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Original Article

THE OPERATIONAL RESILIENCE EVALUATION METHOD AS A TOOL FOR DECISION-MAKING DURING TRAFFIC DISRUPTIONS IN THE RAILWAY SYSTEM

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Highlights:
- multidimensional functionality functions allow for a convergent view on the system operation;
- phased fuzzy models quantify complex functionality functions;
- combining cancelled processes with compensation actions prevents skipping cancellation actions;
- combining punctuality with cancelled processes prevents reconfiguration by cancelling only;
- changes in resource schedules are risk indicators for future failures resulting from the changes.

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Abstract. Basically, node connections and arc capacity issues are taken into account for resilience evaluation. Then, resilience investigation is mainly limited to catastrophic events with focus on the system layer. Nevertheless, from the operation point of view it is not enough to keep the correct node connection of the system but also to keep the appropriate process schedules. Thus, it is important to go beside the classical network (system) resilience and to develop the concept of operational resilience. In the typical resilience analysis, the main function necessary for resilience evaluation is the performance or functionality in time. Normally it is defined by one criterion, for example available railway lines, or number of trains, or hardly ever also punctuality. Therefore, the 1st aim of this article is to propose a multi properties functionality function, that takes into account operation process parameters like punctuality, delay probability, number of launched trains, and correctly assigned resources. 2nd, the article shows a tree stage fuzzy model to calculate the performance function using the incoherent process parameters. The multidimensional character of the functionality function is well covered by the proposed 3 stage fuzzy model. It makes it possible to put together different measures, and to calculate in an effective way the synthetic functionality/performance value. The model is in detail described as well as its developed including theoretical works, operational data analysis, as well as the experience of experts. The model description is followed by a railway case study, where scenarios elaborated by Experts are evaluated and compared, looking for the best one in terms of resilience. A resilient solution will be that one with the smallest performance/functionality loss in time. Basing on the case it can be concluded that the method is a step forward in resilience research. It has also a high practical potential due to simplification of very complex prediction issues. For example, possible further lack of crews or vehicles is represented as negative influence on the functionality function, without the need to make in short decision time complicated and not maybe incomplete.

Keywords: resilience, recovery evaluation, railway transport, operation processes, fuzzy logic.

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Notations

Abbreviations:

CDF – cumulative distribution function;
RTI – reference time interval (e.g., one day);
TTR – time to repair.

Variables and functions:

$A_C^s(t)$ – number of cancelled processes in time moment t in scenario s;

$A_{CIS}^s(t)$ – number of implemented processes with assigned train crews in accordance to the schedule in time moment t in scenario s;

$A_I^s(t)$ – number of implemented processes (scheduled and additional) in time moment t in scenario s;

$A_{IS}^s(t)$ – number of implemented processes from the set of scheduled processes in time moment t, for scenario s;

$A_{PIS}^{s}(t)$ – number of punctual processes from the schedule under implementation in time moment t for scenario s;
$A_{R}^{s}(t)$ – number of replaced processes in time moment t in scenario s;
$A_{S}(t)$ – number of scheduled processes in time moment t;
$A_{UIS}^{s}(t)$ – number of realized processes with assigned clusters in accordance to the schedule in moment t in scenario s;
$A_{VIS}^{s}(t)$ – number of realized processes with assigned vehicles in accordance to the schedule in moment t in scenario s;
$F_{\alpha}(T_{\omega}^{\alpha})$ – cumulated distribution function for $\Delta T_{\alpha} = T_{\omega}^{\alpha}$, for the distribution $f_{\alpha}(\Delta T_{\alpha})$;
$f_{\alpha}(\Delta T_{\alpha})$ – probability distribution of the time deviation ΔT_{α} of process α from the shortest implementation time;
$FL^{s}(t)$ – functionality loss for scenario s;
$N(t)$ – number of individual processes, e.g., a train ride on a track section;
ORo_{ω}^{α} – operational robustness for a pair of two processes α and ω;
$ORo^{o}(t)$ – operational robustness for the scheduled traffic situation;
$ORo^{s}(t)$ – operational robustness for recovery scenario s;
$Pr(\Delta T_{\alpha} \le T_{\omega}^{\alpha})$ – probability that the time deviation ΔT_{α} of process α from the shortest implementation time will be no higher than the time space T_{ω}^{α} to process ω;
S^{ε} – set of reconfiguration scenarios after event ε;
T_{ω}^{α} – scheduled time space between the end of process α and the start of process ω;
α – influencing (first in time) process;
ΔT_{α} – time deviation of process α from the shortest implementation time;
ε – undesirable event with specified consequences;
$\Phi^{s}(t)$ – functionality function for scenario s;
φ_{Cap} – intermediate indicator of the fuzzy model representing the system capacity;
φ_{Cor} – intermediate indicator of the fuzzy model representing the correctness of assigned resources;
φ_{Pl} – intermediate indicator of the fuzzy model representing the implemented processes in relation to the assumed schedule;
φ_{Pu} – intermediate indicator of the fuzzy model representing the process punctuality;
$\theta_{Clu}^{s}(t)$ – proportion of correctly assigned clusters to scheduled processes for scenario s;
$\theta_{Cmp}^{s}(t)$ – proportion of replaced actions/processes for scenario s;
$\theta_{Cre}^{s}(t)$ – proportion of correctly assigned train crews to scheduled processes for scenario s;
$\theta_{Imp}^{s}(t)$ – proportion of implemented actions/processes for scenario s;
$\theta_{Pun}^{s}(t)$ – proportion of punctual actions/processes for scenario s;
$\theta_{RoG}^{s}(t)$ – robustness gradient for scenario s;
$\theta_{Veh}^{s}(t)$ – proportion of correctly assigned vehicles to scheduled processes for scenario s;
ω – influenced (second in time) process.

1. Introduction

The rail transport system is described by many qualities. 5 of the most common quality categories are: the railway network, rolling stock, timetable, passengers and freight. The timetable includes network and rolling stock boundaries, and it should be appropriate to the passenger and freight demand. Boundaries in sociotechnical systems are mainly interpreted as interdependencies, what means a relationship between components or systems in terms of their states (Johansson, Hassel 2010). Such functional dependencies create a system vulnerability to disruptions. An effective recovery from disruptions is a key issue to guarantee a safe operation, because also small consequence events may have influence on accident occurrence like the domino bricks effect.

The recovery from operational inaccuracies, that is typically not taken into account under resilience research, is going to be an important factor in accident prevention. A proper functioning system must meet operational requirements that can be described by the following functionality qualities:

- quantitative implementation of the scheduled processes (number of implemented processes within the assumed schedule);
- qualitative implementation:
  - punctuality of process implementation in accordance to the schedule;
  - train crews assigned to processes in accordance to the schedule;
  - vehicles assigned to processes in accordance to the schedule;
  - clusters assigned to processes in accordance to the schedule;
- risk of further failures:
  - caused by unavailability of system components;
  - caused by delayed processes and dependencies to other ones.

Taking into account the above qualities for the resilience approach could give a new tool for evaluation of recovery and reconfiguration strategies of the railway system under standard operation without or with catastrophic events. Resilience is in literature mainly connected to large scale consequences and system recovery based on the US Presidential Policy Directive to defines resilience as “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions” (Hosseini *et al.* 2016; Rus *et al.* 2018; Liu, Song 2020; Bešinović 2020; Zhang *et al.* 2018b). By defining resilience, other authors also combine recovery issues with the ability to withstand impacts on the system (Alipour, Shafei 2016; Cox *et al.* 2011). The authors represent the standpoint that resilience is limited to the ability to recover the system function or stable state (Cox *et al.* 2011). The system function is represented in the literature in a diverse way. The term resilience is often used instead of performance what can be seen in the review presented in research by Hosseini *et al.* (2016). A most common used point of view is the availability of nodes and arcs in a system modelled as graph (Cornaro, Grechi 2023).

Resilience assessment is a no structured field of this research area. Many authors proposed their own better or worse approach. Hosseini *et al.* (2016) bring together many of them. The Authors divide the resilience assessment approaches into 4 main groups:

- conceptual frameworks – qualitative assessment by descriptive methods (Bruyelle *et al.* 2014);
- semi-quantitative indices – descriptive methods supplemented by point scale measures;
- structural-based models – optimization, simulation or fuzzy logic models;
- general measures – probabilistic or deterministic approaches.

The literature was analysed to find out which parameters and processes describing the system, as well as the utilised techniques, have so far been used. After the literature search, 28t articles connected to the investigation of resilience and the description of functionality were selected for a detailed analysis in terms of the identified criterions. The results are shown in Table 1.

It can be seen that typically one dimension, in other words one system or process parameter, is taken into account to evaluate performance. This strongly limits the resilience analysis. The most common parameters are: time related measures (6 times), capacity (7 times), and the number of node connections (5 times). Other parameters are represented individually. Among them, the number of affected trains and the changes in passenger journeys can be seen to be interesting for the given research. There is also research where the functionality measure is not specified (7 studies).

Among the utilized techniques in the investigation of resilience, simulation modelling dominates (12 times). Simulation modelling is used for consequence and scenario analysis under variable system management. Fuzzy logic is in the 2nd place (4 times). The technique was used 3 times for general investigations without functionality loss analysis.

