sustainability

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Sustainable Disaster Response Management Related to Large Technical Systems

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Abstract: Numerous investigations assess the technical, technological, and managerial aspects of disaster response related to large technical systems. This paper deals with the possibility of synthesizing these aspects in a disaster response methodology, thus combining the technical, technological methods, tools, and software with the art of management. Its objective is to develop a preliminary methodology that supports the response management decision making processes related to earthquake-damaged large technical systems. The introduced methodology is demonstrated with the example of railway systems. It utilizes a combination of (i) a probabilistic model of railway system damage caused by earthquakes, (ii) a Markov model related to the damage and recovery phases, (iii) a probabilistic model of aftershocks, (iv) a statistical model of secondary effects, (v) impact models of management support actions, and (vi) response process management supported by a Markov Decision Process. The simulation results validate the concept. Based on these research results, the authors recommend that the described preliminary response management approach be further specified and implemented in disaster management procedures.

Keywords: earthquake; disaster/emergency management; railway systems; railway damage; response and recovery modelling; Markov decision process; machine learning

1. Introduction

Earthquakes are unexpected violent shakes of the ground, initiated by a sudden release of seismic energy in the Earth's lithosphere. They generate a series of seismic waves that are generally followed by a sequence of aftershocks and secondary hazards (such as fire, volcanic actions, tsunamis, landslide, liquefaction), change in ground level, and/or flooding and dam failure. When earthquakes occur at well-defined locations, at plate boundaries, the long-term prediction (about time, intensity, and location of future events) is estimable by statistical and probabilistic models, while the short-term prediction today is somewhat problematic [1]. In general, aftershocks occur after the main earthquake with a relatively large probability [2] which can be predicted by several models [3,4]. However, these models cannot provide a general approximation due to the significant uncertainties related to the parameters, and the fact that the location of aftershock occurrences cannot be predicted robustly by the recent models. Finally, secondary hazards play a significant role, causing around 30% of fatalities in earthquake disasters. These secondary effects can be observed easily and their evolution at areas with a large population can be simulated and predicted with relatively good accuracy [5–7].

The large-scale technical systems (like transportation, energy networks) play a deterministic role in the economy, society, and strategic defence of states, and thus these systems can be called as large natural-technogenic system [8]. It is a man-made (-genic) technical/technological (techno) system based in natural (ground-soil, water-rivers) environment. Taking a wide approach, such systems are ecological-socio-technogenic systems.

Seismic wave propagation and earthquake fault rupture propagation are studied well in detail [9–11]. Semi-empirical methods use records from real earthquakes or artificial accelerograms combined with 3D physics-based numerical simulation. These methods use hybrid methods combining 3D low-frequency waveforms with high-frequency stochastic synthetics which can be used to provide predictions of ground motion even for regions where seismic records are not available [12,13]. These predictions were used in hazard detection, preparedness and the first level evaluation of possible losses. Such information is further used in seismic models and software tools including even open-source codes like SPEED [14], and databases of motion recordings [15,16]. The seismic models and simulations give the required information on ground motions being used as input for damage estimation. However, numerous uncertainties are still present, mainly depending on the structure of soil and its actual features.

Some of the negative impacts of earthquakes are structural damage to large technical systems and buildings. Earthquake damage and losses can be estimated by different approaches, such as semi-empirical formulas, high-level, complex statistical, dynamic or stochastic methods, finite element methods calibrated by experimental data, and other modelling techniques [17–20]. The critical infrastructure can be destroyed in various distance from the epicentre [21,22]. Moreover, earthquakes generally represent a danger to the economy, society, culture and nature [23].

The damaged large technical systems that support the economy and the population must keep their operational condition in complex load situations [24–26] and must be returned to their operational status as quickly as possible [27,28] Here, operational status means that the system might be used for its primary role, but probably with some limitations, or with reduced performance.

Disaster management, as part of emergency management [29,30], is a set of instruments, technologies, methods, and procedures which applies to preparedness, disaster monitoring, warning, response, and recovery [31]. This is a process of reducing the loss of lives and property and protecting assets from all types of hazards through a comprehensive, risk-based, emergency management program of mitigation, preparedness, response, and recovery. Emergency management was considerably improved after the September eleventh terror attacks [32]. One of the best practices of emergency management is demonstrated by the American FEMA [33], regarding their earthquake response and more particularly those linked to rail damages related to Japan experience [34,35].

Advanced disaster management relies on system engineering [36], well-structured command and control system, C4ISR methods (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance, published first by US Department of Defence [37]). In Europe, emergency management is coordinated by a dedicated center, Emergency Response Coordination Centre (ERCC), which supports a coordinated and quicker response to disasters [38].

This paper deals with disaster response management, thus the use of the capabilities necessary to save lives, to protect properties or the environment, and to meet the basic human needs after the occurrence of a disaster [39]. Such response management is accomplished using the available resources including all the human, material, technological, and supporting resources as software or tools. New technological supports are rapidly developing in the field of theoretical investigations [40], monitoring and measuring methods [41–43], sensing, loads [44–47] and supporting the situation awareness, evaluation, decision processes. Control actions must be defined by a continuously repeated situation awareness-evaluation-decision-making process. This type of control is “active” because the management is the central part of the overall system. Decisions are made actively relying on situational awareness, and adapted to dynamic situations [48]. The terms and methods of “active” and “adaptive” controls are used extensively, for example in building structural dynamics [49]. At the same time, the disaster response highly depends on the knowledge, tacit knowledge, experience and practice of leaders of response management.

Nowadays, response management, especially the situation awareness, is supported by several new and emerging technologies [46,50,51]. The control of the disaster response is a complex process of (partly) subjective decisions [52–54] based on the combination of the available technical methods, software, tools and management techniques.

The overall objective of this paper is to develop a preliminary methodology (set of management rules) to support the response management decision making processes related to the earthquake damaged large technical systems. It is demonstrated with the example of railway systems. Instead of one single system element, it is rather focusing on the entire system, and defines how in general (i) a disaster response plan should be composed, (ii) the status of the system elements could be assessed, (iii) the warning made, (iv) the simulation supporting system help the decision making (e.g., by simulating the potential consequences of earthquakes, the propagation of seismic waves, the appearance of aftershocks), (v) the response initiated, (vi) the real on site collected data on the damage assessed, or (vii) the recovery priorities made (according to the exact damage, and its recovery complexity).

The developed method is applied to earthquake damage related to railways [28], because railway has a strategic role in society mobility, economy and defence, and it has relatively less damage caused by earthquakes than road transport and it can be restored to its acceptable operational level 5–10 times quicker than the road transport. The offered preliminary response management applied to railway is based on the combination of (i) a probabilistic model of railway system damage caused by earthquakes, (ii) a Markov model of damage and recovery, (iii) a probabilistic model of aftershocks, (iv) a statistical model of secondary effects, (v) an impact model of supporting management actions, and (vi) a response process management supported by Markov decision process. Simulation results validate the concept. It is recommended that the described response management approach should be implemented in the general disaster management procedures. The concept is validated by the simulation results. Based on the results of this research, the current authors are recommending that the described response management approach should be implemented into the general disaster management procedures.

This paper develops and introduces a new methodology to support the disaster response management. It deals with preliminary investigations. Before its final application, several general (requirements in establishing an operation center, network of fixed and mobile observation and response units, equipment of critical elements with large number of sensors connected through the Internet, organization of special depots supporting the disaster response) and system specific aspects, problems, limitations (such as tools, software for evaluation of the measurement, prediction of the possible secondary effects, simulation of the restorations processes) must be studied and solved.

2. Methodology

2.1. Governing Ideas

The developed disaster response management systems were preliminarily assessed with the example of a railway system. Railway is a typical large well distributed ecological-socio-technogenic system, with numerous critical infrastructure elements (such as railway stations, bridges, tunnels, lines, embankment, info–communication system, control system). Railway lines (in case of an earthquake) are usually damaged less than roads, but other critical elements may have the same damages as other critical infrastructure elements.

After the detailed study on the available theoretical (articles) and practical (reports, records, data banks) information and consultation with specialists with acknowledged experience in controlling, managing the post-earthquake response and recovery of railway systems, three major governing ideas were defined that could effectively support the disaster response management (as shortly introduced below and shown in the Figure 1).

