changes of the network's overall resilience, i.e., vulnerability. In general, resilience, i.e., vulnerability of given HSR network decreases with increasing of size of its affected part regardless the type of disruptive events.

The sensitivity analysis of the costs of impacts of disruptive vents affecting given HSR network under given conditions can be carried out respecting changes of the following inputs:
 Above-mentioned inputs influencing resilience, i.e., vulnerability of the network; and

Average unit costs of cancelled and delayed transport services of particular actors/stakeholders involved – users/passenger and transport operators.

In general these costs and their particular components are expected to increase with the number of affected – cancelled or delayed – transport services, which is in line with increasing of probabilities of impacts of corresponding disruptive events. In addition, in case when disruptive events have already happened the particular cost components exclude each other, i.e., if disruptive vent caused cancelation of all transport services, the corresponding costs will be maximal, and the cost of delayed transport services will be zero, and vice versa. As well, if disruptive events are expected to happen the share of particular cost of prospectively cancelled and delayed transport services will depend on their corresponding probabilities. Anyway each cost component will tend to increase with increasing of the corresponding above-mentioned unit cost, given the other inputs constant.

The above-mentioned discussion has indicated that resilience, i.e., vulnerability of the given HSR network affected by given disruptive event(s0 are negatively correlated, i.e., decreasing resilience, i.e., vulnerability reflects greater number of affected transport services and consequently increasing of the particular cost components under given conditions.

5 CONCLUSIONS

This paper has developed a methodology for estimating the resilience, i.e., vulnerability and costs of a given HSR network, which can be affected by different disruptive events. The network has consisted of lines each containing nodes/stations and links connecting them. Along particular lines the routes have been established, each defined by the begin and end node/station as the origin and destination of user-passenger lows and HS (High Speed) train services of different types scheduled/planned at the frequency to fully serve them during the specified time

The particular types of HS train services have been characterized by the service frequency, the number of intermediate stops between origin and destination nodes/stations, operating speed, and cost/price for transport operator(s0 and users/passengers.

In such a context, resilience, i.e., vulnerability has been considered as the network's ability to sustain its planned operations during the impact of a disruptive event. Consequently, the resilience has reflected the network's operational level under given conditions. The disruptive events categorized as internal-the system and external have been assumed to individually simultaneously affect the HSR services on particular routes, lines, single or more lines, and the entire network, depending on their type and the intensity of impact. The consequences have been cancelled and/or delayed affected impact transport services. In this context, the disruptive events have assumed to affect particular transport services in the network with certain probability during the specified time. This has enabled estimation of resilience, i.e., vulnerability, and cost of their impact on the given network both a priory (when the event is expected to likely occur) and a posterior (when the event has event occurred).

The costs of impacts of disruptive events have included the costs of cancelled and delayed HS transport services imposed directly on transport operators and users=-passengers, In some sense, these costs have reflected the HSR network's economic (in)-efficiency under given conditions.

The way how the proposed methodology could be applied has contained an elaboration of the necessary inputs and a qualitative analysis of the expected results, both in the general terms.

The results have indicated that the resilience, i.e., vulnerability of give HSR network would decrease with increasing of the probabilities of occurrence and intensity of impacts, and spatial scale of disruptive events. In addition, the costs imposed on particular actors/stakeholders would increase.

What remains for the further research is to demonstrate application of the proposed methodology to the real-life case or by using "what-if" scenario approach related to the real-life HSR network. After that, the judgement of the real usefulness of the proposed methodology could be made. At this moment, it remains in the theoretical domain**.**

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