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# Emergency Management: A System Dynamics View on the Impact of Disasters in the Corporate Realm

Vladimír BUREŠ[1*], Bilal Naji ALHASNAWI[2], Tereza KARLOVÁ[1] and Alžběta DOČEKALOVÁ[1]

[1] University of Hradec Kralove, Hradec Kralove, Czech Republic; vladimir.bures@uhk.cz; tereza.karlova@uhk.cz; alzbeta.docekalova@uhk.cz

[2] Al-Furat Al-Awsat Technical University, Samawa, Iraq; bilalnaji11@yahoo.com

* Corresponding author: vladimir.bures@uhk.cz

Abstract: Natural or man-made disasters affect organizations quite often. Similar events can be coped with to a certain extent as organizations have safety plans, protocols and emergency procedures. Their development and application are associated with the discipline of emergency management. Its task is to minimize or even eliminate damages or casualties related to the occurrence of hardly predictable catastrophes. The aim of this paper is to present a system dynamics model enabling decision support for managers during all four stages of emergency management, namely mitigation, preparedness, response and recovery. Based on the search in scientific databases and consequent content analysis, causal-loop and stock-and-flow diagrams were developed. The model consists of six modules. While the first one represents the source related to tsunami generation, the remaining five modules deal with objects of interest such as buildings, infrastructure, environment or people. The model represents a simple and still immature example that demonstrates how the system dynamics methodology can be utilized in this domain in practice.

Keywords: emergency management; disaster; system dynamics; modelling; simulation

JEL Classification: C36; Q54

## 1. Introduction

The business practice has to deal with different kinds of problems. For various reasons, the influence of disasters on the operation of organizations and their security is becoming more frequent (Suppasri et al., 2022). In some organizations, the traditional approach to occupational safety needs to be intensively expanded to include this aspect. In recent years, the number of disasters, both natural and man-made, have increased very significantly. Due to this fact, the concept of Emergency Management (EM) began to be developed and implemented. According to Huang et al. (2021), EM can be defined as an integrated system composed of various tasks that cover the life cycle of an emergency. The disaster at the Fukushima nuclear power plant of Tokyo Electric Power Company significantly contributed to this development in the Tohoku region of Japan (Kawamura & Narabayashi, 2016). Although this is an extreme disaster, many managers have realized the consequences that natural influences can have on the safety, operability and productivity of the company in case of unprepared or underdeveloped safety protocols (Gisquet & Duymedjian, 2022). Such incidents result in significant loss of life, destroyed buildings, constrained traffic due to damaged infrastructure, and decreased finances due to repairs or increased cash flows through raising funds such as loans or grants. In summary, it can be stated that the overall economic situation of an affected company is changing. The task of EM is thus to reduce potential losses, to make the response more efficient or to set up mechanisms for quick recovery.

## 2. Methodology

This work aims to demonstrate how it is possible to work with the effects of disasters using system dynamics as a modelling and simulation methodical approach enabling managers' work to become more efficient (Bureš & Racz, 2016). Based on the example of the nuclear power plant disaster above, a tsunami wave is used as a selected example. The reason for this choice is also the possibility of describing all relationships between elements that have clearly defined relationships (hard systems) and elements for which the exact definition of relationships is complicated (soft systems). The goal is achieved by developing and presenting a model containing selected modules enabling decision making associated with EM activities and processes, which are mitigation, preparedness, response and recovery (Haddow & Haddow, 2014). In general, systems are modelled and investigated using many different methodologies, which can be divided into three groups: traditional statistical methods, artificial intelligence methods and simulation methods (Huang et al., 2021). The choice of method depends on the nature of the given problem. Traditional methods include, for example, experience-based analysis, time series analysis, a model based on fuzzy theory, or a Bayesian network. Artificial intelligence methods use learning mechanisms that learn from historical data and situations or neural network-based mechanisms. These methods provide a more accurate and comprehensive description of the system. Simulation methods are a very effective tool for displaying the complexity of the emergency system. When creating simulation models, we encounter many problems that affect several areas, such as geology, economics, transport or infrastructure, and all these areas need to be considered. These methods include simulations based on physical phenomena or multi-agent simulations (Bureš & Tučník, 2014; Lee et al., 2022). Based on searches using the keywords Tsunami, Influence, Economy and System Dynamics, relevant papers were identified in the databases of Scopus, Science direct, and SpringerLink, which were then analyzed to identify the critical variables needed to create a causal-loop diagram (CLD) and stock -and - flow diagram (SFD). The Stella Professional application was used for this purpose. The creation of the model and its simulation respected the methodological procedure emphasizing the principles and the order of creating these diagrams and the implementation of subsequent analyzes (Barlas, 2018). The time unit was determined to be one hour, representing a compromise between the speed of the disaster and the speed of reaction and implementation of corrective actions.