Analysing the review articles (Hosseini *et al.* 2016; Rus *et al.* 2018; Liu, Song 2020) it can be found, that typically one dimension, in other words one system or process parameter is taken into account for the performance representation. This limits strongly the resilience analysis. The most common parameters are: time related measures, capacity and number of nodes connections. Other are represented individually. Among them, number of affected trains and change in passenger journeys seems to be interesting for the given research. There are also researches, where the functionality measure is not specified. Among utilized techniques in resilience investigation, simulation modelling is dominating. Simulation modelling is used for consequence and scenario analysis under variable system management. Fuzzy logic is on the 2nd place located. This technique was used also for general investigation without functionality loss analysis. For example, it is used in resilience engineering to perform evaluation of influencing factors (Azadeh *et al.* 2014). In the article by Kierzkowski & Kisiel (2017), the fuzzy logic was used for combining of incoherent factors to one performance functions, but this research is related to system evaluation except resilience.

All analysed articles deal with disasters or critical failures and apply to the system and not to processes. The expectation is which's subject is not related to resilience (Kierzkowski, Kisiel 2017). Some articles related to process resilience were also found, but they refer to chemical processes in systems (Castillo-Borja *et al.* 2017; Dinh *et al.* 2012). Moreover, they base on qualitative or semi-quantitative methods and in general are not applicable for the performed research. This is also due to finite process constraints (Jain *et al.* 2019), which are not necessarily represented in the railway system. Moreover, there is lack of articles dealing with multi parameter analysis in terms of functionality identification. In case of interdependent systems resilience is analysed as a function of one-dimensional functionality function (Zhang *et al.* 2018a). There are in the literature also trials to combine some performance influencing factors, like delays and train cancelling , but they simply the problem and take not into account for example replacement transport.

The problem of railway process reconfiguration after disruptions and the results of performed literature research lead to the main research questions not solved by the available literature and to be solved by the ongoing research:

- can a resilience based approach be developed as a tool for reconfiguration scenario evaluation?
- what functionality influencing factors have to be taken into account?
- can such an approach be applicable and effective for typical operation situations, and not only for catastrophic events?

The contribution is built of 5 sections. The problem description and literature review in the introduction (Section 1) is followed by an overview description (Section 2) of the proposed approach. The Section 3 describes in detail the core model of the functionality function that is necessary for resilience evaluation. The model description is followed by a railway case study in Section 4. Section 5 presents the conclusions.

Table 1. Functionality parameters and techniques for resilience analysis and system evaluation in literature

Subject of study	Performance, functionality properties	Used techniques	Application / focus	Example reference
Network vulnerability	delay time of all delayed passengers	2 layer network modelling	disasters / system	Hong *et al.* (2019)
Network vulnerability	accessibility between stations	graph modelling	major node failures / system	Ouyang *et al.* (2015)
Network vulnerability, robustness	number of affected trains	genetic algorithms	disasters /system	Yan *et al.* (2017)
Recovery optimization	edge capacity	simulation modelling	major disruptions / system	Valcamonico *et al.* (2020)
Network resilience	total travel time, congestion	simulation modelling, swarm optimization	major disruptions / system	Zou & Chen (2019)
Network resilience	not specified	simulation modelling	critical failures of infrastructure / system	Argyroudis *et al.* (2020)
Reliability	number of sensor faults	simulation modelling	critical sensor failures / system	Ouyang *et al.* (2019)
Network resilience, robustness	departure delay	simulation modelling	critical failures / system	Wang *et al.* (2019)
Infrastructure optimization	capacity	mathematical programming	disasters / system	Najarian & Lim (2020)
Resilience assessment	not specified	Bayesian networks	disasters / system	Kammouh *et al.* (2020)
Resilience	population density, natural assets, reduction of the environmental impacts, quality of water sources	semi structured questionnaire, Delphi technique, point scale combined with weights	disasters / system	Sweya & Wilkinson (2020)
Resilience, dependability	not specified	fuzzy logic	critical failures / system	Bukowski (2016)
Resilience	capacity or travel time	simulation modelling	critical failures / system	Balal *et al.* (2019)
Vulnerability	nodes connections	simulation modelling	disasters / system	Pitilakis *et al.* (2016)
System evaluation	capacity, detection efficiency, passengers' evaluation	fuzzy logic	operation / system	Kierzkowski & Kisiel (2017)
Resilience assessment	traffic wave direction and velocity	simulation modelling	disasters / system	Yang *et al.* (2020)
Resilience, lifecycle	not specified	quality function deployment	disasters / system	Mao *et al.* (2019)
Risk management	not specified	fuzzy logic	critical failures / system	Edjossan-Sossou *et al.* (2020)
Robust timetables	train delay	critical path method, Lagrangian heuristics	disruptions / operation	Lu *et al.* (2017)
Resilience assessment	available paths and moving directions	regression	disasters / system	Klimek *et al.* (2019)
Security	change in passenger journeys	time series	disasters / system	Cox *et al.* (2011)
Resilience assessment	nodes connections	simulation modelling	critical failures / system	Cerqueti *et al.* (2019)
Resilience assessment	capacity	hidden Markov models	critical failures / system	Zhao *et al.* (2016)
Organizational resilience	not specified	fuzzy logic	critical failures / system	Aleksić *et al.* (2013)
Network resilience	not specified	simulation modelling	critical failures / system	Lu (2018)
Network resilience	cumulative travel time	simulation modelling	disasters / system	Do & Jung (2018)
Network resilience	nodes connections	simulation modelling	critical failures / system	Ramirez-Marquez *et al.* (2018)
Network resilience	flow between nodes	heat maps	critical failures / system	Gama Dessavre *et al.* (2016)

2. Description of the approach

The section describes in general the approach. The general view at the method is shown in Figure 1. Then all steps of the approach are described in detail, including explanation of calculation of indicators or citations of own research that shows in detail some aspects.

The method consists of a preparation phase (steps 1...4) and the main phase (steps 5...15), where the core model is used in Step 11. The preparation phase is necessary to have the base knowledge for further decision-making.

Step 1. The timetable is analysed in terms of relevant qualities like number and type of trains, constrains resulting from the track occupancy, constrains resulting from train crew and vehicle circulation, as well as applied time reserves.

Step 2. Using the database on undesirable events the possible events are identified and grouped. For each group is a probability density function of the times to repair fitted. All groups together must cover a hundred percent of occurring undesirable events.

Step 3. Using the database on train punctuality, theoretical delay probability distribution functions are fitted to the data for the given processes.

Step 4. Calculation the robustness measures. Robustness is the ability to keep the correct operation after undesirable events occurred (Restel *et al.* 2021). It can be quantified by the probability of no delay propagation between any pair of trains. The robustness measures for all $N(t)$ pairs of processes (α– influencing process, ω – influenced process) and the overall robustness measure according to Friedrich *et al.* (2019) and Restel *et al.* (2021):

$$ORo^{o}(t) = \prod_{\alpha=1}^{N(t)} \prod_{\omega=1}^{N(t)} ORo_{\omega}^{\alpha}, \tag{1}$$

where the robustness measures ORo_{ω}^{α} for given pairs of processes (α, ω) are calculated:

$$ORo_{\omega}^{\alpha} = \Pr\left(\Delta T_{\alpha} \le T_{\omega}^{\alpha}\right) = F_{\alpha}\left(T_{\omega}^{\alpha}\right) = \int_{0}^{T_{\omega}^{\alpha}} f_{\alpha}\left(\Delta T_{\alpha}\right) \mathrm{d}\left(\Delta T_{\alpha}\right). \tag{2}$$

The probability of no disruption propagation for not-dependent processes will be equal to 1. Operational robustness is calculated for a RTI. One day was assumed. If the schedule is repeatable day by day, than the number of process pairs N will be for the scheduled situation not dependent on time. The core method starts after a failure has occurred. Firstly, the failure type has to be identified.

Step 5. Identification of a given failure in the system, and assigning it to a specified group of undesirable events. Depending on the failure type will be the possible TTR.

