Risk Assessment Framework Based on a Human-Infrastructure Model

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Abstract. The paper is devoted to developing the Multi-hazard Risk Assessment Framework containing models, scenarios, and methods for analyzing the risk related to multi-hazards. The multi-layered spatial model and the model of the Human-Infrastructure System based on hierarchies and having great scalability in time and space are proposed. These models take into account all possible relations between people, objects of infrastructure, natural environment, and corresponding spatial areas. The proposed event-based scenario representation model provides sufficient detailization in space and time and can properly represent multi-hazards, including compound events, cascading effects, and risk-related processes driven by environmental and societal changes. A novel extensible Multi-hazard Risk Assessment Framework that is a skeleton containing the multi-hazard risk assessment toolkit dealing with threat/danger, vulnerability, damage, coping capacity, risk and multi-risk is presented. The risk scenarios within this framework can describe multi-hazards as a multitude of spatially distributed dynamic processes influenced by various drivers. The implementation of the proposed models and framework is also considered.

Keywords: Infrastructure, People, Spatial Model, Hierarchies, Multi-hazards, Risk Assessment, Event, Risk Scenario, Framework

1 Introduction

Economy and society in the globalized world are increasingly dependent on the reliable availability of essential goods and services provided by technical and socio-economic infrastructures (TSI). Infrastructure failures can have drastic consequences for people and organizations that are not only close to such failures, but even spatially far from it.

During human life, people interact with their environment and use infrastructures originating human-infrastructure system (HIS). Environmental conditions, in which the HIS operates, can be represented by a multitude of interacting dynamic processes evolving in space and time. Today, deep changes in climate, land use, and socioeconomic evolution constitute several drivers that affect dynamic processes making them hazardous. Since some dynamic processes pose different threats (natural disasters, technogenic emergencies, criminal threats etc.), both people and TSI undergo spontaneous and poorly controlled risks. Within large territories, hazards can occur simultaneously (i.e. multi-hazards), so it is necessary to further investigate their relationships and interactions, including compound events, cascading effects, and risk-related processes driven by environmental and societal changes on different time and spatial scales. To date, such issues have not been fully studied.

Since multi-hazards give rise to spatially distributed risks changing coping capacities of HIS, such risks must be taken into account during land-use and TSI planning. Therefore, the most topical and important issue for today is the development of methods, models, and tools for assessing multi-hazard risks and associated cascading effects considering long-term (climate), mid-term (environmental), and short-term (meteorological) drivers. All of them are important to build an integrated approach to better forecast, prevent, and adapt to multiple hazards, their interactions and impacts, which allows maintaining sustainability and resilience of HIS.

The problem of multi-hazardous risk assessment is the subject of great interest to researchers. Most of them consider certain natural multi-hazards affected on certain critical infrastructures [2]. However, real multi-hazards often involve not only natural disasters but also anthropogenic, technogenic processes, and a range of their interactions. Such interactions have almost never been reflected in the literature. There are a wide range of multi-hazard risk assessment approaches from fully qualitative to fully quantitative, which depends on data availability and intended audience.

Narrative descriptions and Hazard wheels [3] are fully qualitative approaches based on hazard profiles and possible management options. They can be used in the situations of restricted data availability, so they have limited applicability and are beyond our scope. Qualitative/Semi-quantitative approaches such as Hazard matrices [4], Network diagrams [5], and Hazard maps [6,7] require identifying spatially relevant hazards to determine how they relate to each other. Their efficiency differs considerably depending on available information. These approaches need additional information to describe hazards or their interaction quantitatively, and such information is always derived from the domain experts. Accordingly, in addition to qualitative information, statistical or probabilistic assessments are used to build scenarios, network diagrams or overlapped maps [8]. A key challenge is incomparability of various hazards and their weighting issues [9]. These approaches are relatively simple but work only in large-scale spaces.

In contrast, quantitative methods are more complex. Hazard/Risk indices [10], physical modelling [11], probabilistic and statistical frameworks [12, 13] provide expensive and complex but effective solutions. Such methods involve machine learning, artificial neural networks, and other modelling techniques allowing to understand complex connections of several factors. However, they usually work with only a few kinds of hazards from a wide range of possible ones. To evaluate the likelihood of hazard sequences, considered approaches use several knowledge-representation models such as event trees [14], fault trees [15], Bayesian networks [16], fragility functions [17], life cycle cost assessments [18], etc.

As a result of the literature analysis, we make the following conclusions. Evaluation of risk must be hazard-specific as well as location-specific. Although multi-hazard risk assessment should be provided for the targeted components or the infrastructures as a whole to evaluate potential losses, existing approaches do not use any models of the infrastructures or HIS as well. Therefore, such estimates are mainly abstract.

The most used concept to model various hazardous processes is an event, which is a basic element of the most used event trees and risk scenarios. However, event representation is quite restricted. Although a hazard risk is considered as the probability of occurrence of a potentially damaging phenomenon within a specified period of time or a given area [19], event representation includes probability of event occurrence but usually does not consider spatio-temporal reference of the event, so the existing approaches are weakly scalable. Instead of this, it considers triggers as convenient model for representation of causality and impacts of hazardous events, their interactions, and cascade effects [20]. Thus, the existing approaches do not meet the requirements for multi-hazard risk assessment of TSI on different time and spatial scales in conditions of multiple interacting hazardous processes driven by environmental and societal changes. We need to develop a novel knowledge representation model, which will allow properly describing the components of HIS and highlighting the necessary target objects with respect to their spatial positions.