## 3. Model Development

The qualitative modelling based on creating a CLD diagram was the first step. The main variables that emerged as the most important in the primary literature search were listed. Iteratively, the variables were modified and expanded into the final form of the diagram.

The CLD diagram is based on the following reasoning. An earthquake under the sea causes a wave and increases its volume and, subsequently, the height of the wave. Due to its height, the wave spreads to the coast and affects the residents, buildings and other assets of the company. The larger the affected area, the more people will be injured, lives lost, property damaged and the damage caused in general. After a disaster strikes, it is common to activate financial flows. The larger and more destructive the disaster, the more money must be allocated. This money is then invested in materials, supplies and post-disaster repairs. Recovery can also be financed, for example, by state authorities in the form of subsidies. The second step was transforming the CLD into an SFD diagram, which enabled quantification and subsequent simulation. As part of this step, the following modules were identified: The formation of the Tsunami (hereafter Tsunami), People, Buildings, Infrastructure, Finance and Environment.

The formation of the Tsunami module represents the only part of the model that does not relate to the company's own environment and is considered a fully exogenous variable. But its creation was necessary for the purposes of a meaningful wave simulation. For the sake of simplicity, only earthquakes are considered the cause of tsunamis. Similarly, the Environment module is perceived as an additional one not directly related to business problems (except for cases of a specific type of enterprises dependent on the surrounding environment such as agriculture, mining etc. The interconnection of the modules can be seen in Figure 1.

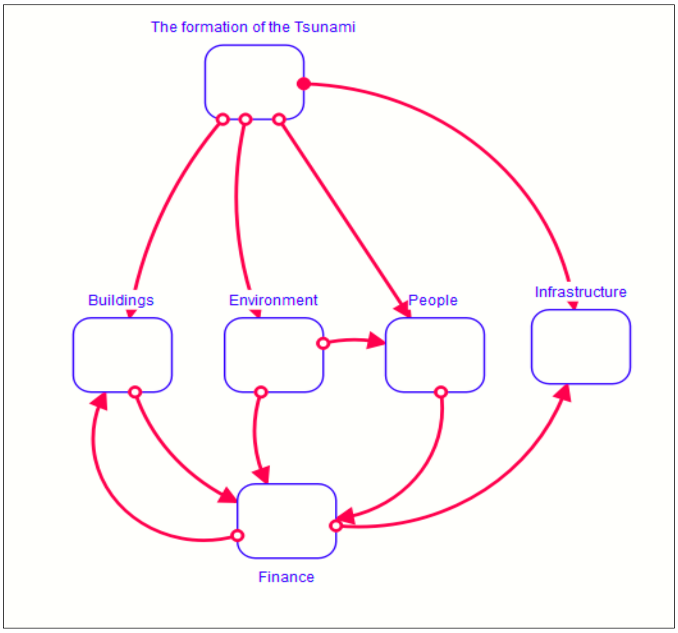


Figure 1. Structure of modules

Table 1 presents the content of the individual modules with a focus on stocks, existing arrays, essential converters and sources from which the creation of the individual diagrams in the modules was based on.

Figure 2 below is used for demonstration purposes only as it provides an example of SFD diagram in the People module. Interlinking with Tsunami and Environment modules from Figure 1 is ensured by the converters Flow velocity of the run-up and Contaminated Water.