Step 6. Calculation of a specified TTR quantile for the given event type. The used quantile will influence the further decision-making. A higher quantile will allow to cover the real time to failure by a higher probability. On the other hand, it will cause the analysis of a longer time interval of the system unavailability. Therefore, the time effort for elaboration of solutions will be higher and the solutions may be more complex than necessary. The chosen quantile depends on the decision-maker, but it is suggested to

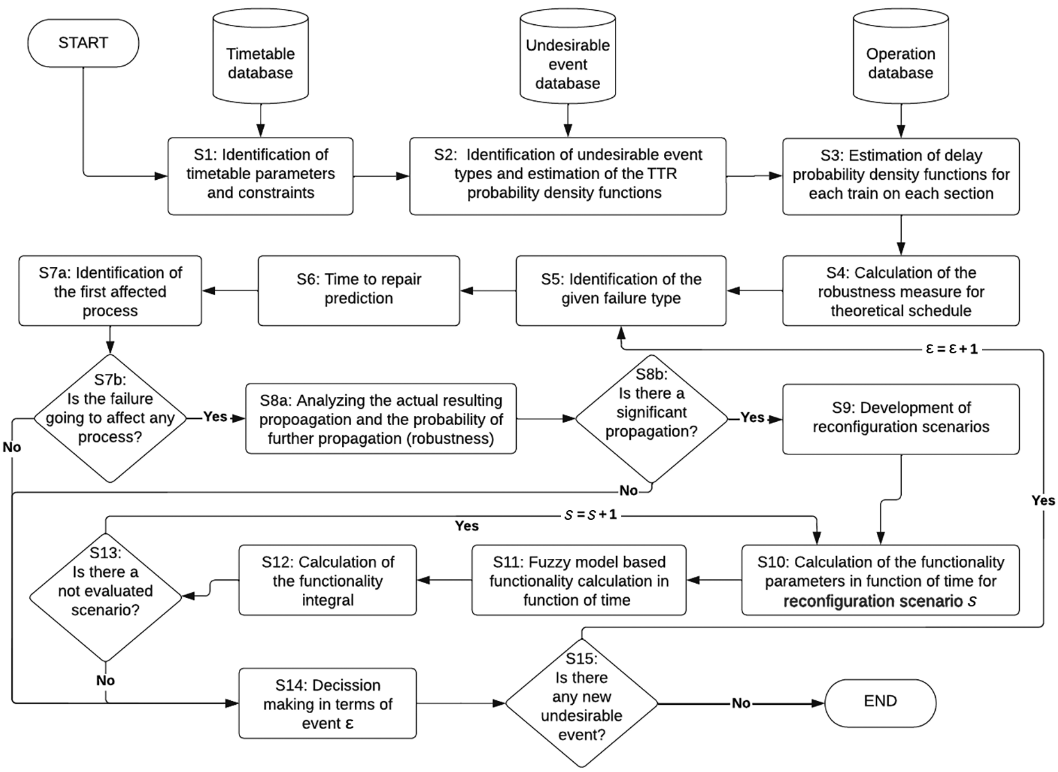

Figure 1. Operational resilience evaluation method diagram (S – step)

take a value between the 7th and 9th decile. The calculated probable TTR has to be insert into the actual time table with the typical consequences:
- total closing of a network part;
- lowering of capacity.

Step 7. According to the timetable identified in Step 1. and the calculated TTR in Step 6, the influence of the event on processes is analysed. If the time space to the next process is longer than the TTR than it is assumed, that there will be no influence, and no recovery is necessary.

Step 8. According to the dependencies identified in Step 1. and the calculated TTR in Step 6, the propagation of delays to further processes is analysed. If the time margins and time space to other processes allow to compensate the delay than no reconfiguration is necessary. Moreover, the decision-maker has also to analyse in this step how the probability of further delays will change according to the robustness approach from Step 4.

Step 9. When there is a possible disruption propagation than reconfiguration scenarios have to be developed. Due to a high variability of the possible traffic situations, the scenarios are normally developed by dispatchers and can take into account different strategies (Bergantino *et al*. 2024). The elaboration methods can vary, but the following reconfiguration actions has to be taken into account:
- rerouting of trains;
- cancelling of trains;
- compensation of cancelled/delayed trains by busses or other additional trains;
- changing of train order in the schedule;
- waiting till the end of the event.

As a result, a set of reconfiguration scenarios S^{ε} is prepared after event ε.

Step 10. In the next step the calculation of functionality parameters in function of time is performed. Depending on the complexity of the traffic situation the parameters can be calculated using a basic calculation tool like *Microsoft Excel*, a universal simulation tool like *FlexSim* or a dedicated railway simulation tool like *OpenTrack*. For the ongoing research all these tools have been used, but the most times *OpenTrack* described in research by Restel *et al*. (2021).

The 1st, robustness will be calculated according to Step 4. For robustness, it may be necessary to calculate new delay probability distributions, because of cancelling processes and launching of new ones. Also, the new set of dependencies must be known. More relevant than absolute robustness values are its changes in relation to the desired schedule. The indicator was described in detail in the research by Restel (2021). Therefore, the operational robustness gradient will be calculated:

$$\Theta^{s}_{RoG}(t) = \frac{ORo^{s}(t)}{ORo^{o}(t)}. \qquad (3)$$

Actual punctuality, for a given moment in time is the next parameter. Actual punctuality is normally represented as proportion of punctual processes to all implemented processes from the schedule:

$$\Theta^{s}_{Pun}(t) = \frac{A^{s}_{PIS}(t)}{A^{s}_{IS}(t)}. \qquad (4)$$

Processes predicted for implementation are treated as delayed starting from their planned ending till the rescheduled ending. Thus, a delayed process is still represented in the schedule as ongoing process. Punctuality issues represent the quality of process implementation. Besides that, the number of implemented processes can be used for the quantitative description. The quotient will be calculated of the number of implemented processes to the desired number of processes in the schedule, for a given moment in time:

$$\Theta^{s}_{Imp}(t) = \frac{A^{s}_{IS}(t)}{A_{S}(t)}. \qquad (5)$$

Temporary launched processes after reorganization are not included. On the other hand, new processes can be launched to compensate cancelled ones. Thus, it has to be taken into account, how many processes can be classified as replaced by new ones. A cancelled process will be treated as replaced if the new ones destination is the same as the replaced ones. A cancelled process is taken for calculation till the next similar process will be launched or the compensating process will start. The quality will be represented by the quotient of replaced processes number to the number of cancelled processes:

$$\Theta^{s}_{Cmp}(t) = \frac{A^{s}_{R}(t)}{A^{s}_{C}(t)}. \qquad (6)$$

The implementation correctness represents the accuracy of assigned resources during implementation of the processes in terms of the schedule assumptions. It will be quantified by 3 parameters. The 1st one is the quotient of correctly assigned clusters for processes in relation to all implemented processes. Additional processes are treated as processes with not correct assigned clusters, but correctly assigned crews and vehicles:

$$\Theta^{s}_{Clu}(t) = \frac{A^{s}_{UIS}(t)}{A^{s}_{I}(t)}. \qquad (7)$$

The 2nd parameter is the quotient of correctly assigned crews for processes in relation to all implemented processes:

$$\Theta^{s}_{Cre}(t) = \frac{A^{s}_{CIS}(t)}{A^{s}_{I}(t)}. \qquad (8)$$

The 3rd parameter is the quotient of correctly assigned vehicles for processes in relation to all implemented processes:

$$\Theta^{s}_{Veh}(t) = \frac{A^{s}_{VIS}(t)}{A^{s}_{I}(t)}. \qquad (9)$$

Temporary (additional) processes launched after reconfiguration are treated as not correct, in terms of clusters, crews, and vehicles.

Moreover, in case of no scheduled processes for a given moment in time, for the indicators from the Equations (4)–(9) will be assigned values of one.

Step 11. After calculation of the input parameters, the functionality evaluation can be performed. Because of the input parameter inherency, it is not possible to use them directly for analytical calculations. Therefore, a multilevel fuzzy model was developed to calculate the functionality value. The general view of the fuzzy model is shown in Figure 2.

The operation functionality model is built of 3 inference stages. The evaluation process starts with estimation of the 7 process parameters shown in Step 10. The functionality evaluation model consists of 5 fuzzy sub-models. The structure is shown in Figure 2.

The shapes of membership functions have been developed basing on interviews performed with specialists in railway vehicle operation, crew assignment, and timetabling (described in the next section).

Step 12. After calculation of the functionality function from the fuzzy model, the operational resilience as the functionality integral can be calculated. It covers a time interval from the beginning of the undesirable event till the end of functionality loss or till the end of the reference interval (for example 24 h). The reference interval is assumed as one day measured from the beginning of the event.

$$FL^s(t) = 1 - \int^{RTI} \Phi^s(t)\,\mathrm{d}t\,. \tag{10}$$

Step 13. If there are not evaluated scenarios, then the evaluation steps must be repeated for a next scenario. The algorithm moves than back to Step 10.

Step 14. After the evaluation, the decision-making can take place either basing on resilience alone or taking into account also other factors.

Step 15. The algorithm ends or another event and its consequences are analysed, then we go back to Step 5.

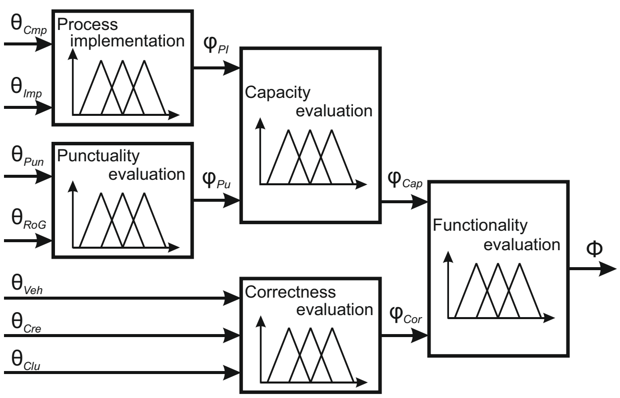

Figure 2. Fuzzy model of multidimensional functionality

3. The multistage fuzzy model of railway functionality

A key element of the proposed method is the functionality evaluation model. It bases on 5 fuzzy sub-models. The general description is in Section 3.1. The model structure, the type and number of membership functions was developed during the theoretical and operational phase of the research. Moreover, the parameters of the membership functions and the rules have been developed using Experts knowledge. This stage is described in Section 3.2. Section 3.3 shows the resulting input and output variable description by the developed membership functions. Due to lack of space in the article, the rule tables were placed in the Appendix Supplementary Tables.