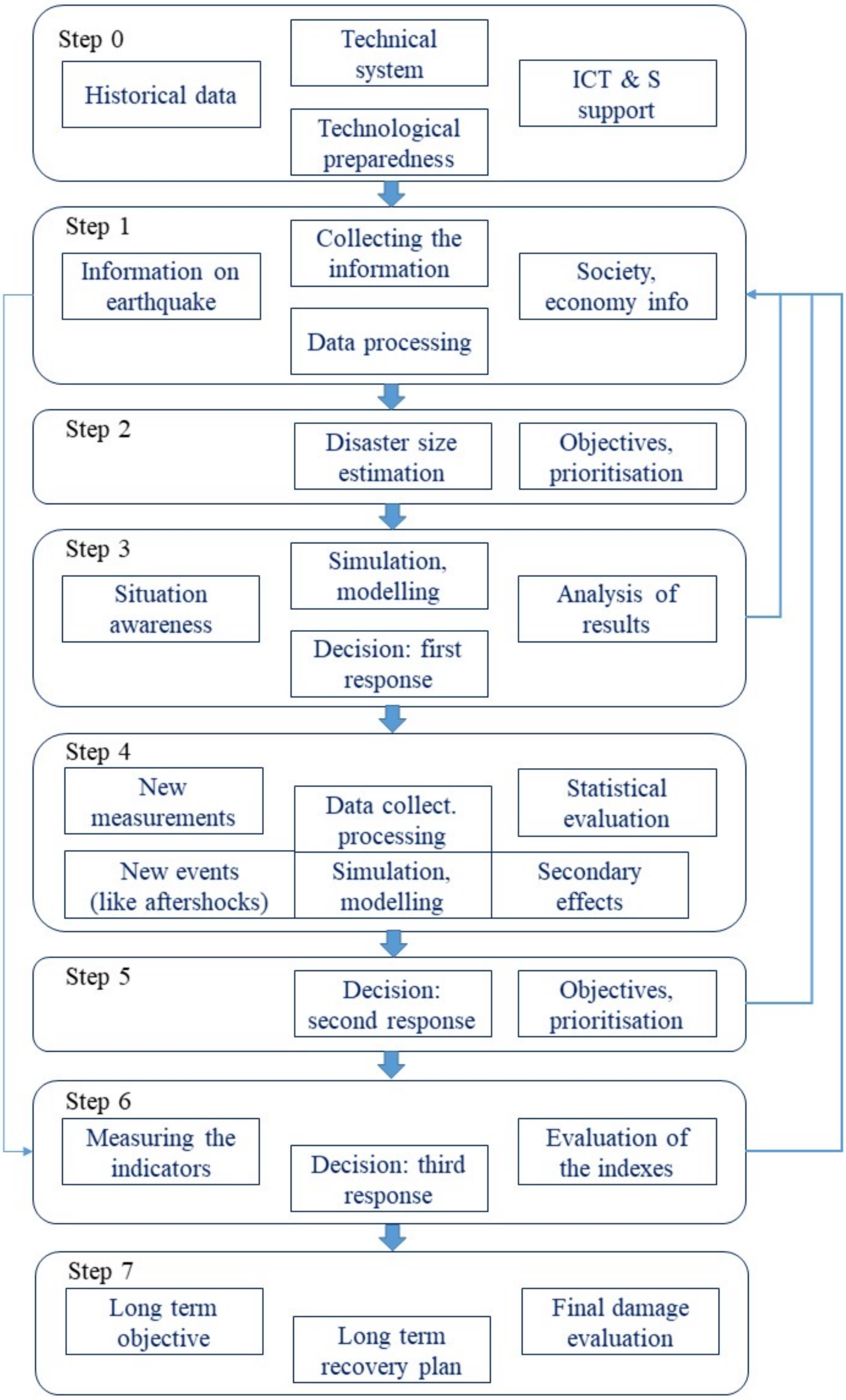

Figure 1. The developed preliminary response management system related to large technical systems damaged by serious disaster events, such as earthquakes [28] (Source: Authors).

2.1.1. Requirements of the Generally Applicable Indicators or Indexes

Large technical systems (as water, energy supply, info-communication or transportation systems) might be only partly destroyed, even in serious disasters (caused by earthquakes) [55]. According to real historical data [56,57], the electric and info-communication systems were restored in a couple of days and their performance (capacity, accessibility) reached 100%. Railway systems returned to their 70% of capacity within a month and to 100% after 7 months Highway system reached 70% of capacity after 13 months, and 100% after 21 months. Following these facts, a special general indicator as per cent of usability or un-usability is recommended to be defined, to capture the capability of service provision or the possible use of the system.

$$\overline{x}_u(t) = \frac{x_u(t)}{x_T(t)}, \tag{1}$$

where x_u, x_T, $\overline{x}_u$ are the unusable part, the total usable and relative usable part of the system, respectively.

This is a general indicator that can be defined by the network length, the capacity of the system and many different analogic forms like the ratio of people being unable to use the system.

Another important set of indicators must be defined to measure the importance and the damages of the critical infrastructure. This set provides the required information to prioritize the planned actions during the response management. Several indicators can be developed, measured and applied as usability ratio (1), time, $\tau_{\overline{x}_{u,d}}$, work (as man-hours), $w_{\overline{x}_{u,d}}$, cost, $c_{\overline{x}_{u,d}}$ required to return the system to the predefined operational level $\overline{x}_{u,d}$, (generally to $\overline{x}_u = 0.9$) or similar, to increase the usability by $\Delta\overline{x}_u$, usually applied as one per cent ($\tau_{\Delta\overline{x}_u}$, $w_{\Delta\overline{x}_u}$, $c_{\Delta\overline{x}_u}$) as well as time, $\tau(t)$, work, $w(t)$, cost $c(t)$, applied to the system to start the response (at the time when the earthquake occurred, $t = 0$) until time, t. The last indicator can be, for example, calculated as

$$w(\tau) = \int_{t=0}^{t=\tau} w_{\Delta\overline{x}_u}(t), \text{or } w(\tau) = \overline{w}_{\Delta\overline{x}_u}(\overline{x}_u(t=\tau) - \overline{x}_u(t=0)) \tag{2}$$

2.1.2. Improving the Supporting System

The leaders of response management as operators must make their decisions according to the available data. This process is a well investigated process of situation awareness-evaluation-decision making-action. The process can be studied by the well-known models of decision making [58,59] and using the methods of subjective analysis [53,60], as operators make decisions depending on their knowledge, personal nature and practice. Therefore, the response management is a controlled stochastic process.

Nowadays, the computerized info–communication and the available software tools allow the development and implementation of special decision support systems. They may utilize a wide range of methods from simple to semi empirical up to multi-criteria and intelligent systems [61,62].

Generally, it seems that the use of the so-called objective criteria (as defined above, see (2)) to create the priority list of critical infrastructures that require serious restoration, selection and realization of actions, is a deterministic process. Unfortunately, it is a highly complex process. Even the system of prioritization criteria is estimated from partial information being robust. The damages of the critical object might be significantly more or less serious than is expected from the first data. For example, roads could be closed, and trucks might be unable to reach the given critical object. The time, used materials, parts, and cost are scattered around the expected values. The results of actions are stochastic. During the restoration of the selected critical elements, aftershocks and secondary effects can appear that will considerably change the priorities, and the restoration process. Therefore, the total process is always stochastic.

Three major problems were identified related to the operators' decision making in case of disaster response management

- information reliability−the provided information as inputs for response management is very robust, deficient and even antinomy,
- short information presentation−this usually, even in developed operation centers, is well behind the possible solutions presenting information in preliminary evaluated forms together with short time predictions and the prioritized list of required actions,
- a lack in competences of operators and staff−due to fortune, the disasters occur vary rarely.

These problems call for special supporting methods synthetizing the available scientific, technical, technological and managerial methods and tools into a unique system that may provide a systematically ordered, clear and preliminary evaluated presentation of the available information and the possible solutions, as well as recommended actions.

2.1.3. Make the System Effective

Nowadays, effectivity is often translated as sustainability. At least in the case of such systems–as preparedness for disaster response that should be prepared and planned for 20–50 years ahead−sustainability might be used as an important governing factor.