Table 1. Model elements

| Modules | Stocks | Arrays | Key Converters | Resources |
|---|---|---|---|---|
| The formation of the tsunami | Wave amplitude | N/A | Wave height; Phase velocity of the wave; Distance to shore; Wave run-up; Flow velocity of the run-up; Maximum run-up height; Inclination of the coast; Inundation distance | Röbke & Vött (2017); Smart et al. (2016); Thran et al. (2021) |
| People | Population; Affected population; Injured people; Unharmed people; Dead people; Rescuers; Paramedics in the area; All available paramedics | N/A | Rate of impact; Population density in the area; Share of paramedics; Injury rate; Mortality rate; Cure rate | Takabatake, Esteban, & Shibayama (2022); Chiu et al. (2020) |
| Buildings | Buildings; Damaged buildings; Destroyed buildings; Repaired buildings | Types of buildings:<br>Sheet metal and wood buildings, Brick buildings, Larger reinforced brick buildings, Buildings with unreinforced concrete structures, Buildings with a reinforced concrete structure<br>Types of damage:<br>Slight damage, Medium damage, Severe damage, Very severe damage of construction | Average level of damage; Average level of destruction; Intensity of destruction; Rate of destruction | Ghobarah et al. (2006); Rossetto et al. (2007); Leone et al. (2011) |
| Infrastructure | Communications; Destroyed communications; Repaired communications; Water pipes; Destroyed water pipes; Power cables; Destroyed power cables; New columns and cables | Types of communications:<br>Roads, Railways<br>Types of water pipes:<br>Plastic, Copper, Steel<br>Columns:<br>Material – Wooden, Concrete, Metal<br>Height:<br><5m, 5-10m, 10m< | Destructiveness | Ghobarah et al. (2006); Leone et al. (2011) |
| Finance | Available financial resources; Costs of damage; Finance allocated; Financial support | Finance allocation:<br>Food, Infrastructure recovery, Water, Healthcare, Shelter, Defensive elements | Value of damage; Subsidies; Number of contributors | Heger & Neumayer (2019); The Guardian (2014) |
| Environment | Dead animals; Contaminated water; Destroyed coastal and sea life; Waste in the sea | Vegetation:<br>Coral reefs, Marine plants, Mangrove forests, Coastal vegetation<br>Waste in the sea:<br>General waste, Soil, Debris | Mortality from dehydration; Length of the coast | Srinivas & Nakagawa (2008); Thanawood et al. (2006) |

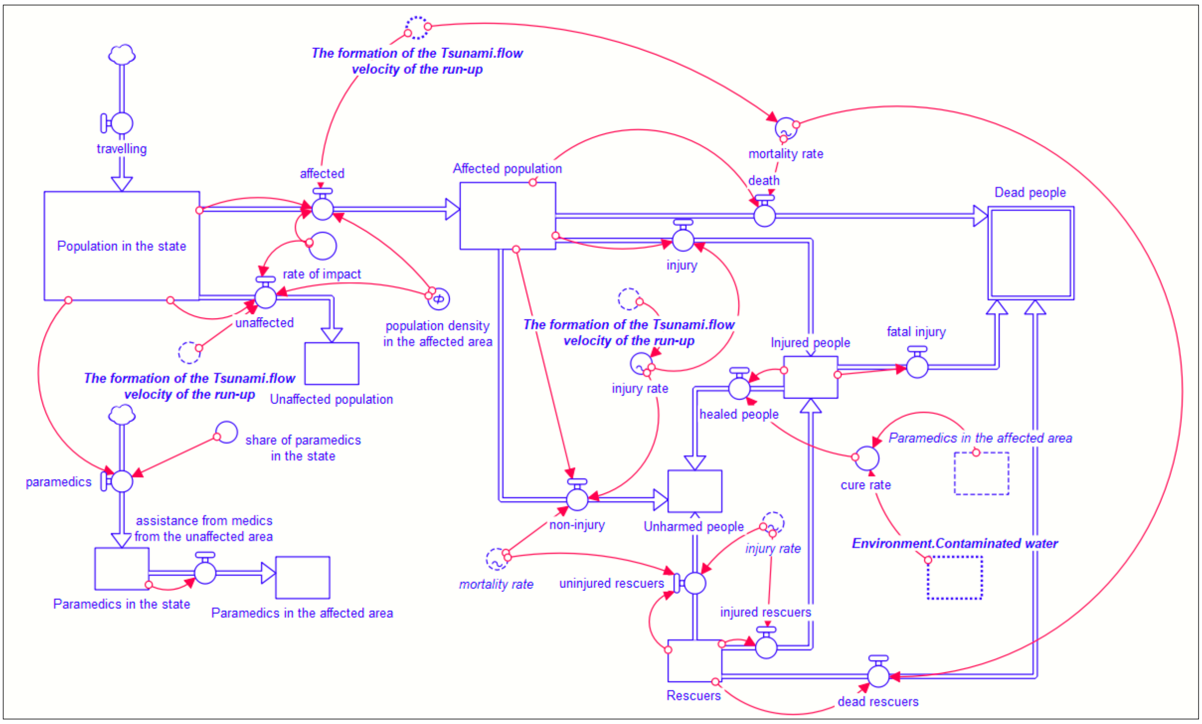


Figure 2. People module

## 4. Simulation

Although not a corporate sector, the validation of the model is based on the existence of the tsunami in the Indian Ocean in the region of Indonesia, which took place in 2004. However, there are variables; for instance, in the Environment module, for which the values from the actual situation in the Indian Ocean are not recorded. In these cases, it is impossible to check whether the simulation results correspond to the actual situation.