This paper, therefore, aims to develop the hierarchical model of HIS and the scalable event-based model of risk scenarios considering temporally and spatially referenced events. These models must constitute a basis for multi-hazard risk assessment framework (MRAF). The paper is organized as follows. Section 2 describes a scalable multi-level spatial model. Section 3 proposes a model of the Human-Infrastructure System. In Section 4, a risk scenario model based on temporally and spatially connected sequences of events is proposed. Section 5 describes a multi-hazard risk assessment framework. Section 6 presents the result of the research.

2 Spatial Model

Let us consider that hazardous processes are definitely dynamic processes evolving in space and time on different scales. The domain specifics require a spatial model with a flexible scale depending on the tasks and the territorial coverage of the dynamic processes since some of them cover the territory of an entire country, while others can occur locally requiring a higher level of detailization. Thus, the analysis of ongoing dynamic processes must be provided within a certain territory of consideration called the area of interest (AOI). It's a rationale to describe the spatial model of the AOI as a multi-level structure representing spatial objects of different levels.

Consider a three-dimensional Euclidean space C, which contains the AOI X as an openly connected subspace $X \subseteq C$. Suppose e_1, e_2, e_3 is a basis in C such that decomposition of a vector $v_x = \alpha_1 e_1 + \alpha_2 e_2 + \alpha_3 e_3$ gives us the coordinates $(\alpha_1, \alpha_2, \alpha_3)$ of some point x within C. Suppose $A = \{a_1, ... a_m\}$ is a non-empty finite set of attributes, V is a domain of A, and f is an attribute value function such that $f : X \times A \to V$. Each spatial point $x \in X$ can be associated with a certain subset of attribute values $\{a_{x1}, ... a_{xm}\} \subseteq A$ being possibly incomplete and inaccurate. Thus, we obtain a coordinate level, which represents the AOI as continuous space and can be implemented as a basic layer within a Geo-Information System (GIS). Looking ahead, all the objects located within the AOI should be geolocated using the basis e_1, e_2, e_3 and geographical coordinate system.

At the second level, we impose a metrical grid D of isometric cubic cells with the size being $\delta \times \delta \times \delta$ on C using a linear map ξ such that $\xi : D \to C$. As a result, the space C is discretized by the grid $D = \{d_{ijk}\}$ of isometric cubic cells d_{ijk} , where ijk represent the coordinates of this cell within the grid D . A cell $d \in D$ is considered as a spatial object of minimal size. It is advisable to enable varying the cell size δ to make it possible changing the scale of the discretized AOI. Each cell $d \in D$ is also associated with a certain subset of attribute values called the cell state via the value function $f(d, A)$. The proposed discretization assigns the equal values of the attributes to each point belonging to a certain cell d , therefore each cell $d \in D$ represents a homogeneous area within the AOI in the sense of its attribute values. Thus, all points within the cell are indiscernible with respect to A: $(\forall x, y \in d)(\forall a \in A)\left[f(x,a) = f(y,a) \right]$. Now, we obtain a cell level, which represents the AOI discretely instead of coordinate level and can be implemented as a second layer of GIS.

At the third level, the two-dimensional projection of the AOI X on the terrain plane e_1, e_2 is divided into a finite set of disjoint objects, which can be described as the geometric shapes and represent geo-referenced areas having the same characteristics. Such areas can describe land-use objects that have a spatial extent such as fields, forests, ponds, etc. Consider a non-empty subset of attributes $A_i \subseteq A$ and define an A_i-indiscernibility relation $\mathrm{R}_X^{A_i} = \left\{ (x,y) \in X \times X \,\middle|\, \forall a_j \in A_i, f(x,a_j) = f(y,a_j) \right\}$ within X [22]. Thus, if a pair of points $x, y \in X$ belongs to $\mathrm{R}_X^{A_i}$, $(x,y) \in \mathrm{R}_X^{A_i}$, these points have the same values of attributes $a_j, \ldots a_m \in A_i$. All adjacent A_i-indiscernible points of AOI constitute a homogeneous area in the sense of attribute's values, which is a structural element of the spatial model called a region and denoted by g . Each region represents the area of a certain class at the definite layer of GIS. Regions cannot overlap or cover one another within the certain layer of GIS but they can be adjacent or adjoin to one another having the properties of connectivity and continuity. Since several indiscernibility relations $\mathrm{R}_X^{A_i}, \ldots \mathrm{R}_X^{A_j}$ can be given simultaneously based on the different subsets $A_i, \ldots A_j$ of the attribute set A, there can be several partitions of the AOI X into regions, each of which can be implemented as a separate GIS layer. Detached layers can represent different natural parts of the territory by the regions called geotaxons, for example, homogenous areas with different vegetation, soil, relief, etc.

Within the spatial model, each region $g_k \in G$ is approximated by the underlying set of cells $\{d_{km}\}_{m=1}^{z} \in D$ using a linear surjection $\varsigma : G \to D$, where the grid D and the set of regions G are aligned to the origin $(\alpha_1, \alpha_2, \alpha_3)$. Obviously, all cells that underlie the region g are A_i-indiscernible. This allows considering the dynamics of processes at the cell level including their spread while localizing different natural or artificial objects by the geographical coordinates. Since the cell size is variable, regions can be covered by different sets of cells of various sizes at different time moments.