The short definition of sustainability is the ability to be maintained at a certain rate or level. The most commonly used definition of sustainability is [63] " ... meeting the needs of the present without compromising the ability of future generations to meet their own needs ... ". Taking this approach makes a balance in the economy, environment, and society [64].

Numerous articles deal with the evaluation of sustainability in a general form or according to the given investigated systems, like smart cities [65–70]. Some of them ponder on anomalies caused by the use of sustainability approaches and the possible misunderstandings of its meaning. Of course, several questionable aspects can be identified, like a contradiction between the long-term sustainable development and short-term welfare, diminishing the importance of the environmental dimension or/and possible separation of social from economic aspects [71].

First, the so-called classic approach to sustainability was based on the harmonization of the social and economic aspects intending to save the environment. The recommended definition of sustainability shows a balance between the social, cultural, economical, technological systems, material resources, environment (nature) and the interest of next generation. The optimal balance can be found by the optimization of special objective functions with strong constraints. The objective function can be based on the total life-cycle cost determined (predicted) for time (τ) 20 or 50 years ahead.

There are numerous high level sophisticated solutions to calculate the life-cycle costs (TLCC) [72–74], the total environmental impact, the total emissions [75–77], to determine the externalities [78,79], the interaction of economy, externalities and the use of resources [80,81].

All the available knowledge can be synthetized in a new recommended total (overall) sustainable index (*TSI*):

$$TSI = \frac{TLCC}{\tau} = \frac{1}{\tau}\sum_{i=1}^{n} TLCC_i \tag{3}$$

where $i = 1, 2, \ldots n$ define the social (also including cultural values), economical (containing the available technologies as well), built environmental, natural (with the available resources) and future generation interest.

The total life-cycle cost must consider all cost elements. See for example its application to transportation systems [82,83] (Second transport paper).

2.2. Developed Methodology Supported by Predictive Simulation

The required disaster management and especially the required preparedness level is what is (i) expected by the economy and people (stakeholders), (ii) estimated by professional experts and (iii) defined by the policy and rule makers. The preparedness level should make a balance between the demands of the economy, society, the available financial support, the acceptable risk and the willingness to pay for hazard reduction (as integrated in the total sustainable index (3)).

The laws, directives, rules, and requirements regulating the disaster management were investigated. The top-level emergency management is defined by policy makers [84] and by the legislation. Numerous international and national laws are defined to support the emergency management.

The comparison of the international regulations [85,86] shows that the national regulations usually follow the concept described by the CMDA (The Caribbean Disaster Emergency Management

Agency) [87]. The further analysis of the emergency management regulations of US, Japan, European, Hungarian and Kazakhstan regulatory systems helped to conclude the followings:

- there are no principal differences in the compared regulatory systems, neither in the structure, nor the contents,
- there is a lack of regulation related to the use of railway systems in disaster management,
- the best practice in the general regulation of disaster management are developed, used, and published by FEMA (Federal Emergency Management), while, according to the railway disaster management to earthquakes, it could be learned from the Japanese regulation.

After a more in-depth investigation of requirements, regulation policy, available solutions, rules, software, the practice of disaster response to large technical systems to earthquake damages, the authors developed a unique methodology by combining the technical, technological solutions, and tools with management techniques. This is a continuously repeatable (iterative), adaptive, hierarchically built-up methodology.

As seen in Figure 1, the developed methodology contains zero + six + one steps. Each step has collected and/or measured data (left-side), copious governing or supporting information (right-side), and the simulations or calculations (middle) supporting the decisions to be made by the response manager. The steps focus on the following actions:

2.2.1. Step 0-Prepardeness

In case of large technical systems (especially in geographically distributed systems like energy support or railway systems) and earthquake disaster, beyond the normal preparation (collection of papers, reports, including theoretical investigations and using practical, historical data on previous events), two special actions are required. Firstly, the possible damage of technical systems caused by predictable earthquakes should be identified, the required tools, human resources to accelerate the reparation duties should be named, and which should be optimally distributed between the resource centers. This can be called as "technology preparation" which must be optimized from a sustainability point of view. (See objective function (1) and its explanation.) Secondly, response management must be supported by centralized info-communication and simulation centers. Such centers must apply and adapt to the given geographical regions based on the latest results of sciences and technologies, including the methods, rules, tools software, to predict the possible size and consequences of such disasters as earthquakes.

According to the legal control on disaster management, the following major requirements must be met:

- design the system for the maximum earthquake magnitude that might be accoutered by 1% probability during the next 50 years,
- the system should be returned to its 70% of operability (usability) within one week and 86% in two weeks,
- the technical, the organizational performance, and the distribution of provisions (depots with materials, instruments, machines required for restoration) must be planned and optimized for the minimum (life cycle) cost, and must be sustainable,
- the materials, instruments, machines must be stored in depots not more than 20 years, with their continuous replacement.

For example, transport systems' applicability is analyzed and evaluated by different modelling and simulation methods [88]. According to the railroad damage, a semi-empirical approach based on utilized Geographic Information System (GIS) maps [89,90] can be used for the expert definition of the disaster (for example, earthquake) damages. Figure 2 represents an example of utilizing GIS to support the possible evaluation of the disastrous consequences. The map is developed for Almaty (Kazakhstan) regions [28].

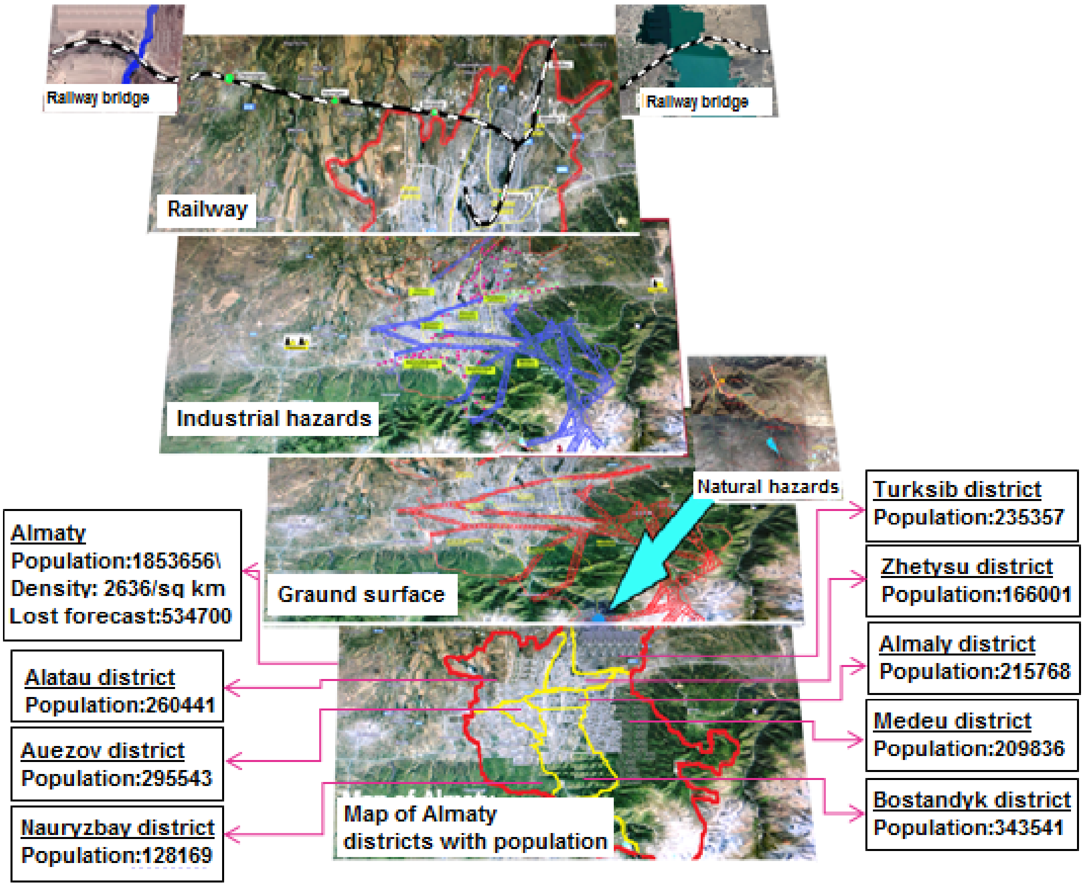

Figure 2. Using Geographic Information System (GIS) to support the estimation of the possible secondary effects, damage and determination of the unusable track length (Source: Author Sergey Kinzhikeyev).