3.1. General description

Each sub-model uses the input variables according to the structure from Figure 2. The final functionality model uses 2 fuzzy modelled input variables (correctness and capacity indicators).

There are 7 triangular and 2 half-triangular membership functions assigned for the input variable *Capacity*. For correctness there are 4 triangular and 2 half-triangular membership functions assigned. The output variable *Functionality* is characterized by 13 triangular and 2 half-triangular membership functions. That sub-model uses 49 rules. The remaining parameters (of the methods: *And*, *Or*, *Implication*, *Aggregation* and *Defuzzification*) are shown in Table 2. Moreover, the same way in Table 1 is characterized the remaining 4 sub-models.

The shape of the membership functions was in the next step developed in cooperation with Experts. The parametrization process is described in Section 3.2, while the final shapes are shown in Section 3.3.

3.2. Fuzzy model parameterization process

The fundamental qualities of the model have been determined, and are not able to be changed. In example the model structure as shown in Figure 2 as well as the number, the type (triangular functions) and the linguistic descriptions of the membership functions. To get the best possible results, the triangular membership function parameters and the rules have been developed in cooperation with Experts (active working in Polish railway companies):

- 4 dispatchers;
- 3 timetable designers;
- 2 vehicle circulation planners;
- 3 train crew work planners.

Step 1. All of the Experts got the same survey with questions about parameters of the triangular membership functions. The questions were ordered from the top level (functionality model) to the basic input parameters. For each input or output variable the Experts knew, what num-

Table 2. Model parameters for functionality evaluation

Model / output variable	Input variables (No of membership functions)	No of output membership functions	No of rules	*And* method	*Or* method	Implication	Aggregation	Defuzzification
Functionality evaluation Φ	φ_{Cap} (9), φ_{Cor} (6)	15	49	min	max	min	max	centroid
Correctness evaluation φ_{Cor}	θ_{Veh} (5), θ_{Cre} (5), θ_{Clu} (5)	11	125	min	max	min	max	centroid
Capacity evaluation φ_{Cap}	φ_{PI} (9), φ_{Pu} (5)	14	41	min	max	min	max	centroid
Process implementation evaluation φ_{PI}	θ_{Cmp} (5), θ_{Imp} (6)	14	36	min	max	min	max	centroid
Punctuality evaluation φ_{Pu}	θ_{RoG} (5), θ_{Pun} (6)	13	30	min	max	min	max	centroid

ber and what linguistic description have the membership functions. The vehicle and train crew planners had to answer 32 questions each, while the remaining Experts had to answer 101 questions each of them. In each question the Experts answered what is the starting value (*a*), what is the value for the function maximum (*b*) and what is the ending value (*c*) of the given triangular membership function.

Step 2. For the *b* parameter of the membership functions were calculated the mean value, the maximum value and the minimum value from the Experts answers. For *a* and *c* parameters were calculated the distances to the *b* parameter for every Expert answer separately. For the distances were next calculated the maximum, minimum and average values.

Step 3. Basing on the results of Step 2. were the membership functions designed. For each input/output variable were developed 3 variants:

- mean value of the *b* parameter, *a* and *c* parameters with the maximum distance to *b*;
- mean value of the *b* parameter, *a* and *c* parameters with the minimum distance to *b*;
- a hybrid solution based on the answers.

Step 4. Using the Analytic Hierarchy Process approach were evaluated the prepared variants of membership functions for all input/output variables.

Step 5. From each Expert group was one person chosen. The final versions of the membership functions were them presented (Figures 3–15). Then, in a work group of 5 persons (including the author) the Brain Storming method was used to develop the rules for each fuzzy model.

The so gathered model parameters works properly for the Polish railway case. For other countries it can be necessary to perform the parametrization process again as described above.

3.3. Detailed description of the fuzzy model

The *Functionality* Φ evaluation model consists of the input variable *Capacity* φ_{Cap} and *Correctness* φ_{Cor}. The input variables are connected by 49 rules (shown in the Appendix Supplementary Table 1) to the output variable. Membership functions of the variables are presented in Figures 3–5.

Fifteen membership functions have been assigned for the output variable *Functionality* Φ. Symmetric triangular membership functions with a changing length are used for the linguistic variables *Bad*, *Low*, *Sufficient*, and *Good*. To represent extremal values like 1 and 0, half-triangular functions are used for the linguistic variables *No* and *Scheduled*. The functions are more concentrated in the neighbourhood of the variable values 0 and 1, because of the criticality of those values for the system operation.

For the input variable *Capacity* φ_{Cap} (Figure 5) 9 triangular or half-triangular membership functions are assigned. The functions are concentrated around the boundaries of the variable domain, that means zero and one. 4 symmetric triangular and 2 half-triangular membership functions are used for the input variable *Correctness* φ_{Cor} (Figure 4). Their length is constant.

The variable *Correctness* φ_{Cor} is estimated by a fuzzy model with 3 input variables, one output variable and 125 rules connecting them (shown in the Appendix Supplementary Table 2). For this model, eleven triangular or half-triangular output membership functions are used (Figure 6). They are concentrated around the domain borders 0 and 1.

The operation correctness model has 3 input variables. They represent correctly assigned resources to processes according to the desired schedule. The resources are mainly vehicles (represented by the proportion θ_{Veh}), train crews (represented by θ_{Cre}), and clusters (represented by θ_{Clu}). The variables have the same shape of membership functions (Figure 7) due to a similar influence on the system operation.

The capacity evaluation model as well as the process implementation evaluation model have the same shape of output linguistic variables with similar membership functions (Figure 8). 14 linguistic variables are described by triangular or half-triangular membership functions are used with concentration around the domain borders.

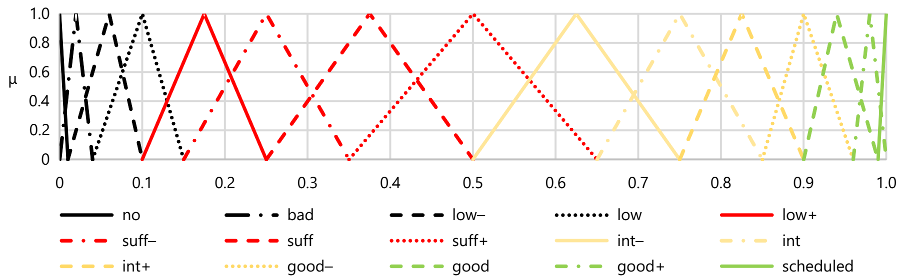

Figure 3. Membership functions for the output variable *Functionality* Φ

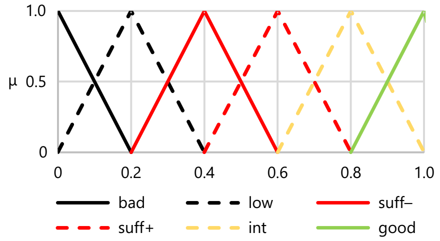

Figure 4. Membership functions for the input variable *Correctness*

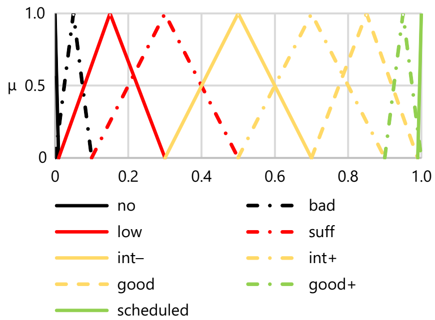

Figure 5. Membership functions for the input variable *Capacity*

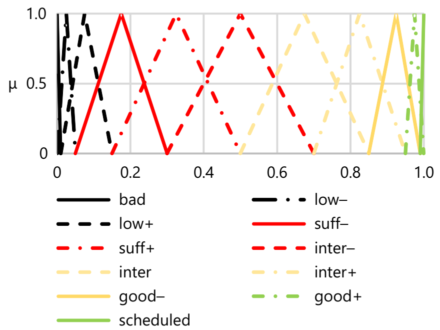

Figure 6. Membership functions for the output variable *Correctness*

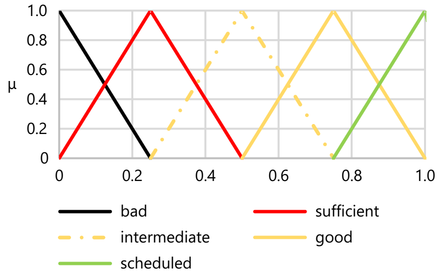

Figure 7. Membership functions for the input variables *Vehicles*, *Crews* and *Clusters*