At the fourth level, there is a spatial hierarchy J representing the administrative structure of the considered AOI (municipalities, districts, provinces, countries), which can be used to help users be aware of threatened areas and infrastructure objects being at risk from multi-hazards. Obviously, the spatial hierarchy should be two-dimensional, so we define it over the projection of the AOI X on the terrain plane e_1, e_2. Suppose $H = \{h_1, \ldots h_m\}$ is a set of administrative units being in the relation of inclusion υ_1 or connection υ_2, and h_i is the least element of the administrative hierarchy. Imposing a partial order $\prec_1$ corresponding to υ_1 onto H, we obtain the spatial hierarchy, which can be also extended by other partial order $\prec_2$ corresponding to υ_2, so $J = \langle h_i, H, \prec_1, \prec_2 \rangle$. This spatial level corresponds to separate layers within the GIS. The borderlines between administrative units are determined by the corresponding geographical points over the coordinate level. Since such borders usually do not take into account the partitioning of the AOI into regions, the least administrative units can contain incomplete regions.

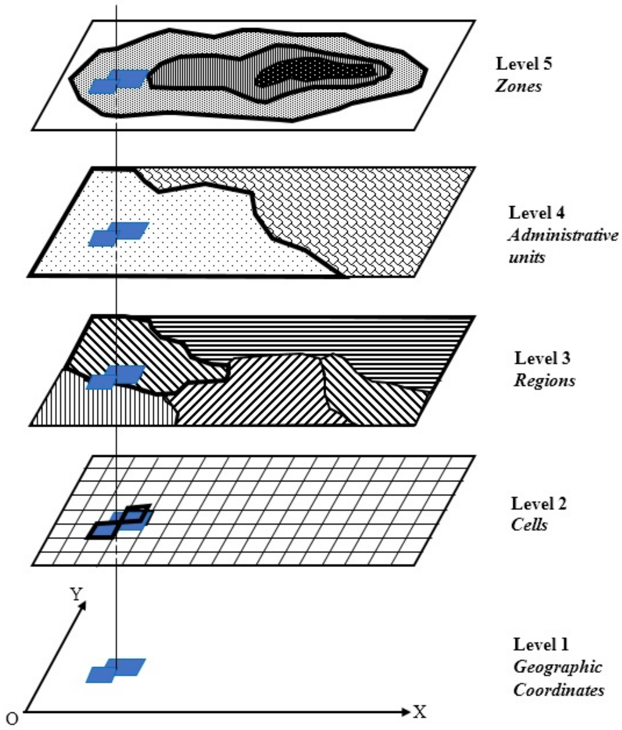

Fig. 1. The levels of the spatial model

The fifth level of the spatial model defines zones over the cells as the spatial areas containing a plurality of separate regions spatially distributed over X with the certain relations between them. Zones can represent homogenous areas in the sense of definite assessments of the certain indicator from the given indicators set $I = \{I_1, ... I_m\}$ (e.g. danger, threat, risk, etc.). Consider a grid D. Suppose ζ_k is an evaluation function such that $\zeta_k : D \times I_k \to \rho$ and $\mathrm{R}_D^{I_k} = \{\forall d_i, d_j \in D,\ \zeta(d_i, I_k) = \zeta(d_j, I_k)\}$ is the I_k-indiscernibility relation on the set of cells D. Thus, all cells $d_i, ... d_n$ belonging to $\mathrm{R}_D^{I_k}$ are indiscernible in the sense of the same value of the indicator I_k and constitute a distributed spatial area $z_k = d_i \cup ... \cup d_n$, which is called a zone. Zones do not have a property of continuity as distinct from regions and can be represented at the separate layers of GIS for each $I_k \in I$. Suppose Z is a zone set. Each zone $z_k \in Z$ is approximated by the underlying set of cells $\{d_i\}_{i=1}^n \in D$ using a linear surjection $\varsigma : Z \to D$. Since the distribution of zones depends on the cell size and the definition of the function ζ_k for each indicator $I_k \in I$, such distribution is dynamic and both hazard-specific and location-specific. This distribution is scalable due to the variable cell size, so zones, as well as regions, can be covered by different sets of cells of various sizes at varied time moments depending on the scale of the considering, but zones are dynamic as distinct from static regions and administrative units. It should also be noted that the coordinate, cell and zone levels are three-dimensional, while the regions and the administrative hierarchy levels are definitely two-dimensional given over the terrain plane.

The proposed model allows taking into account the inaccuracy and incompleteness of the spatial information. If the coordinates of the object are unknown exactly, it can be referenced spatially in an ascending hierarchy, i.e. within the specific cell, region, and even administrative unit as it is shown in Fig. 1. Thus, the spatial model represents the scalable AOI in a hierarchical manner based on the multi-levelled structure.

3 Human-Infrastructure System

Consider the socio-economic system (SES) as a complex dynamic system resulting from the interaction between people, environment, and TSIs. The main element of SES is people. They study, work, rest, travel, etc. At that people interact with the environment, consume natural resources, and use various elements of the SES such as infrastructure, manufacturing, education, finance, goods, etc. TSI is a dynamic spatially distributed system consisting of the components important to the activity of people and society. Both people and TSI constitute the human-infrastructure system (HIS). HIS can be represented as a network of networks containing such components as people and infrastructures. The HIS model should reflect all kinds of possible relations between a large variety of components.