2.2.2. Step 1–3-First Level Response (Iteration Cycle)

The first level response is "Step 1-Calculation and Simulation Support" which determines the consequences of the occurred earthquake, by calculating the amplitudes and the propagation of seismic waves and simulating the possible damage caused by earthquakes. The assessment is initiated by the information on the disaster event (like an earthquake being occurred). The data processing uses measured and collected data on the event, from all available information sources covering the event, for example important sports events, a mass demonstration in the city, holidays or reduced industrial production.

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"Step 2-Evaluation Identification of the Events" deals with the identification and preliminary description of the event, including the localization and assessment of the size of the damage zones. This step estimates the consequences and defines the first hierarchical orders of the required response depending on the predefined prioritization rules.

"Step 3-Situation Awareness, Simulation Evaluation and Decision Support" is a complex process. It estimates the situations based on the provided input by Step 2, which studies and evaluates the possible solutions by simulations and provides information for decision-making. The simulation aims to investigate and assess the available solution methods (by utilizing the sources) and the results being possible to reach with the given methods.

In this stage, the approach is generally changing from a clear technological approach (Step 1) through using the prioritization (partly defined in subjective ways by interests of the economy and the society) until combining the technical, technological solutions with the start of art, which results in subjective decision-making (Step 3).

The developed situation awareness–simulation, evaluation, and decision support process might be defined as the goal and object-oriented semi-optimization process by introducing a special indicator(s) group. According to the large technical systems, such indicators might be chosen as per cent of operation level (working or usability-see Figure 3) or non-operability (non-usability) of the systems, per cent of people and/or goods, being able to save or evacuated. The first one (Figure 3) defines the recovery process from the user point of view as change in system performance depending on time [57,91,92]. In case of a highway, the usability can be presented by the performances related to (i) the total length of open highway, and (ii) the total distance based on accessibility [57]. This idea is shown in the Figure 3 as an improved version being applied when aftershocks, or other secondary effects are also present.

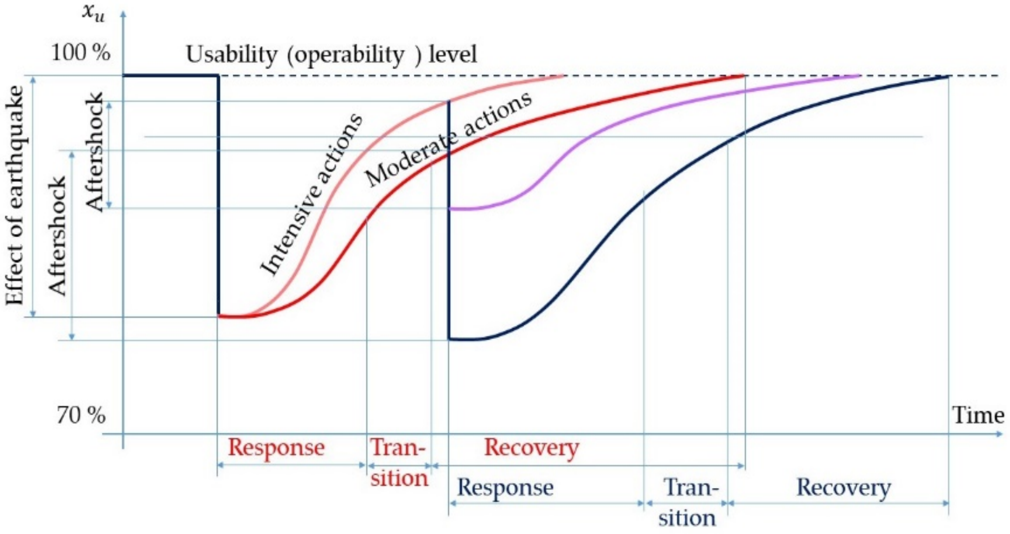


Figure 3. Changes in the usability of the technical systems during response and recovery applied to earthquake disaster. (Source: drawn by the Authors based on the idea of [91]).

From the recovery management point of view, a simple variable, the ration of unusable railroads, l_{ut} is recommended to be applied as a state variable or state index to evaluate the damage and manage the railway's recovery in response to earthquakes. It can also be called the relatively unusable railroad length. Unusable means that it cannot be used as the line or part of the track. For example, the length of unusable track sections due to a destroyed bridge can be calculated as the length of a given track from the deviation point to the return to the initial track. Of course, its value may vary from zero to 100%, while the total railroad length is calculated as the total length of track potentially applicable in disaster response.

The relative unusable length of a railroad, l_{ut} , can be determined as

$$l_{ut}(t) = \frac{1}{L}\sum_{j=1}^{m} L_{ut_j}\left(w_j, M, r_j, \alpha_j, V_{s_j}, d_j\right), \tag{4}$$

where: L is the total usable length of the railway network (sum of the length of all the network elements that can be operated), $j = 1, 2, \ldots, m$ are numbers of critical objects in railway systems (such as railway station, bridges, tunnels) and segments of track between the critical elements, L_{ut_j} is the unusable track length caused by the damage of the "j" object, w_j—weighting coefficient depending on the structural solutions, lifetime, time since last restoration or maintenance/repair, determining the damage of the given j-th object), M-the magnitude of the earthquake, r_j —a distance of the given object from the center of the earthquake, α_j—the angle between rupture propagation and mean axis of the object, V_{S_j}—shear wave velocity that is a soil measurable mechanical property, and d_j—is a statistical damage coefficient.

As noticed, this is a relatively simple indicator, which can be determined from the available information about the damages of the network elements.

Figures 3 and 4 demonstrate that the applied indicator changes are controlled stochastic processes controlled by response management. It is stochastic because of the fact that (i) aftershocks, and partly, secondary effects might appear randomly, and (ii) even results of the applied response management methods are partly stochastic.

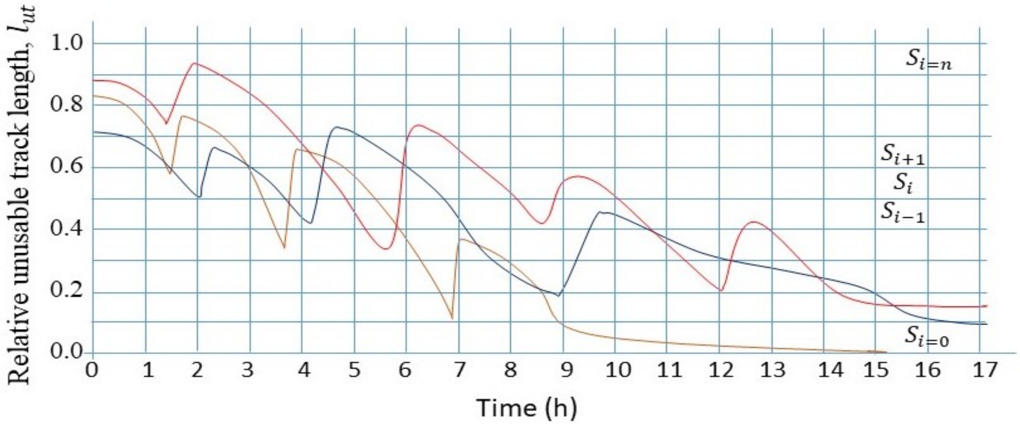


Figure 4. Division of possible space of relative unusable track length (Source: Authors).

By taking into account the completeness of the space of changes in relative unusable track length, l_{ut} can be represented as

$$l_{ut}(t) = \sum_{i=1}^{n} P_i(t) l_{ut_i} , \tag{5}$$

where P_i is the probability that the relative unusable track length parameter, l_{ut} at time t is in the i-th sub-space, and $l_{ut_i} = \frac{\left(l_{ut_i} - l_{ut_{i-1}}\right)}{2}$ for i = 1, 2, … n.