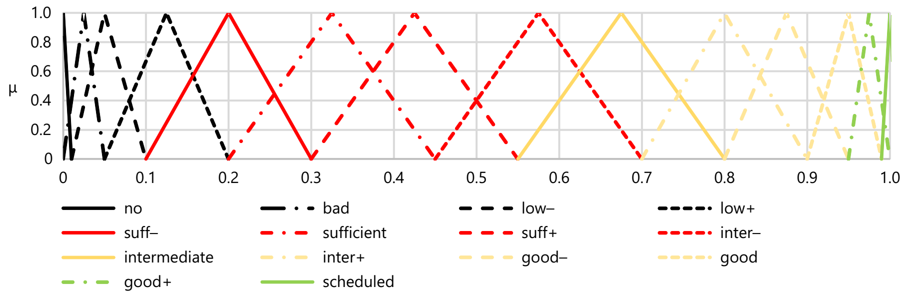

Figure 8. Membership functions for the output variables *Capacity* and *Process implementation*

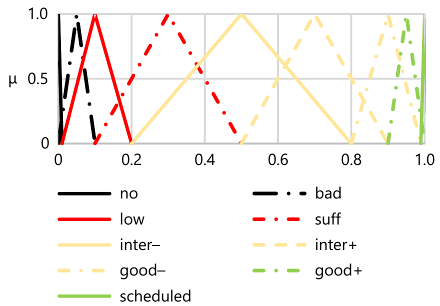

Figure 9. Membership functions for the input variable *Process implementation*

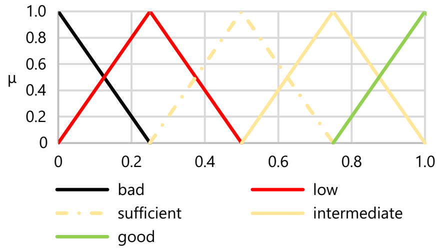

Figure 10. Membership functions for the input variable *Punctuality*

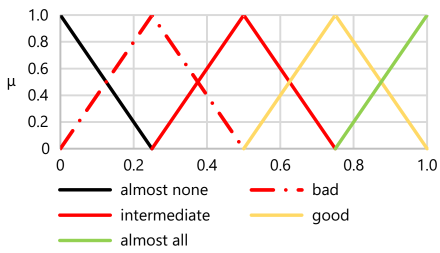

Figure 11. Membership functions for the input variable *Compensating processes*

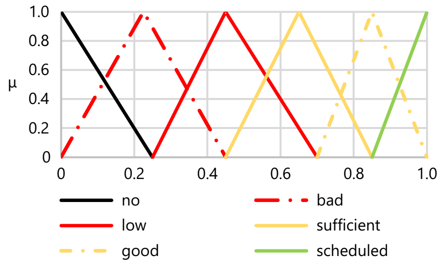

Figure 12. Membership functions for the input variable *Implemented processes*

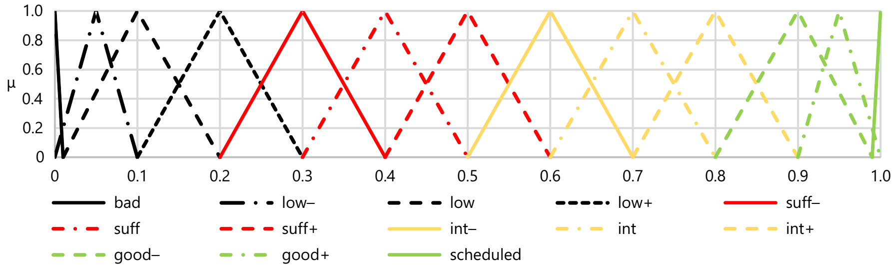

Figure 13. Membership functions for the output variable *Punctuality*

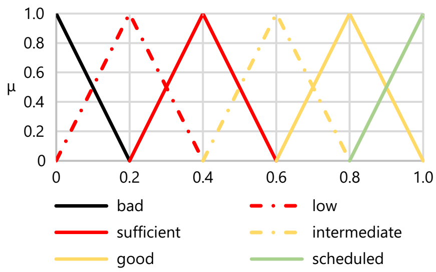

Figure 14. Membership functions for the input variable *Actual punctuality*

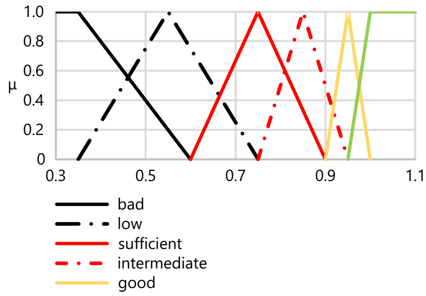

Figure 15. Membership functions for the input variable *Robustness gradient*

For the capacity evaluation (output variable φ_{Cap}), 2 input variables are taken into account. The 1st one, punctuality φ_{Pu} is described by 5 linguistic variables, defined by symmetric triangular or half-triangular membership functions (Figure 10). Symmetric but concentrated to the domain borders membership functions describe also the 2nd input variable, the *Process implementation* φ_{Pl}. 9 linguistic variables define the process implantation (Figure 9). The input and output linguistic variables for the capacity evaluation are connected by 41 rules (shown in the Appendix Supplementary Table 3).

The process implementation evaluation model bases on the same output linguistic variables like *Capacity*. Thus, the same membership functions are assigned, that are shown in Figure 8.

For the process implementation evaluation model (φ_{Pl}) 2 input variables are used. *Implemented processes* θ_{Imp} is described by 6 linguistic variables that are defined by different triangular membership functions, concentrated around the domain borders (Figure 12). The *Compensating processes* input variable θ_{Cmp} is described by 5 linguistic variables. They are defined by triangular or half-triangular membership functions (Figure 11). The input and output linguistic variables are connected by 26 rules (shown in the Appendix Supplementary Table 4).

The output variable *Punctuality* φ_{Pu} is described by 13 linguistic variables (Figure 13). They are defined by 9 similar triangular membership functions and 4 concentrated by the domain borders.

The input variable *Actual punctuality* θ_{Pun} is described by 6 linguistic variables (Figure 14).

They are defined by triangular or half-triangular membership functions concentrated by right domain border.

The *Robustness gradient* θ_{RoG} is connected to 6 linguistic variables, 2 half-trapezoidal and 3 triangular ones (Figure 15). The input and output linguistic variables are connected by 36 rules (shown in the Appendix Supplementary Table 5).

4. Case study

The section shows the application of the resilience evaluation method in the railway dispatching and decision-making process. Section 4.1 describes the scheduled situation that is the starting point for the analysis. Section 4.2 shows the undesirable situation as well as the recovery proposals elaborated by a team of 3 dispatchers-scientists. For each developed reconfiguration scenario, the input indicators (according to the Equations (3)–(9) have been estimated in function of time by a step of one minute for the time interval 4:00...23:06 when trains are scheduled. Section 4.3 discusses the results and concludes the case study.

4.1. System and process description

For the method application, a railway system was chosen consisting of 2 parallel lines. Both are electrified and have a modernized linear infrastructure within the last 10 years. The traffic control system bases on relay technology and there is no automated blocking system. The system connects cities A and E. The lines have a joint section (A–B) and beside that are independent. The line via stations C and D is double-tracked and used for passenger-regional trains (23 pairs). The line via stations X and Z is a single track 1 and it is mainly used for 6 pairs of passenger-express trains, which are supported by 4 pairs of regional trains.

The timetable is graphically shown in Figure 16 on 3 time–way diagrams. The 1st 2 show respectively the trains moving in odd and even direction on line A–B–C–D–E. The last one shows the alternative line through X–Z with representation of all trains on the shared network part.

Regional trains are operated from a depot in station A while express trains start from a station beside the system about 2 h travel time in one direction. The colours related to train paths represent given circulations of vehicles and connected crews.

According to the formulated definition of an action/operation process, there were identified 264 processes with 502 interactions. Depending on the section and the train type, delay probability functions have been estimated according to the approach (Friedrich *et al.* 2019). These parameters are shown in Table 3. Moreover, also other parameters describing processes were shown in the table. The number of clusters for each section describes the possibility of keeping processes in case of track closings. The minimum time space between process and the number of trains describe how occupied can be the system part.

The availability of busses on a given section gives information how fast replacement busses can be introduced.

4.2. Failure and recovery description

A track damage was assumed on section X–Z, which occurred during the night brake. The damage was identified by the operator of the 1st train that day and provided to the dispatcher. According to the parameters of the failure and system (damage of a track modernized within the last 10 years), as well as the assumed probability of finishing the maintenance actions about 0.8, the TTR was estimated. It was done using a distribution fitted to the appropriate operational data from the Polish railway. For the modernized track, the TTR is described by the lognormal distribution LN (5.1913; 1.0138). As a result, a TTR about 7 h was predicted. 9 processes are directly affected and cannot be implemented within the schedule and 18 indirectly due to lack of train crews and vehicles.