3.1 Time

Consider a set of time points T having the initial point $t_0 \in T$ and a full order $<_T$ imposed onto the time points $t_i, t_j \in T$ such that t_i precedes t_j if $t_i <_T t_j$. Thus, a triple

$\langle t_0, T, <_T \rangle$ describes a fully ordered timescale over T. The time intervals can be defined as $[t_s, t_f]$ pointing to start time $t_s \in T$ and final time $t_f \in T$ within the timescale.

Using the time intervals, we build a time hierarchy $\mathcal{T} = \langle t, \tau, <_T \rangle$ over the set of elements τ = {*seconds*, *minutes*, *hours*, *days, months, years...*} and full-order relation $<_T$. The time hierarchy allows taking into account the uncertainty of the time-specific information. If the certain time is unknown exactly, it can be referenced temporally in an ascending hierarchy to the higher element of time hierarchy.

3.2 People

Suppose $\mathcal{P}$ is a set of persons, p_{id} is a person, and id is an identifier used to distinguish persons. Assume that each person can be geolocalized using its identifier and GPS, wireless, mobile tracking, or other techniques. Thus, the spatio-temporal state of each person can be described as a triple $\langle p_{id}, t, \chi \rangle$, where t is a time reference and χ is a georeference (location) within the spatial hierarchy J.

People are always in certain relations $\vartheta_i, \ldots \vartheta_m$ with other people and with various components of infrastructure. For example, people work at enterprises, study at schools, eat at restaurants, visit concerts, theatres, etc. Thus, they are organized into groups $q_1, \ldots q_u$ based on certain relations. With respect to the time scale, groups can be static that do not change or change very rarely in long-term scale, semi-dynamic that change in mid-term scale, or dynamic that change quite often in short-time scale. Static group can be represented by family, co-workers within the enterprise, group of students, residents of the building. Dynamic group can be represented by cinema or theatre audience, recreational visitors, participants of various events, etc. Each person can enter into some relation ϑ_i that maps him to a certain group q_i at the long time interval, for example, he studied at school during the interval $[\tau_l] \in \mathcal{T}$ given over years, as well as short or repeated time intervals and their unions, for example, he is at home from 20-00 to 6-00 and from 14-00 to 16-00 daily, he works at the enterprise from 8-00 to 17-00 on workdays, etc. Clearly, each person $p_i \in \mathcal{P}$ can be simultaneously involved in several relations $\vartheta_i, \ldots \vartheta_k$. Suppose $\mathcal{V} = \{\vartheta_1, \ldots \vartheta_m\}$ is a set of relations, $\mathcal{Q} = \{q_1, \ldots q_q\}$ is a set of groups, and γ is a bijective mapping $\gamma : \mathcal{V} \leftrightarrow \mathcal{Q}$. The participation of the certain person $p_i \in \mathcal{P}$ in the group $q_j \in \mathcal{Q}$ during the time intervals $\tau_1, \ldots \tau_l \in \mathcal{T}$ can be described as a tuple $\langle p_i, (\tau_1, \ldots \tau_l), q_j \rangle$ and the participation of the person in the different groups can be described as $\mathcal{p}_i = \left\langle p_i, \left((\tau_1, \ldots \tau_l), q_j\right)_{j=1}^{q} \right\rangle$. Correspondingly, each group $q_j \in \mathcal{Q}$ that is based in a certain location $\chi_j \in J$ and consists of the subset of persons $\{p_e, p_u\} \subseteq \mathcal{P}$ can be defined both as person-ordering composition $q_j = \left\langle \left(p_i, (\tau_1, \ldots \tau_l)\right)_{i=1}^{u}, \chi_j \right\rangle$ or timeordering composition $q_j = \left\langle \left(\tau_k, (p_i)_{i=1}^{u} \right)_{k=1}^{l}, \chi_j \right\rangle$. Thus, the model of people within HIS can be represented as $\mathcal{W} = \left\langle \mathcal{V}, \mathcal{P}, \mathcal{Q}, \gamma, \{p_i\}_{i=1}^{N}, \{q_j\}_{j=1}^{q} \right\rangle$.