This way, changes in the index can be reduced to model changes in a probability vector (**P**). Assuming that (i) the state of the railway is in the relative unusable track length parameter in i-th subspace depicted as the i-th state, (S_i) can be approximated by an exponential distribution process, (ii) the time of changing from one state to any other $\left(S_i \rightarrow S_j\right)$ is nearly zero and, (iii) the process must always be in one of the states, the changes in probability might be defined by the following transition probability density:

$$\lim_{\Delta t \rightarrow 0} \frac{P\left\{S_{t+1} = j \middle| S_t = i, a_t = i\right\}}{\Delta t} = \beta_{i,j}\ i, j \in \overline{1, n} . \tag{6}$$

By using the probability transition matrix, $\boldsymbol{\beta}$, the probability vector **P** can be calculated from the following matrix equation:

$$\dot{\mathbf{P}}(t) = \mathbf{P}(t)\boldsymbol{\beta}(t) . \tag{7}$$

This equation approximates the stochastic process of continuous space and time, by a well-known stochastic process, the Markov process of discretized space and continuous time [93]. As a result, Equation (4) might be rewritten into the discretized form:

$$\mathbf{P}(k+1) = \mathbf{P}(k) + \boldsymbol{\beta}(k)\mathbf{P}(k)\,. \tag{8}$$

The analysis of Equations (5)–(8) leads to the following conclusion: all-important effects governing the damage-recovery process can be characterized by the definition of the transition matrix **β.**

The time interval k can be chosen as $\Delta t = 0.05$ or $\Delta t = 0.1$ h. This interval is small enough to model the damage–recovery process and large enough to approximate the earthquakes as simple impulse events and its effect on the relative unusable track length, l_{ut}, might be modelled as a step function.

The introduced model (7), (8) is a simplified, first-order model. Here, first order means that the future step only depends on the present step. In addition, the transition matrix elements are constant or−as provided−estimated for each present state depending on the applied actions. At least the following four comments must be underlined: (i) the model is stationary in which the transition matrix β is rather robust, (ii) the elements of the transition matrix might be approximated by using the time, $\tau_{i,j}$ (approximated from its exponential or normal distribution) of being in a different sub-space during the transition $S_i \rightarrow S_j$ in the space of the indicator l_{ut} , ($\beta_{\mathrm{I,j}} = 1/\overline{\tau}_{\mathrm{I,j}}$), (iii) the model can be applied to the full recovery process or sub-processes like a response to the railway station in city regions, (iv) the full system−as usual−is difficult to be modelled by such simple techniques. Further improvements may focus on these aspects. At least, the iterative estimation of the transition matrix elements or higher level of simulation and decision making should be utilized. However, because of a very robust, deficient and even antinomy in the available information, in the size of the critical infrastructure damages, further improvements based on more complex models may not result in a considerably better, more accurate simulation.

It is important to note that the elements of the transition matrix depend on the selected actions. For example, starting the restoration of the critical infrastructure with significant damages, or with the largest influence on the usability, will result in greater values of transition matrix elements in the upper, middle or lower regions of the space of unusable track lengths (see Figure 4).

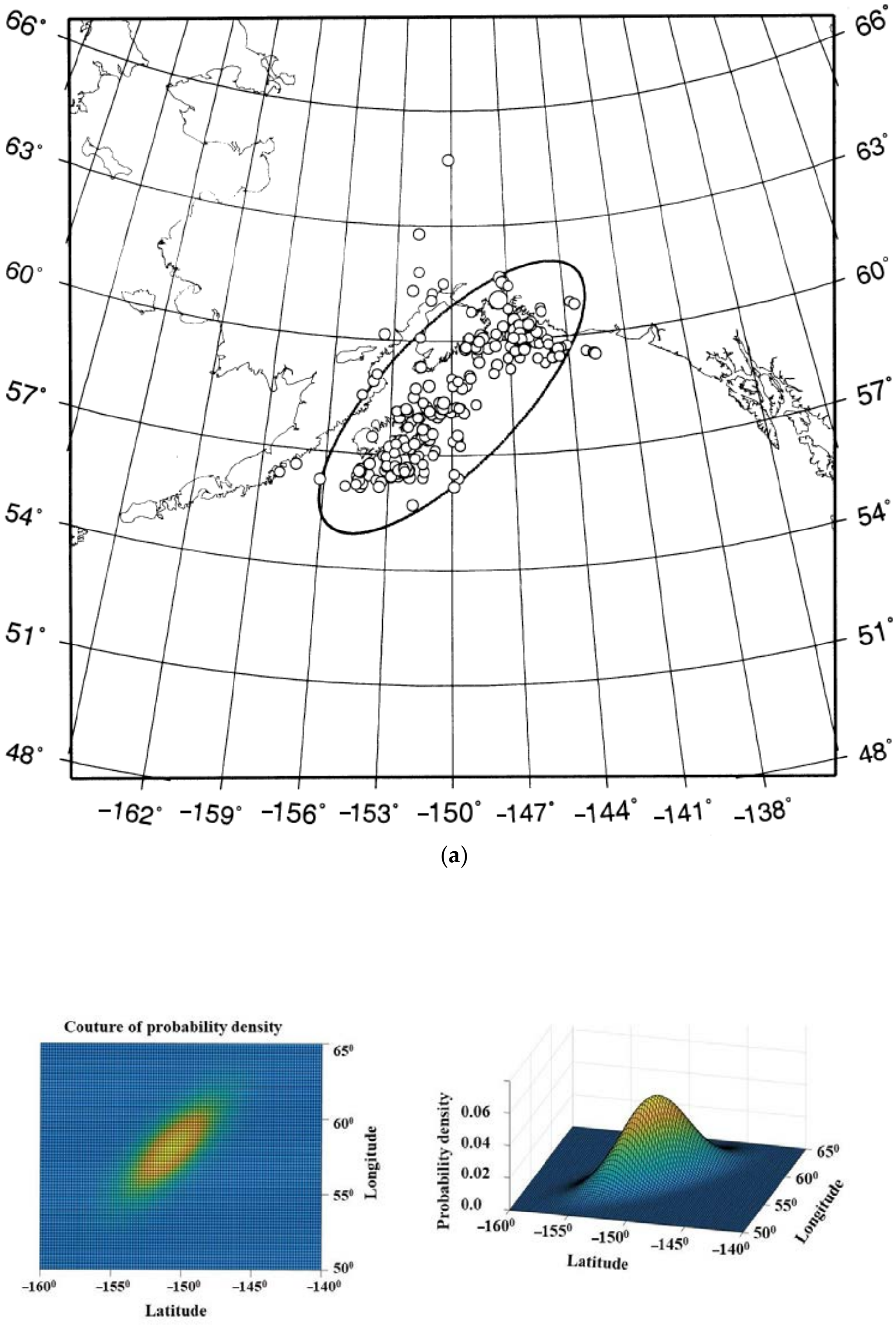
2.2.4. Step 4–5-Second Level Response

"Step 4-Further and Broader Evaluation" is applied after getting considerably new information or expectation. The new information can be obtained from three different sources: (i) established normal monitoring systems (like signals on aftershocks), (ii) extra measurements (including the special measurements made by staff, remote measurements by mobile centers, drones, satellites), and (iii) changes in prioritization (due to the warning signals indicating the damage of dams and possible flood, or tsunami). This step covers (i) the collection and summary of new data, (ii) the comparison of previous simulation results with the available new and statistical data, (iii) the identification of new (like aftershocks) and secondary (such as floods, tsunamis) events, and (iv) the realization of extensive simulations.

"Step 5-Higher Level Decision", namely reconsidering and redefining the prioritization concepts and making a higher-level decision.

The first and second level decisions on response are supported by simulations including physics-based modelling, predictions of the possible new events by statistical empirical approaches (for predefining the possible secondary effects), stochastic approximations, modelling (like aftershock forecast) and numerical simulations to characterize the moving events as the motion of flow during flood, or waves propagation in cases of tsunamis [94–96].

For example, a special method was developed to predict the aftershocks' appearance based on a Monte Carlo simulation [97] and using four random values in simulation cycles, two of which define the possible appearance of the aftershocks by the given magnitude (based on an empirical probability density function) estimated from historical data of earthquakes occurred in given regions [95], [98,99]). Another two describe the epicenter of the occurred aftershock (Figure 5), by a bivariate normal distribution model.



(**a**)

(**b**)

Figure 5. Typical ellipse of aftershock distribution (**a**) aftershocks following the $M_W = 9.2$, Alaskan (1964) earthquake (epicenters of 243 earthquakes larger than magnitude 5.0 within 1103 km of the mainshock and 10 months after the mainshock [100]), (**b**) bivariate normal distribution approximating the aftershocks of the Alaskan earthquake: top: ellipse of the simulated distribution; bottom: three-dimensional images of the estimated bivariate normal (Source: Authors).