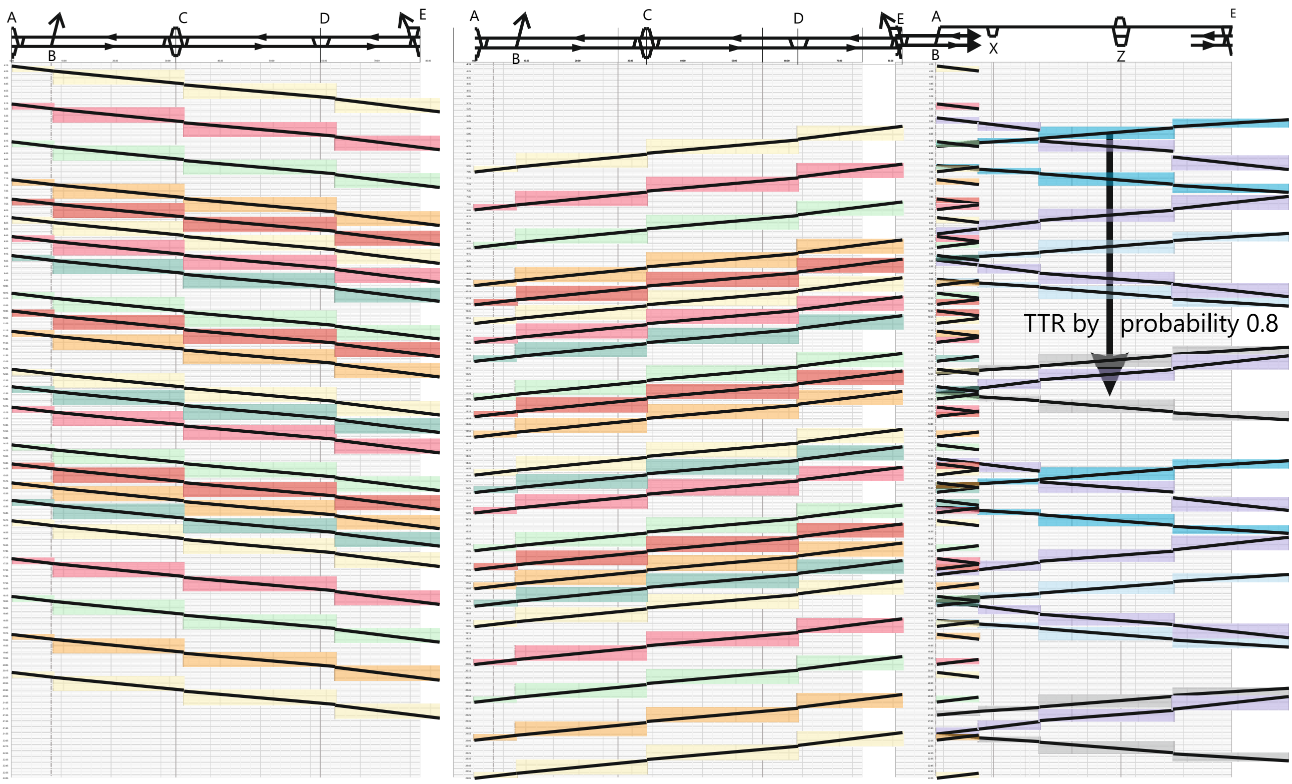

Figure 16. Time–way diagram for a theoretical railway system

6 recovery scenarios have been developed in a group of 3 dispatchers within 20 min. 2 scenarios (Scenario 1 and Scenario1a) limit the recovery to the damaged railway line with usage of busses. The next 2 (Scenario 2 and Scenario 2a) base on express train rerouting to the alternative railway line. The last 2 (Scenario 3 and Scenario 3a) combine these 2 approaches. The general characteristics of the scenarios are listed in Table 4.

The Scenario 1 leads to cancelling of express trains between station Z and A. The regional trains run between A and X with the scheduled resources and from E to Z by an additional set of resources gathered from A through stations C and D. Busses implement 2 processes to compensate 2 cancelled regional train processes. The last 12 processes (3 trains) are delayed to be implemented after the failure will be fixed. Scenario 1a is an upgraded version of Scenario 1. There are 2 more additional processes realized by busses. 6 processes are launched by resources waiting for tasks in the idle state due to lack of connection between X and Z.

For Scenario 2 it was assumed that express trains are rerouted through stations C and D. 2 additional processes are launched by busses. Scenario 2a has the same upgrade like Scenario 1a. It means 2 more buss processes and 6 processes implemented by using other resources.

Scenario 3 and Scenario 3a combine the Scenario 1a and Scenario 2a. In Scenario 3 – 1 express train (from A to E) is kept on the basic line instead of rerouting, without delay. In Scenario 3a – 1 pair of express trains is kept on the basic line, taking into account an intermediate delay.

For all scenarios, the system parameters have been extracted from matrices with processes in function of time, with a time step of one minute. The following parameters were used for input variable estimation:

- number of processes under implementation (including additional and delayed ones, cancelled and compensated processes are excluded);
- number of processes in the schedule (including delayed ones till they are finished and cancelled ones till their compensation or starting of the next similar process);
- number of delayed processes till their real finish;
- number of not compensated cancelled processes till the next similar process will be launched;
- number of cancelled but predicted for compensation by other process till the compensating process will start;
- number of additional processes;
- number of processes with vehicles assigned according to the schedule;
- number of processes with train crews assigned according to the schedule;

Table 3. Operation parameters for the analysed case

Section	No of clusters	Minimum time space between processes [min]	Busses available after time [min]	Scheduled No of express train pairs	Travel time of express trains [min]	Probability distribution (CDF) describing express train delay	Scheduled No of regional train pairs	Travel time of regional trains including stops [min]	Probability distribution (CDF) describing regional train delay
A–B	2	22	40	6	6	$0.9695 + 0.0305 \cdot LN(1.080; 1.0001)$	27	8	$0.9746 + 0.0254 \cdot LN(1.2686; 0.9171)$
B–C	2	9	65	0	12	$0.9457 + 0.0543 \cdot LN(1.1013; 0.9815)$	23	21	$0.9391 + 0.0609 \cdot LN(1.3164; 0.9331)$
C–D	2	9	90	0	18	$0.9201 + 0.0799 \cdot LN(1.1297; 0.9689)$	23	21	$0.9391 + 0.0609 \cdot LN(1.3164; 0.9331)$
D–E	2	9	30	0	13	$0.9406 + 0.0594 \cdot LN(1.1029; 0.9795)$	23	21	$0.9391 + 0.0609 \cdot LN(1.3164; 0.9331)$
B–X	1	8	65	6	6	$0.9695 + 0.0305 \cdot LN(1.080; 1.0001)$	4	12	$0.9504 + 0.0496 \cdot LN(1.3481; 0.9217)$
X–Z	1	1	90	6	18	$0.9201 + 0.0799 \cdot LN(1.1297; 0.9689)$	4	20	$0.9403 + 0.0597 \cdot LN(1.3253; 0.9239)$
Z–E	1	2	30	6	12	$0.9457 + 0.0543 \cdot LN(1.1013; 0.9815)$	4	20	$0.9403 + 0.0597 \cdot LN(1.3253; 0.9239)$

Table 4. Recovery scenario characteristics

Scenario	Number of rerouted express trains	Number of cancelled processes	Number of compensating processes	Number of processes replaced by busses	Number of delayed processes	Number of additional processes
1	0	16	2	2	14	8
1a	0	12	4	4	19	10
2	4	22	6	2	18	20
2a	4	14	8	4	24	22
3	3	11	7	4	16	19
3a	2	8	6	4	24	16

- number of processes with clusters assigned according to the schedule.

After calculation of the input parameters, the values were put into the functionality model implemented in *MATLAB R2018b Simulink* software.

4.3. Discussion of the results

The functionality function values for each scenario in time function are shown in Figure 17. Using the results, from the total daily functionality (equal to 1) the functionality integral was subtracted. Thus, the functionality loss in relation to the undesirable event was obtained for all scenarios. The exact values of the functionality loss are shown in Table 5.

The best results were get for Scenario 1a and Scenario 3a, what was marked by text bolding. In fact, these scenarios are balanced in terms of process cancelling, delays, process changes and additional processes needed.

The table contains also the results of an evaluation performed by the same twelve Experts listed in Section 3.2. It shows the mean value of grades given by the Experts (1 for the best, 6 for the worst). They had to rang the scenarios basing on a short spoken introduction about the situation as well as each scenario. Moreover, they base also on the data from Table 4.

As Table 5 shows, the 3 best scenarios (Scenario1a, Scenario 3, Scenario 3a) according to the presented method are similar to the 3 best ones from the Experts average.

To improve the visibility and to show a more macroscopic trend of the scenario functionality functions, the moving average with an interval of 30 min was calculated. The results are shown in Figure 18.

Scenario 1 and Scenario 2 are defined by the lowest intervention level in the processes. Thus, the recovery is long and the functionality resumption is slow. The remaining scenarios base one an extended process reconfiguration. Therefore, the functionality resumption is faster.

In case of Scenario 2a and Scenario 3, trains are rerouted after 11:45. Thus, processes are cancelled, intermediate stops are lost, and there is a functionality breakdown. It is quickly recovered in terms of Scenario 3, because only one train is rerouted (3 processes cancelled). In Scenario 2a one more train is rerouted, what results in a longer functionality breakdown.