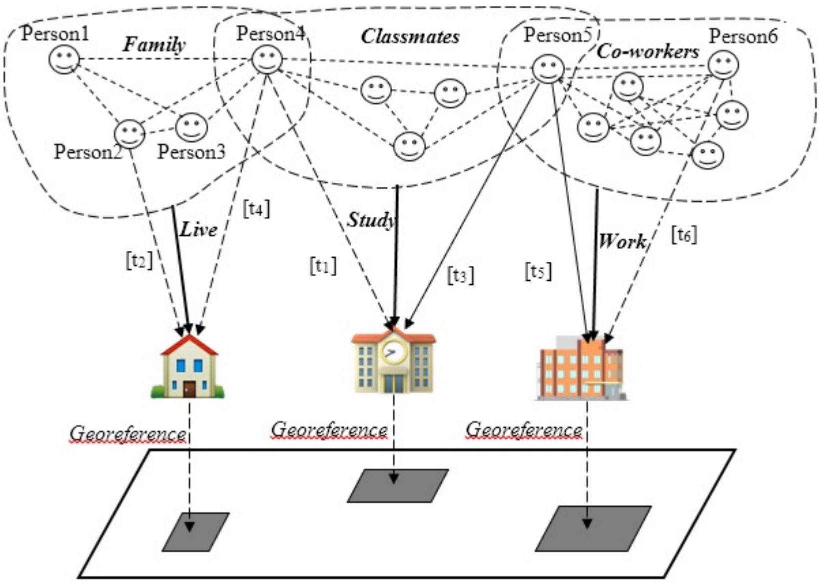

Fig. 2. Groups of people

Regardless of the time scale, all groups are geo-referenced within the AOI as it is shown in Fig. 2. Obviously, the same person can be simultaneously involved in many different groups both at the different or at the same time intervals. The proposed model allows representing also dynamic and ever remote relations that cannot be exactly geo-referenced, for example, a group of friends in a social network or a group of visitors of a web-site. It should be noted that there can be a lot of relations between people and infrastructure objects, but fortunately, for the considered domain it is enough to highlight only a few relations, such as study, work, meet, attend, etc.

3.3 Infrastructures

We can represent HIS as a hierarchical network of networks containing:

1. ***buildings*** organized in a hierarchy $\mathcal{B}$ like "house-quarter-street-district…". Some nodes of the people model $\mathcal{W}$ can be connected to some nodes of the hierarchy $\mathcal{B}$ both in the long-time (a family lives in a house) and short-time (people visit offices, hotels, theatres) intervals. Buildings can be classified as residential and nonresidential (industrial buildings, stores, etc.) and have the spatial positions represented within the spatial hierarchy $\mathcal{J}$. Suppose $B = \{b_1, \ldots b_m\}$ is a set of buildings and

$L = \{l_1,...l_u\}$ is a set of the groups of buildings such that $l_1 = \langle b_j,...b_k \rangle$. Thus, the hierarchy $\mathcal{B}$ is represented as $\mathcal{B} = \langle b_i, L, <_3 \rangle$, where b_i is its least element (building) and $<_3$ is the strict order relation over L, which corresponds to the inclusion relation υ_3 between the group $l_j \in L$ and the building $b_i \in B$. Each b_i corresponds to a certain region defined within the spatial model of the AOI.

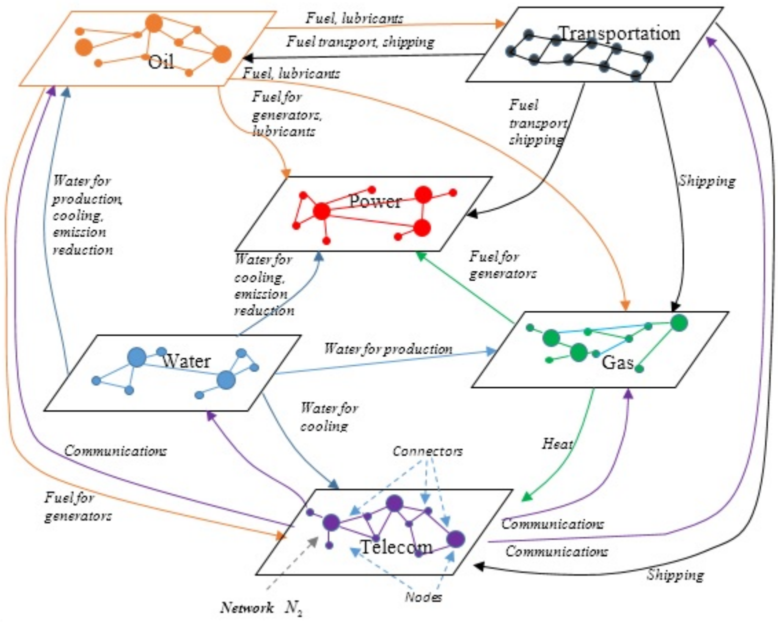

Fig. 3. The model of infrastructures

2. ***infrastructure*** organized in a set of networks $\mathcal{N} = \{N_1,...N_s\}$ (Fig. 3), where each network N_i represents roads, electrical, gas, telecommunications, pipelines, etc. Suppose $\mathcal{V}$ is a set of nodes and $\mathcal{L}$ is a set of connectors. A network N_i is represented as an oriented connected multigraph $\mathcal{G} = \langle \mathcal{V}, \mathcal{L} \rangle$, which doesn't contain cycles. Each node $v_i \in \mathcal{V}$ is represented as a tuple $v_i = \left\langle id(v_i), cl(v_i), \chi(v_i), \{l_j\}_{j=1}^{n} \right\rangle$, where $id(v_i)$ is an identifier of the node v_i, $cl(v_i)$ is a class of the node v_i given on the set of classes C, $cl(v_i) \in C$, $\chi(v_i)$ is a georeference point, and $\{l_j\}$ is a set of connectors attached to the node v_i. Thus, the nodes of the multigraph $\mathcal{G}$ are spatially referenced and connected to buildings, group of buildings, or other nodes. Each connector $l_j \in \mathcal{L}$ is represented as a tuple $l_j = \left\langle id(l_j), cl(l_j), \{\chi_k\}_{k=1}^{q}, \{v_i\}_{i=1}^{m} \right\rangle$, where $id(l_j)$ is an identifier of the connector l_j, $cl(l_j)$ is a class of the connector l_j given