2.2.5. Step 6-The Third Level of Response (Decision)

"Step 6-Regular Evaluation of Reaching the Objectives" means the response management must regularly evaluate the state and results of the response process. It should provide information to develop and plan the recovery process that can be started when the systems' operation level is restored. The decision must be supported by the evaluation of the measurements and the estimation of the indicators or index being developed for this purpose.

2.2.6. Step 7-Long Term Recovery Planning

The recovery process is started after the response and aims to restore the system to its operation level with some special limitations in performances (like reduced speed, using interim pontoon bridges). The output from Step 6 initiates this step. There are three sub-tasks that require solutions: (i) the evaluation and characterization of the "final" damages of the critical elements (damages require long-term repairing or the construction of new elements), (ii) the definition of the objective of the long-term recovery process, and (iii) the preliminary design of the long-term recovery process including the technical and financial aspects.

3. Results-Concept Testing

3.1. Dilemma on Concept Evaluation

The accuracy and the applicability of the newly developed concepts and methods must always be evaluated, verified and validated. Verification means that the methodology works as expected, defined by the design specification, while validation shows that the methodology can be applied in the real environment [101]. With the accelerated developments in info-communication technologies, and simulation techniques, the possible evaluation, verification and validation of the simulation methods were developed about 25 years ago [102,103].

The described methodology is based on the following novelties:

- modelling the full process by a Markov chain being continuously adapted (every 3–6 min), with re-estimated elements of the transition matrix,
- using a special Monte Carlo simulation to predict the aftershocks' appearance,
- predicting the secondary effects based on the previously available historical data and
- using a wide range of further calculations (like computational fluid dynamics to study the motion of flood, finite elements methods to study the structural damages).

Numerous acknowledged mathematical descriptions can be applied to study the variation in parameters and their sensitivity analysis (see for example how the Markov process might be preliminarily evaluated with [104]).

Unfortunately, the verification and validation of the introduced disaster response methodology are very difficult tasks due to the lack of required initial data, and the possible realization of validation tests. Firstly, the methodology is planned to provide supporting simulation results every 3–6 min with a continuous adaptation of the model to the available real data. Secondly, there is no available description of disaster response made to railway systems damaged by earthquakes that describes the applied management rules, control with a frequency of 3–5 min. Finally, even if we may find such records of conversations, actions of response management, we might face two other problems: (i) it might be not clear why the given decisions were chosen and (ii) the records might not be publicly available due to their confidential nature.

The validation is an even more complex problem. Researchers are not focusing on small earthquake experiences, and thus there are no available ideas, methodologies of such validation efforts with small size experience, or simulation tests. It seems that the experiences with serious accidents might provide some inputs and supporting data. Unfortunately, simply down-scaling the records is not reasonable, as at a small scale, accidents injures and death are at the accident sites only, while large earthquakes cause damages and losses over a very large territory, damaging hundreds of sites of the railway system. This is a serious dilemma that requires a solution.

The authors of this paper selected a special technique to test the methodology in the concept validation with quasi virtual situations. It is quasi virtual because a real land endangered by earthquake is used as a basis, and the appearance of the earthquake, aftershocks, secondary events are generated by simulations. The introduced methodology was evaluated, with the results shown on a small workshop, and with the analysis of the experts' opinion being present.

In this quasi virtual concept validation all the available and shortly introduced technical and managerial sub-systems, sub-models, and parameters were applied. For example, in case of large technical system (like railway system), the system performance can be applied to evaluate the system and the results. Changes in technical parts of the response process are (more or less) deterministic, while the trigger effects are appearing in a stochastic way.

The leaders of response management use decisions developed by subjective and stochastic ways depending on their knowledge, practice and personal habits. Such process brings a large robustness in the response process.

As a result of these circumstances, it is more than complex to evaluate the sensitivity of the system parameters. Such studies must be based on a large number of simulations, and more particularly on a Monte Carlo simulation. Due to this complexity, a special concept validation was made in a simulation environment. Table 1 summarizes the applied simulation studies.

Table 1. Short version of record of the concept simulation resulted in the Figure 7 (Source: Authors).

Time (hour)	Event, Actions, Works Done or Need to be Done	Comments
pre-event	Preparedness: Make a disaster response plan and plan the required supporting system. Preparedness includes the preliminary studies with the latest result of sciences and technologies (as probabilistic prediction of hazards, seismic wave propagation, new construction materials, new measuring, observing systems as UAVs), monitoring and warning systems to be applied, methods of restoration education and training of the required staff. Outputs of preparedness are estimated reserve materials, parts, instruments, details, machines, including the mobile machines, required staff size and their optimized distribution in the zone of the possible earthquakes' appearances.	Step 0 Operability, or usability means the ratio of the system that can be used even with some limitations (like seriously reduced speed of trains). It must be re-evaluated at every five years.
prewarning	In case of seismic activities the supporting system must be "turned" into stand-by condition.	It can happen 1–10 days before the main earthquake appearance. Check the availability of the techniques and the staff
0.0	Earthquake occurring	
0.005	Warning signal to reduce the operation level (like sped of trains), stop the system operation	Due to transferring the warning signal with higher speed than the seismic waves are moving
0.015	Initiating the response supporting systems, actions and starting the response management: definition of the responsibilities, inputs, and warning –up the simulation supporting system.	Major input size (magnitude) and location of the earthquake's epileft

Table 1. Short version of record of the concept simulation resulted in the Figure 7 (Source: Authors).

Time (hour)	Event, Actions, Works Done or Need to be Done	Comments
0.05	Getting first results by using the preliminary prepared GIS information data block, making the first estimation on the preliminary estimation of size of damages and losses (in critical infrastructure), determining the first value of the major indicator (for example for railway system the relative unusable length of track), definition of the first priority list (which critical infrastructure must be restored firstly) and preparing the mobile staff for their required actions (where, what by which technical support, materials, machines they must do).	First l_{ut} estimated by (1) and (4), list of critical infrastructure must be firstly restored (prioritised on the basis of indicators types (2)), first commands for first response actions
0.1	Starting the response. The mobile monitoring, rescue and measuring machines move to the defined critical infrastructures. Drones are used to have further real information on the damages, losses. First machines, trucks departure to the predefined sites in order to start the restoration. Simulation support has initiated in adapting recurring process. Every 0.1 h, the simulation results appear on the screens in the operation lefts to make further evaluations, develop new decisions and improve the response process. The simulation process is adapting to the available information, objectives of prioritisation and priority list might be changed during each cycle.	Step 1–3 By step 0.1 h the process is adapted to the following cycles of simulation. Simulation uses the Markov model (8), Monte Carlo simulation to predict the aftershock, empirical (statistical) models to evaluate the secondary effects and series of software to predict the transition (moving) of the secondary effects.
0.82	Specialist shown up. They join to the staff works. If it is required the leaderships and different managing positions are shifted to the person having large practice or higher rank, position.	The process is running without serious changes
3.2	New information from the mobile measuring staff and from applied UAVs. Drones arrived and the simulation process is adapted. Measurements show that the damages are more serious than it was estimated.	Step 4–5 considerable changes in l_{ut} (here increased) estimated by the new measurements provided by the mobile (UAV), applications, after it returns to Steps 1–3.
11.7	In the simulation the possible appearance of aftershocks are predicted by a Monte Carlo simulation. Now, it is a real situation, when the aftershock is greater than 4 M. The partly restored infrastructures have new damages.	Step 4–5 l_{ut} increased considerably, after it returns to Steps 1–3
26.7	There is a warning signal about the dam failure. The simulation starts to CFD analysis of moving water to the railway infrastructures. Every 0.1 h cycle new information appears on the screens showing results of simulations and real information on flood. Mobile measuring lefts, UAVs are sent to observing the development of the flood.	Following Step 1–3 adapted to the real situation, and including sub-simulations of different problems, like moving the flood studied by CFD methods.
48.6	Real information about the damages caused by flood that reached the railway lines, infrastructures.	Step 4–5 l_{ut} increased considerably after it returns to Steps 1–3
after 6.0	Every 2 h, initiating the final evaluation of the objectives of the first response management	Step 6.
62.2	New information about the real damages caused by flood.	Step 4–5 l_{ut} decreased considerably, after it returns to the Steps 1–3

Table 1. Short version of record of the concept simulation resulted in the Figure 7 (Source: Authors).