Table 5. Recovery scenario characteristics

Scenario	Cumulated functionality loss	Evaluation performed by Experts
1	0.1653	4.00
1a	0.0923	2.91
2	0.1933	4.46
2a	0.1371	4.64
3	0.1122	2.63
3a	0.0976	2.45

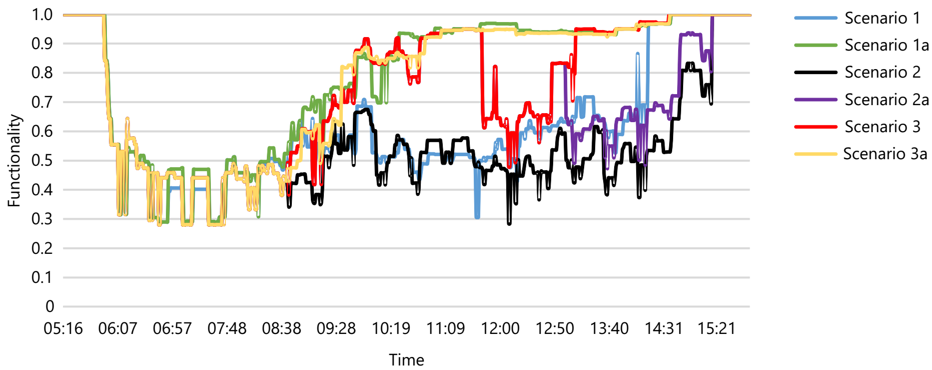

Figure 17. Functionality function values for the analysed scenarios

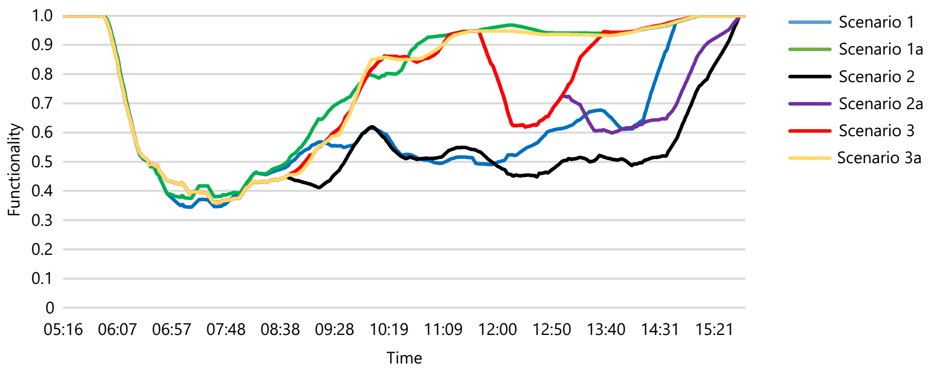

Figure 18. Moving average of the functionality function values for the analysed scenarios

5. Conclusions

The presented research is a step forward to include the resilience approach in decision-making under system disruptions. Moreover, the concept of operational resilience and robustness used for evaluation processes and decision-making fill an important gap in resilience research. These concepts are very promising in terms of operation processes evaluation, which are disrupted by small and medium undesirable events, and not necessarily by catastrophic events.

The built fuzzy evaluation model combines key qualities of the railway operation. Thus, the assessment performed is more complete than taking into account only one dimension. Dealing with inherent variables was effectively possible using fuzzy modelling with expert support. The proposed sub-models bring together complementary but opposite qualities. The capacity model brings together punctuality and traffic intensity (process implementation) according to the schedule. After a disruption, it would be easiest to cancel trains and maintain the punctuality of the remaining trains. Therefore, a scenario without trains will result in the lowest delay rate. On the other hand, keeping the maximum train intensity would result in delay propagation throughout the operation day. It follows that a compilation of these 2 features gives a balance between these opposites.

The process implementation sub-model solves the problem of cancelling trains accompanied by substitute processes, for example, buses instead of trains after a track closure. Such compensation will have a positive influence on the consequences of the disruption. They will be not lost in terms of the functionality function but still taken into account in other performance factors, like punctuality.

Finally, the sub-model for correctness of resource assignment. It is close to a risk function that describes the possibility of other undesirable events due to lack of resources. For example, if the basic schedule is kept, then the train crews and the vehicles will be on duty till the end of the day. But if something will change, then it could be that in a given amount of time the train crew working time will expire and they will be not available to continue the train ride.

The mentioned 7 measures for functionality evaluation cover in a wide range the most important factors were identified in Section 3. The robustness gradient and the actual punctuality describe the time correctness of current and future implemented processes. The implemented processes and the compensating processes describe the work performed by the system. And the correctness of assigned resources gives an important information about the current and future operation safety.

The multidimensional character of the functionality function is well covered by the proposed Fuzzy model. It makes it possible to put together different measures, and to calculate in an effective way the synthetic functionality value. The 3 stage structure of the model makes it possible to deal with 7 input variables and to control their influence on the final result. This aspect is important due to finding and fixing of failures in the model. The model structure makes it also easier for the Experts to fit the parameters and to evaluate them. The presented complex method complements the present methods for resilience quantification and performance measures, which are turned to be unsatisfactory for the analysed problem.

Basing on the performed case in Section 3, it can be concluded that the method is a step forward in scenario evaluation for decision-making in railway dispatching.

The method has also a high practical potential due to simplification of some complex prediction issues. For example, possible further lack of crews or vehicles is represented as negative influence on the functionality function, without the need to make in short decision time complicated and not maybe incomplete.

The biggest drawback of the method is the need for predictive development of the movement situation. This requires separate simulation tools, the use of which needs additional time and resources. The lower the accuracy of these forecasts, the more likely it is to assess the loss of functionality without additional secondary events resulting from decisions. Therefore, it is important to develop tools that support effective forecasting and combine them with the presented evaluation method.

Nevertheless, basing on the gathered results it can be concluded that the method is a step forward in scenario evaluation for decision-making in railway dispatching.

For the future work it is planned to evaluate the method using a larger sample of real scenarios as well as with more experts from the railway industry. It is also planned use this method, and the resulting resilience quantification for optimization of the system reconfiguration.

Appendix. Supplementary Tables

Supplementary Table 1. Rules of the *Functionality* fuzzy model

Rule	FUNCTIONALITY		
	IF *Capacity*	AND *Correctness*	THEN Functionality
1	scheduled	good	scheduled
2	scheduled	intermediate	good+
3	scheduled	sufficient+	good
4	scheduled	sufficient-	good–
5	scheduled	low	intermediate+
6	scheduled	bad	intermediate
7	good+	good	good+
8	good+	intermediate	good
9	good+	sufficient+	good–
10	good+	sufficient-	intermediate+
11	good+	low	intermediate
12	good+	bad	intermediate–
13	good	good	good
14	good	intermediate	good–
15	good	sufficient+	intermediate+
16	good	sufficient-	intermediate
17	good	low	intermediate–
18	good	bad	sufficient+
19	intermediate+	good	intermediate+
20	intermediate+	intermediate	intermediate
21	intermediate+	sufficient+	intermediate–
22	intermediate+	sufficient-	sufficient+
23	intermediate+	low	sufficient
24	intermediate+	bad	sufficient–
25	intermediate-	good	intermediate-
26	intermediate-	intermediate	sufficient+
27	intermediate-	sufficient+	sufficient
28	intermediate-	sufficient-	sufficient–
29	intermediate-	low	low+
30	intermediate-	bad	low
31	sufficient	good	sufficient
32	sufficient	intermediate	sufficient–
33	sufficient	sufficient+	low+
34	sufficient	sufficient-	low
35	sufficient	low	low–
36	sufficient	bad	bad
37	low	good	sufficient-
38	low	intermediate	low+
39	low	sufficient+	low
40	low	sufficient-	low–
41	low	low	bad
42	low	bad	bad
43	bad	good	low+
44	bad	intermediate	low
45	bad	sufficient+	low-
46	bad	sufficient-	bad
47	bad	low	bad
48	bad	bad	bad
49	no	–	no