on the set of classes S, $cl(l_j) \in S$, and $\{v_i\}$ is a set of nodes connected by l_j. The *i*-th network N_i is represented by a graph $N_i = \left\langle \{v_{ij}\}_{j=1}^{m}, \{l_{ik}\}_{k=1}^{n} \right\rangle$ while the infrastructure as a whole – by a multi-graph $\mathcal{N} = \left\langle \left\{ \{v_{ij}\}_{j=1}^{m}, \{l_{ik}\}_{k=1}^{n} \right\}_{i=1}^{s} \right\rangle$, where v_{ij} is the *j*-th node of *i*-th network and l_{ik} is *k*-th connector of the *i*-th network, $\{\chi_k\}_{k=1}^{q}$ is a set of points defining a sequence of points, which constitute a polyline within the coordinate level of the spatial model.

3. ***natural environment*** $\mathcal{E}$ (water, soil, vegetation, etc.) represented by the sets of corresponding geotaxons within the third level of the spatial model, so that $\mathcal{E} = \{r_i\}_{i=1}^{N}$.

Thus, HIS is defined as a tuple $\mathcal{Z} = \langle \mathcal{P}, \mathcal{W}, \mathcal{B}, \mathcal{N}, \mathcal{E} \rangle$, where $\mathcal{P}$ is a set of persons, $\mathcal{W}$ is a people model, $\mathcal{B}$ is a hierarchy of buildings, $\mathcal{N}$ is a network of infrastructures, and $\mathcal{E}$ is a model of the natural environment.

The model of SES can be obtained by imposing a network of enterprises, organisations, and other institutions of different sectors such as finance, manufacturing, trade, etc. providing flows of finance, goods, and services within some territory over HIS model. Such enterprises can be located in certain buildings, involve the groups of people, use certain elements of infrastructure, and so on, but this is beyond our scope.

4 States, Events, and Scenarios

The dynamic model of multi-hazard risk assessment is based on the assumption that an event can be represented as a change of the certain parameter of the state of the considered component of HIS. Thereby, each event has both temporal and spatial references and describes the transition of a certain component from one state to another.

4.1 States

One of the important properties of the models proposed above is that any object has its own state available for the use in threat/risk assessment methods. This applies to any building, any infrastructure component, any element of any group or hierarchies within the models, including areas of any level of the spatial model. Further, we will consider a generalized concept called "object" against all above-mentioned. Thus, *i*-th object O_i (cell, region, group, building, etc.) has its own state $w_t^{O_i}$ at the time t represented by the subset of attributes $w_t^{O_i} = \{a_{ij}, \ldots a_{im}\}$ such that $a_{ij}, \ldots a_{im} \in A$. Suppose $f : O \times A \rightarrow V$ is the attribute value function, so $v(a_{ij}, t)$ is a value of the attribute a_j of the object O_i at the time t. Suppose the non-empty finite set of attributes A is divided into subsets of static attributes A_S and dynamic attributes A_D, $A = A_S \cup A_D$. Suppose $W = \{W_0, \ldots W_F\}$ is an ordered set of the object state classes and π is a classification function such that

$\pi: O \times A \rightarrow W$. Clearly, a variation of the value of any attribute $a_{ik} \subseteq A_D$ of the object O_i at the time t changes its state $w_t^{O_i}$. If the object state class has also changed, we consider this is an event denoted by ψ, so that $\psi: w_t^{O_i} \rightarrow w_{t+1}^{O_i}$, where $w_t^{O_i} \in W_j$, $w_{t+1}^{O_i} \in W_k$, $W_j, W_k \in W$, and $W_j \neq W_k$. Thus, during the lifecycle, each object can pass through a sequence of different classes of its states. Whenever the value of the certain object state attribute is unknown, the value of the corresponding attribute of the object, which is higher in the hierarchy, can be considered. The same applies to the states of the objects. Obviously, a change in the state of the certain object can entail a change in the state of the higher (within the certain hierarchy) object covering it.

4.2 Events

Suppose c_i is an event class and $Class = \{c_i\}_{i=1}^{n}$ is a set of event classes. We can classify the events using a certain taxonomy hierarchy based on partial order relation $\prec_c$ over the elements of the set $Class$, such that $c_1 \prec_c c_2$ means the event class c_1 is more abstract than c_2. Thus, the taxonomy hierarchy is represented as $\mathcal{I} = \langle \perp, Class, \prec_c \rangle$, where $\perp_i$ is the least element of $\prec_c$ (empty event).

Suppose $Z = \langle A, V, \mathcal{I}, \mathcal{J}, \mathcal{T} \rangle$ is an event signature, where A is the set of attributes, V is the domain set for A, $\mathcal{I}$ is the hierarchy of event classes, $\mathcal{J}$ is a spatial hierarchy, and $\mathcal{T}$ is the time hierarchy. The event ψ can be represented by a structure $\psi = \langle o, c, t, d, y \rangle$ within the signature Z, where $o \in O$ is the object identifier, $c \in Class$ is the event class, $t \in \mathcal{T}$ is a time reference, $d \in \mathcal{J}$ is a georeference, and y is an attribute change descriptor. The latter describes the conditions, under which an event ψ occurs and is represented by $y = \left\langle \left(a_j, \lambda_j, \delta_j, \Delta_j \right)_{j=1}^{m} \right\rangle$, where a_j is a certain attribute of the state of the object o, λ_j is a state susceptibility with respect to the attribute a_j, δ_j is a minimum threshold value of a_j for the changing of the object state, and Δ is an absolute variation value for a_j. The event model $\mathcal{M} = \left\langle \{\psi_k\}_{k=1}^{n}, t, \chi \right\rangle$ is a set of events restricted by a certain time interval $t \in \mathcal{T}$ and a spatial area $\chi \in \mathcal{I}$.