Time (hour)	Event, Actions, Works Done or Need to be Done	Comments
89.6	Again, an aftershock occurred with a magnitude of 5.6.	Step 4–5 l_{ut} increased considerably, after it returns to the Steps 1–3
11.1	Reaching the operation level defined preliminary, $l_{ut} = 0.1$	Step 7.
12.0	Simulation is stopped	

3.2. Concept Validation Test

The recommended recovery management (Figure 1) requires preliminary studies, good infrastructure, and technical staff (to perform measurements, simulation studies and result assessment), in order to make the appropriate decisions. The leaders of this management process must have outstanding theoretical and practical knowledge as well as an extensive experience (implied knowledge) to use the recommended methodology successfully and efficiently.

The described concept was tested with a simple and presumed event case. It was applied to a simplified railway system being analogical to Kazakhstan's southern railway network, with one tunnel and 338 bridges from a total of 1720 railway bridges in the state (Figure 6). This part of the Kazakh railway system is endangered at the western part by floods, at the eastern part by earthquakes [95,105] and from the south of Almaty by mudflow (glacial lake outburst flood) [106], while from north of Almaty by flood and industrial hazards [28].

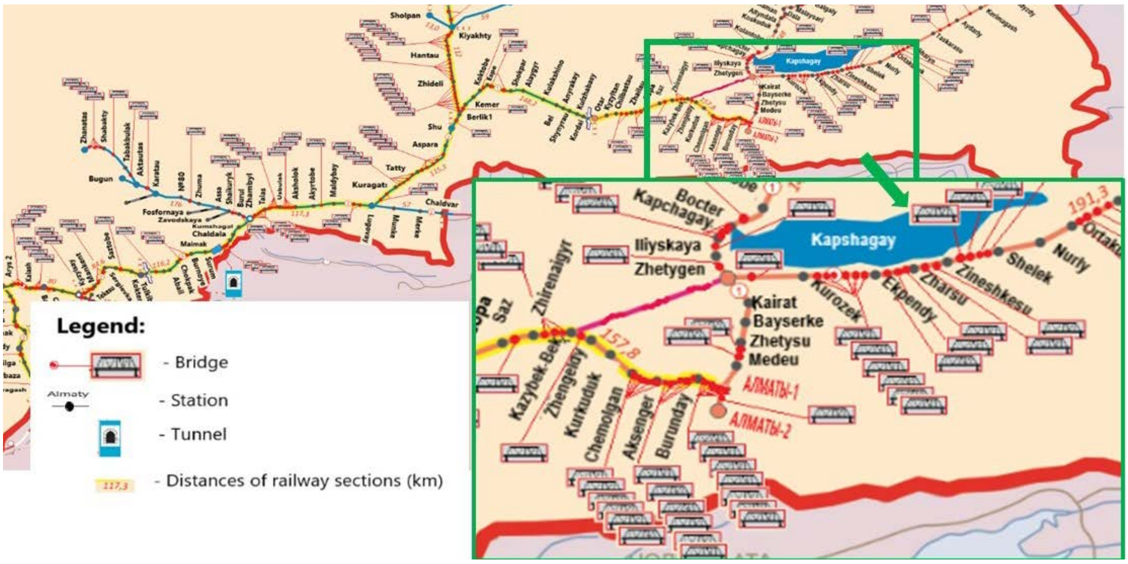


Figure 6. The area of the simulation study: Southern railway lines in Kazakhstan (Source: Author Sergey Kinzhikeyev).

The railroad system shown in Figure 6 has a serious disadvantage from a disaster response point of view: the system has no loop-lines, while there are too many bridges in operation. Therefore, the total loss of one of the bridges might fully block a large section of the track, due to missing alternative routes/tracks.

Several simplified models were studied in simulation aiming to validate the possible concept of the proposed management methodology: (i) the tracks having several bridges over short ranges were modelled by one bridge only, (ii) the system shown in Figure 6 were cut into smaller parts which are easier to handle, and thus (iii) the line containing a series of bridges over short distances were modelled separately as sub-systems.

Figure 7 demonstrates the typical simulation results supporting response management. Here, state space (of the probability of staying in the given sub-space) was divided into 20 subspaces (with 0.05 range) and the two extreme values (zero and one) were also added as sub-spaces. During the simulation, the chosen time interval (as cycle step) was 6 min (0.1 h). Figure 7a,b show the situation results, when only a simple Markov modelling was applied, with constant transition matrix and without any adaptation of the real processes. As has been recognized, the earthquake caused serious damage to the railway network, with nearly 60% of tracks being influenced. As shown, the railway can practically be returned to the operational level in 5 days (probably with limitations).

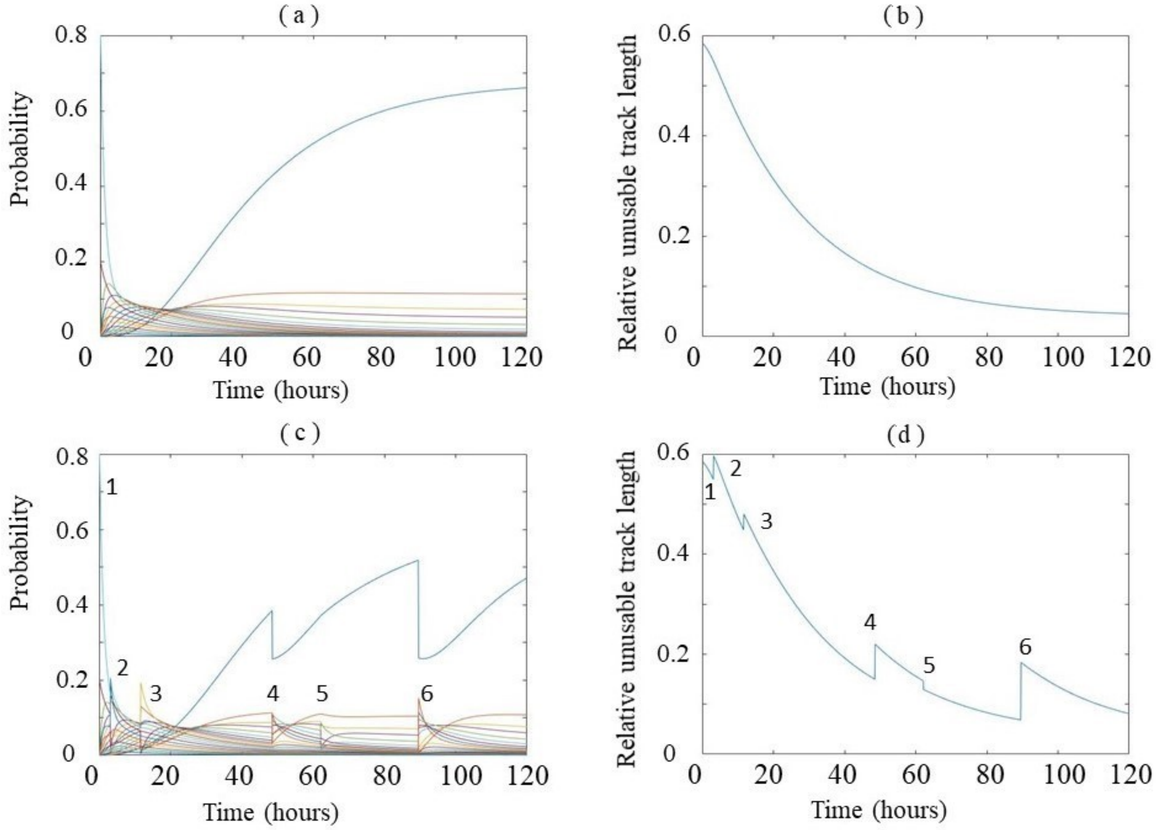


Figure 7. Concept validation using simulation based on the described methodology and sub-models, (**a**,**b**)—simulation with constant transition (recovery) matrix without any further effects, (**c**,**d**)—simulation with constant transition matrix and after event effects: 1.—earthquake caused the effect, 2.—correction after measurements (by UAV or other tools), 3.—aftershock, 4.—flood, 5.—system indicator updates due to updated information on flood and real damage caused, 6.—aftershock (Source: Authors).