Supplementary Table 2. Rules of the *Correctness* fuzzy model

Rule	CORRECTNESS			
	IF *Vehicles*	AND *Crews*	AND *Clusters*	THEN Correctness
1	scheduled	scheduled	scheduled	scheduled
2	scheduled	scheduled	good	good+
3	scheduled	scheduled	intermediate	good–
4	scheduled	scheduled	sufficient	intermediate+
5	scheduled	scheduled	bad	intermediate
6	scheduled	good	scheduled	good+
7	scheduled	good	good	good–
8	scheduled	good	intermediate	intermediate+
9	scheduled	good	sufficient	intermediate
10	scheduled	good	bad	intermediate–
11	scheduled	intermediate	scheduled	good–
12	scheduled	intermediate	good	intermediate+
13	scheduled	intermediate	intermediate	intermediate
14	scheduled	intermediate	sufficient	intermediate–
15	scheduled	intermediate	bad	sufficient+
16	scheduled	sufficient	scheduled	intermediate+
17	scheduled	sufficient	good	intermediate
18	scheduled	sufficient	intermediate	intermediate–
19	scheduled	sufficient	sufficient	sufficient+
20	scheduled	sufficient	bad	sufficient–
21	scheduled	bad	scheduled	intermediate
22	scheduled	bad	good	intermediate–
23	scheduled	bad	intermediate	sufficient+
24	scheduled	bad	sufficient	sufficient-
25	scheduled	bad	bad	low+
26	good	scheduled	scheduled	good+
27	good	scheduled	good	good–
28	good	scheduled	intermediate	intermediate+
29	good	scheduled	sufficient	intermediate
30	good	scheduled	bad	intermediate–
31	good	good	scheduled	good-
32	good	good	good	intermediate+
33	good	good	intermediate	intermediate
34	good	good	sufficient	intermediate–
35	good	good	bad	sufficient+
36	good	intermediate	scheduled	intermediate+
37	good	intermediate	good	intermediate
38	good	intermediate	intermediate	intermediate–
39	good	intermediate	sufficient	sufficient+
40	good	intermediate	bad	sufficient–
41	good	sufficient	scheduled	intermediate
42	good	sufficient	good	intermediate–
43	good	sufficient	intermediate	sufficient+
44	good	sufficient	sufficient	sufficient–
45	good	sufficient	bad	low+
46	good	bad	scheduled	intermediate-
47	good	bad	good	sufficient+
48	good	bad	intermediate	sufficient–
49	good	bad	sufficient	low+
50	good	bad	bad	low–
51	intermediate	scheduled	scheduled	good–
52	intermediate	scheduled	good	intermediate+
53	intermediate	scheduled	intermediate	intermediate
54	intermediate	scheduled	sufficient	intermediate-
55	intermediate	scheduled	bad	sufficient+
56	intermediate	good	scheduled	intermediate+
57	intermediate	good	good	intermediate
58	intermediate	good	intermediate	intermediate-
59	intermediate	good	sufficient	sufficient+
60	intermediate	good	bad	sufficient–
61	intermediate	intermediate	scheduled	intermediate
62	intermediate	intermediate	good	intermediate–
63	intermediate	intermediate	intermediate	sufficient+

End of Supplementary Table 2

Rule	CORRECTNESS			
	IF *Vehicles*	AND *Crews*	AND *Clusters*	THEN Correctness
64	intermediate	intermediate	sufficient	sufficient–
65	intermediate	intermediate	bad	low+
66	intermediate	sufficient	scheduled	intermediate–
67	intermediate	sufficient	good	sufficient+
68	intermediate	sufficient	intermediate	sufficient–
69	intermediate	sufficient	sufficient	low+
70	intermediate	sufficient	bad	low–
71	intermediate	bad	scheduled	sufficient+
72	intermediate	bad	good	sufficient-
73	intermediate	bad	intermediate	low+
74	intermediate	bad	sufficient	low–
75	intermediate	bad	bad	low–
76	sufficient	scheduled	scheduled	intermediate+
77	sufficient	scheduled	good	intermediate
78	sufficient	scheduled	intermediate	intermediate–
79	sufficient	scheduled	sufficient	sufficient+
80	sufficient	scheduled	bad	sufficient–
81	sufficient	good	scheduled	intermediate
82	sufficient	good	good	intermediate–
83	sufficient	good	intermediate	sufficient+
84	sufficient	good	sufficient	sufficient–
85	sufficient	good	bad	low+
86	sufficient	intermediate	scheduled	intermediate–
87	sufficient	intermediate	good	sufficient+
88	sufficient	intermediate	intermediate	sufficient–
89	sufficient	intermediate	sufficient	low+
90	sufficient	intermediate	bad	low–
91	sufficient	sufficient	scheduled	sufficient+
92	sufficient	sufficient	good	sufficient–
93	sufficient	sufficient	intermediate	low+
94	sufficient	sufficient	sufficient	low–
95	sufficient	sufficient	bad	low–
96	sufficient	bad	scheduled	sufficient–
97	sufficient	bad	good	low+
98	sufficient	bad	intermediate	low–
99	sufficient	bad	sufficient	low–
100	sufficient	bad	bad	bad
101	bad	scheduled	scheduled	intermediate
102	bad	scheduled	good	intermediate–
103	bad	scheduled	intermediate	sufficient+
104	bad	scheduled	sufficient	sufficient–
105	bad	scheduled	bad	low+
106	bad	good	scheduled	intermediate–
107	bad	good	good	sufficient+
108	bad	good	intermediate	sufficient–
109	bad	good	sufficient	low+
110	bad	good	bad	low–
111	bad	intermediate	scheduled	sufficient+
112	bad	intermediate	good	sufficient–
113	bad	intermediate	intermediate	low+
114	bad	intermediate	sufficient	low–
115	bad	intermediate	bad	low–
116	bad	sufficient	scheduled	sufficient-
117	bad	sufficient	good	low+
118	bad	sufficient	intermediate	low–
119	bad	sufficient	sufficient	low–
120	bad	sufficient	bad	bad
121	bad	bad	scheduled	low+
122	bad	bad	good	low–
123	bad	bad	intermediate	low–
124	bad	bad	sufficient	bad
125	bad	bad	bad	bad

Supplementary Table 3. Rules of the *Capacity* fuzzy model

Rule	CAPACITY		
	IF *Process implementation*	AND *Punctuality*	THEN *Capacity*
1	scheduled	good	scheduled
2	scheduled	intermediate	good+
3	scheduled	sufficient	good
4	scheduled	low	good–
5	scheduled	bad	intermediate+
6	good+	good	good+
7	good+	intermediate	good
8	good+	sufficient	good–
9	good+	low	intermediate+
10	good+	bad	intermediate
11	good-	good	good
12	good-	intermediate	good–
13	good-	sufficient	intermediate+
14	good-	low	intermediate
15	good-	bad	intermediate–
16	intermediate+	good	intermediate+
17	intermediate+	intermediate	intermediate
18	intermediate+	sufficient	intermediate–
19	intermediate+	low	sufficient+
20	intermediate+	bad	sufficient
21	intermediate-	good	intermediate–
22	intermediate-	intermediate	sufficient+
23	intermediate-	sufficient	sufficient
24	intermediate-	low	sufficient–
25	intermediate-	bad	low+
26	sufficient	good	sufficient
27	sufficient	intermediate	sufficient–
28	sufficient	sufficient	low+
29	sufficient	low	low–
30	sufficient	bad	bad
31	low	good	sufficient–
32	low	intermediate	low+
33	low	sufficient	low–
34	low	low	bad
35	low	bad	bad
36	bad	good	sufficient–
37	bad	intermediate	low+
38	bad	sufficient	low–
39	bad	low	bad
40	bad	bad	bad
41	no	–	no

Supplementary Table 4. Rules of the *Process implementation* fuzzy model

Rule	PROCESS IMPLEMENTATION		
	IF *Implemented processes*	AND *Compensating processes*	THEN *Process implementation*
1	scheduled	–	scheduled
2	good	almost all	good+
3	good	good	good+
4	good	intermediate	good
5	good	bad	good
6	good	almost none	good–
7	sufficient	almost all	good
8	sufficient	good	good–
9	sufficient	intermediate	intermediate+
10	sufficient	bad	intermediate
11	sufficient	almost none	intermediate-

End of Supplementary Table 4

Rule	PROCESS IMPLEMENTATION		
	IF *Implemented processes*	AND *Compensating processes*	THEN *Process implementation*
12	low	almost all	good–
13	low	good	intermediate+
14	low	intermediate	intermediate
15	low	bad	intermediate–
16	low	almost none	sufficient+
17	bad	almost all	intermediate+
18	bad	good	intermediate–
19	bad	intermediate	sufficient
20	bad	bad	low+
21	bad	almost none	bad
22	no	almost all	intermediate
23	no	good	sufficient+
24	no	intermediate	sufficient–
25	no	bad	low–
26	no	almost none	no

Supplementary Table 5. Rules of the *Punctuality* fuzzy model

Rule			
	IF *Robustness gradient*	AND *Actual punctuality*	THEN *Punctuality*
1	scheduled	scheduled	scheduled
2	scheduled	good	good+
3	scheduled	intermediate	good–
4	scheduled	sufficient	intermediate+
5	scheduled	low	intermediate–
6	scheduled	bad	sufficient+
7	good	scheduled	good+
8	good	good	good–
9	good	intermediate	intermediate+
10	good	sufficient	intermediate
11	good	low	sufficient+
12	good	bad	sufficient
13	intermediate	scheduled	good–
14	intermediate	good	intermediate+
15	intermediate	intermediate	intermediate
16	intermediate	sufficient	intermediate–
17	intermediate	low	sufficient
18	intermediate	bad	sufficient–
19	sufficient	scheduled	intermediate+
20	sufficient	good	intermediate
21	sufficient	intermediate	intermediate-
22	sufficient	sufficient	sufficient+
23	sufficient	low	sufficient–
24	sufficient	bad	low+
25	low	scheduled	intermediate–
26	low	good	sufficient+
27	low	intermediate	sufficient
28	low	sufficient	sufficient–
29	low	low	low+
30	low	bad	low–
31	bad	scheduled	sufficient+
32	bad	good	sufficient
33	bad	intermediate	sufficient–
34	bad	sufficient	low+
35	bad	low	low
36	bad	bad	bad

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