4.3 Scenario

An event sequence S in the model $\mathcal{M}$ is an aggregate of events ordered by $<_T$, $S = [\psi_1, \psi_2, \ldots \psi_n]$, such that $\psi_1.t \leq_T \psi_2.t \leq_T \ldots \leq_T \psi_n.t$ for all events.

A scenario can be represented by a time-ordered event structure $G = \left\langle \{\psi_j\}_{j=1}^{n}, \tau, \{\varphi_l\}_{l=1}^{w}, \{\psi_k\}_{k=1}^{v}, \mu \right\rangle$, where $\{\psi_k\}_{k=1}^{n}$ is the event set, $\tau: \psi \rightarrow S$ is a mapping of the event ψ into the sequence S, $\{\varphi_l\}_{l=1}^{w}$ is a set of arcs, which connect certain events

ψ_j and ψ_k with the likelihood λ_l, such that $\varphi_l = \langle \psi_j, \psi_k, \lambda_l, \sigma_l \rangle$, σ_l is a sensitivity point (optional) of φ_l, and $\{\psi_k\}_{k=1}^{\nu}$ is a set of meta-arcs, which connect the certain event ψ_j and corresponding sensitivity point of arc φ_l with the degree of acceleration γ_k such that $\psi_k = \langle \psi_j, \sigma_l, \gamma_k \rangle$, and μ is the complex likelihood model [21]. Using the proposed event and scenario models, we can adequately represent all kinds of relationships between events (causal, temporal, etc.) and objects (spatial, temporal, etc.) combining various likelihood measures such as probability, possibility, or fuzzy in one frame.

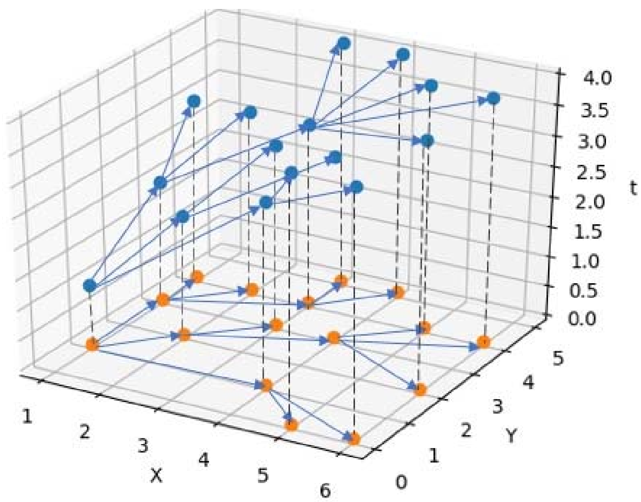

Fig. 4. Scenario representation in space and time

The proposed event-based model is applicable for a multitude of interacting spatially-distributed hazardous processes evolving in space and time including disasters of different classes influenced by meteorological or climatic drivers, other kinds of hazards, their interactions and cascading effects, which often give rise to danger and risk. The dynamics of multi-hazards can be reflected by scenarios (Fig. 4), which describe the dynamics of hazards as possibilities of transitions between object states.

5 Multi-hazard Risk Assessment Framework

The spatial, HIS, and event-based scenario models have been implemented within the extensible Multi-hazard Risk Assessment Framework (MRAF). MRAF is a certain skeleton containing the multi-hazard risk assessment toolkit dealing with threat/danger, vulnerability, damage, coping capacity, risk and multi-risk. The risk scenarios describe multi-hazards as a multitude of spatially-distributed dynamic processes influenced by meteorological, climate, environmental, and societal drivers.

The theoretical basis of the MRAF consists of the following models:

1. the HIS model representing people, TSI, and ecosystem;
2. the event-based scenario model representing the hazard dynamics, their potential direct and indirect effects;
3. The dynamic model of the vulnerability of the infrastructure components;
4. The model of multi-hazard risk assessment considering spatially distributed multi-hazardous threats and risk for TSI elements allowing to identify vulnerable and threatened objects, areas and infrastructures most at risk.

All of them are grounded on the multi-layer spatial model having the variable cell size. All levels of the spatial model have been implemented within corresponding layers of GIS. MRAF contains several methods based on the proposed models and assessment tools (Fig. 5). The following methods have been developed within MRAF:

1. The method of multi-hazard diagnosis of HIS;
2. The method of multi-hazard threats/risks assessment;
3. The method of damage assessment based on dynamic vulnerability;
4. The method of multi-hazard forecasting within HIS;

MRAF is extensible; it allows creating and adding new methods and procedures to assess multi-risk and vulnerability of target objects, areas, or infrastructures.