Figure 7c,d demonstrate how the adaptation of the model to real processes/estimated real processes influence the results of the applicable responses. In this simulation, the same time interval (as cycle step) was used. For easier comparison, the simple and adapted Markov models used the same constant transition matrices. Occurrences of the aftershocks were simulated using a Monte Carlo method. The secondary effects were evaluated using the available statistical data and models as well as data provided by the information and observation sub-systems.

The concept simulation results (from the management point of view) are summarized in Table 1. The simulation is started at time 0.00. The simulation used a typical hybrid simulation. Simulation itself is a recurrent process with continuous time. The decision making process is a discrete process applied or might be applied after every 6 min. At these discrete states the simulation models, their parameters can be adapted to the latest information about the process running in reality.

Generally, the first simulation cycle, step 2 and 3 (Figure 1) might be repeated every time-cycle, while the further cycles including steps 4, 5 and if it is required step 6 should be included in the time cycles depending on the available data (after 3–5 time-cycles or after getting new information).

Effect of aftershocks and secondary effects such as flood, appear in Figure 7c,d as sudden changes. In the case of aftershocks, these sudden changes are realistic, while in the case of secondary effects, the occurrences of the effects can be identified earlier. Here these delays are not modelled, and the secondary effects are taken into account at the time of their occurrences.

The concept validation, shown in the Figure 7, demonstrates the applicability of the methodology which describes their optimal distribution nearby the technical system and the optimization of the resources that secures the sustainability of the response management.

4. Discussion

This paper introduced a new disaster response methodology, which is recommended to be implemented as an active adaptive response to earthquake damage at large ecological-socio-technogenic systems playing a deterministic role in the economy and society. A special indicator was introduced, defining the relatively unusable track length of the system as a governing indicator in response management. The recommended concept was tested on a railway system. The methodology has several special features described and briefly discussed here.

It is developed for large technical/technological systems but is relatively easily adaptable to other (like biological) systems.

It supports the (first) response management, aiming to return the system to its operational (usability) level. For example, the operation level means that the railways may transport people, goods, while the system's performance might be limited. Therefore, the operation level depends on e.g., the initial infrastructure condition, damages, damages of the other transport means. This is a performance that must be defined and maintained by response managers. Another important feature is that the track of high-speed rail must be fully repaired and tested before starting its operation.

The methodology of synthetized engineering and management methods. Another interesting dilemma: implementing the methodology must be actively adapted to the real situation because of the large robustness of the management decisions' technical systems and subjective character. In addition to this, the system must be sustainable as well. According to the requirements, the critical infrastructures, such as the railway system, must be designed and constructed to withstand the strongest earthquake which can occur generally every 50 years. This is a condition (constraints) for the optimization of sustainability.

It is important to notice that the introduced indicator of the unusable part (in the example the unusable length of railroads, l_{ut}) as state variable or control vector has legal and physical control elements, especially the regulatory requirements on the design and construction of safe system (railroads and railway systems) as well as methods of monitoring the continuous maintenance and repairing and rebuilding of the critical objects (like tunnels, bridges, tracks).

The applicability of the recommended methodology depends on the available sources, methods, simulation techniques, software, which must be preliminarily tested and adapted to the given region. For example, the GIS maps supporting the response management (as shown in Figure 2, estimation and optimal distribution of the sources restoring the systems) must be prepared before implementing the developed methodology.

Instead of a simple, but adapted Markov model, more complex models can be developed and applied. However, the augmentation of the accuracy and quality of response management by implementing more complex modelling features is questionable. The problems caused by errors, and robustness in first data on damages and losses. This is the cause of the created methodology, being based on the recurrent estimation of the model parameters and using available resources, including remote sensing and simulations.

Several special sub-models must be developed and applied before the use of the recommended response management. For example, a Monte Carlo simulation was used for modelling the aftershocks. It uses four random variables in each (iteration) cycle. The first two define the magnitude and probability of aftershocks occurrence at a given time (step). If the aftershock is predicted to appear, then another two random values generated might identify the location of the predicted aftershock (Figure 5b) This methodology takes into account only the predicted aftershocks with magnitude 4 or greater. It seems that the results are applicable, while the models require accurate estimation of the distribution parameters for the probability of aftershocks and their bivariate normal density function.

From the disaster recovery management point of view, there is an important difference between earthquakes' primary and secondary effects. Earthquakes last as aftershocks from several seconds up to several minutes, while the time of the secondary effects and the damage caused by them might take from 15–30 min to a few hours. In some cases, this time might even grow up to a few days. The post-disaster situation can be determined from the changes in the tension in the upper crust around the fault rupture that can influence neighboring faults and volcanoes' behavior.

In the case of using Markov decision process (MDP) as an improved approach to response management to earthquake damage, another important aspect calls for special attention and introduces serious barriers. During the response, the transition probability matrix, rewards, possible actions, as well as the value and control law policy are changing radically by the random behavior caused by the aftershocks and secondary effects. The response management methodology developed and recommended by this paper eliminates this disadvantage by regularly revising the required inputs in the applied simulation.

The results of simulations (Figure 7) demonstrate that the developed methodology supports response management to earthquake damage related to railways and can be applied to reduce the required time to recover and assist the effective use of the available resources. The objective of quick recovery is to return the railroad and the railway system to the operational level. Therefore, this part of the recovery can be finished in 2–3 days. In the case of having a long-term secondary effect, for a destroyed river dam for example, the quick recovery time might increase to 6–10 days. The complete recovery of the railroad and railway system might require up to 1–3 years.

The concept simulation is valid in using another type of leading indicators. Instead of the relatively unused track length, we can also apply the number of influenced passengers, being unable to leave the region affected by the earthquake. In such cases, recovery management will switch from technical/technological to disaster management dealing with social affairs.

The proposed methodology (Figure 1) does not intend to create a universal and comprehensive program for response management but rather to propose guidelines for the well-educated and trained leaders engaged in the management of the response to the railway damages caused by earthquakes. The methodology implies getting new information regularly, taking advantage of situational awareness, making analyses based on the obtained scientific and practical results, making a decision or adapting the decision to the continuously changing situations.

5. Conclusions

In this paper, the available information on emergency management and the possible responses to disaster recovery were analyzed, with a specific focus on sustainability, related to railway systems damaged after an earthquake [28]. This investigation reached the following significant results:

- The role of railway systems in the (earthquake) response management should be considerably improved because
    - ○ it is underestimated today
    - (a) its damage (caused by an earthquake) is usually less severe relative to other transportation means (in the case of having a well-prepared earthquake-resistant infrastructure and a developed monitoring system),

    (b) it could be rapidly recovered to the operational (usable) level within 6–24 h (in case of having a conventional system) or 30 days maximum (in case of having a high-speed train system that requires preliminary test runs of trains), therefore
    (c) it is especially relevant for countries having a limited road system and/or high risks of earthquake occurrence.

- An extensive literature survey was performed, models and methodologies analyzed, which could be applied to
    ○ response to the railway damages caused by earthquakes,
    (a) collection of historical data on the railway system recovery after earthquakes, including primary and secondary effects and aftershocks,
    (b) evaluation of the damage by the introduction of a new indicator–relative unusable track length (like a parameter of the lost capacity) and
    (c) select/improve/develop the sub-models to support response and recovery management.
- An active and adaptive methodology was developed, which is recommended to improve earthquake response management techniques that are;
    ○ based on recurring cycles of the zero + six + one steps,
    (a) including semi-empirical situation awareness-evaluation-decision making between each step,
    (b) supported by the discussed sub-models employing different theoretical, semi-practical calculations and simulations.
- The introduced methodology was applied to simulations and concept validation tests that
    ○ applied the available historical data on railway damages caused by earthquakes and fast recovery,
    (a) followed experts' recommendations advising possible decisions in different simulated situations and
    (b) used simulation models employing approximation of the relative unusable track length changing process by a Markov chain adapted to the applied decision at each step and included a Monte-Carlo simulation of the aftershocks' possible occurrence (and secondary effects).

The developed methodology will significantly reduce the number of deaths in the earthquake zone since the dynamics of the number of deaths caused by earthquakes depends directly on the scale and place of rescue operations.

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