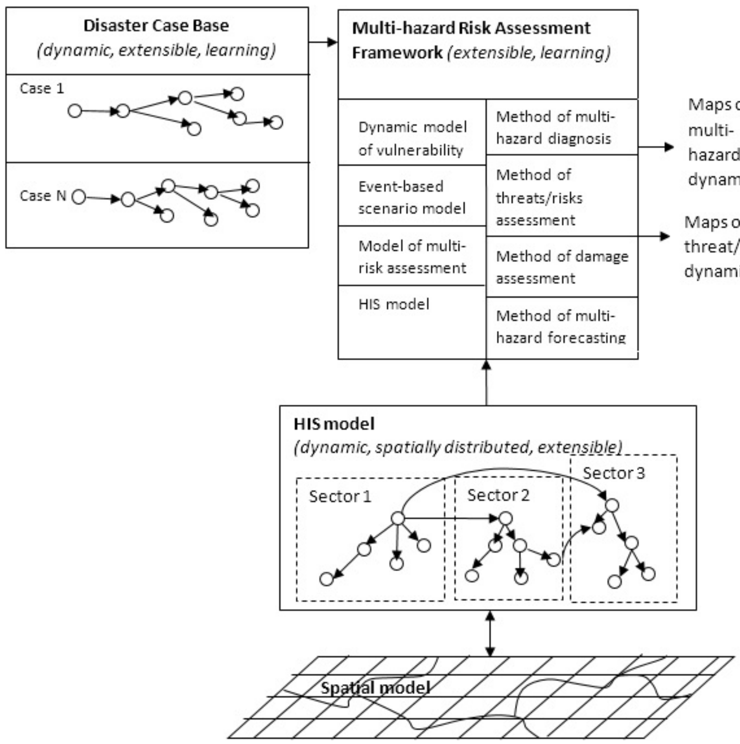

Fig. 5. Multi-hazard Risk Assessment Framework

Disaster Case Base (DCB) is a component complementary to MRAF. It has been developed to accumulate and store templates represented by the sequences of observed events and contains plausible scenarios and hazard dynamics models. Both MRAF and DCB are user-friendly tools for modelling and visual representation of hazard dynamics models and scenarios.

6 The Results of the Research

The proposed models have been implemented using Visual C++ and combined into the Multi-hazard Risk Assessment Framework named MuRKy. Python programming language has been used as well as the framework Django, its GIS extension GeoDjango, DBMS PostgreSQL, and geospatial extension PostGIS to integrate MuRKy framework into GIS-based risk management environment. The PETN Library presented in [21] has also been used to develop event-based structures and hierarchies. The use of double indexed lists allowed us to provide a fairly high performance of the framework when processing specific queries necessary for the multi-hazard risk assessment methods.

MuRKy framework has been approbated on the simulated area represented by the HIS model that includes 280 000 people united in about 18 000 groups, approx. 8300 of which are dynamic, as well as 3 700 buildings and 16 000 infrastructure objects located on the territory of 130 km^2 (a fragment of Kherson City, Ukraine). MuRKy framework has been tested within the local network based on two servers HP ProLiant ML350 (Intel Xeon E5-2620, 8 cores up to 3 GHz) and client computers with Pentium i5-7400 3 GHz processors and 16 GB RAM. The test queries were intended to select a multitude of people present in the given spatial areas (building, quarter, and region) at the given moment in time. Thus, an experiment has been conducted to evaluate query response time-varying the cell size within the spatial model from 5 m to 50 m. The results of the experiment are shown in Fig. 6.

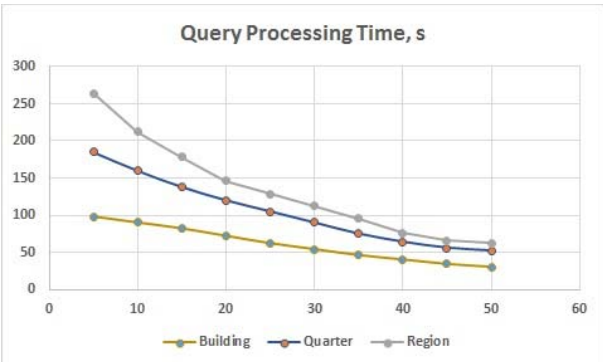

Fig. 6. The simulation results

The results of simulation experiment confirmed the adequacy of the proposed model and the efficiency of the framework; the developed framework MuRKy provides acceptable performance for the GIS-based multi-risk assessments.

7 Conclusions

In this paper, the spatial model, the model of the human-infrastructure system, and the event-based scenario model are presented. These models are embedded into developed Multi-hazard Risk Assessment Framework and implemented as MuRKy framework.

The proposed spatial model is multi-levelled and scalable due to the variable cell size, its spatial areas can be dynamic. The spatial model is robust to the inaccuracy and incompleteness of the information. If the coordinates of the certain object are unknown, it can be referenced in an ascending hierarchy. The model of HIS represents people, their groups, infrastructures, and natural environment as a network of interrelated networks and hierarchies within the spatial model. It takes into account temporal, spatial, and other aspects of the people, objects, and areas relations and interactions. The event-based scenario model is based on the changes of states of the spatial areas and corresponding objects of HIS. The framework contains models, scenarios, and methods for analyzing risks related to multi-hazards triggered by various drivers on different time and spatial scales. The MuRKy framework is planned to be open, extensible, and applicable for natural and technogenic disasters as well as terroristic, cybernetic threats, and ever migration processes. It has been implemented within GIS-based risk management environment to enhance cross-sectoral sustainability and resilience of TSI.

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