Nevertheless, the Environment module is not the most significant one. For the People module, there are recorded statistics regarding the casualties and injured people due to the wave impact. In this case, the model's simulation results can be compared with the actual data. The simulation results of the model in Figure 3 correspond to the real data. For example, the model shows that roughly 24,000 people died from the affected section examined in the model, which roughly corresponds to the real data.

The next module focuses on Buildings in the impacted area. In Figure 3, only buildings with slight damage are presented because if all possible combinations of buildings and damage types were in the figure, it would become unreadable and messy. It is possible to see here that the most damaged buildings are from ordinary buildings made of wood and metal, and the fewest are from the group with reinforced construction. We can also find out that the buildings are destroyed only in the first few hours. After about a day, the value of some groups of buildings will start to decrease as they start to be repaired, but these are the most common buildings and the repairs will also be temporary.

The behavior of the Infrastructure module in time is captured in Figure 4, where the most critical outputs are the values related to destroyed roads, water pipes and power cables, or more precisely, the poles on which these cables hang. As seen in Figure 4, the communication

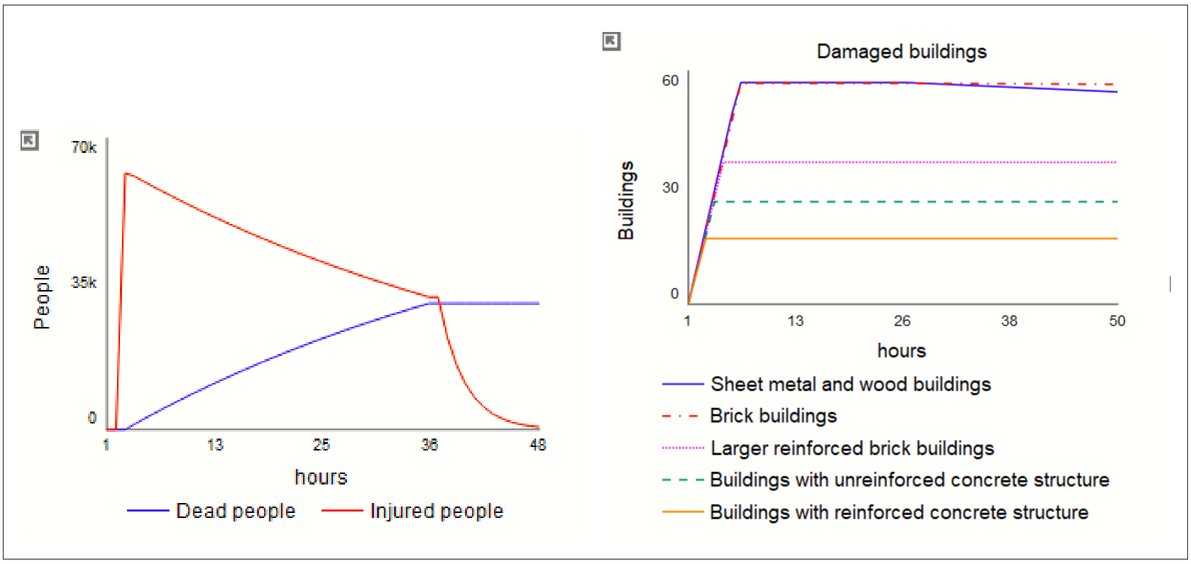


Figure 3. Simulation in the People and Buildings module

will be damaged within the first few hours. Still, it is clear that, when the wave goes away, the repairs (minimum repairs needed to make the communication usable again) will happen quickly. Furthermore, power cables on low and wooden poles will be destroyed the most, while the least damage will occur on high metal poles. We can also find out that the poles with electric cables started to be repaired slowly, but only the low and wooden ones. For water pipes, the plastic ones are the most destroyed and the metal ones are the most durable.

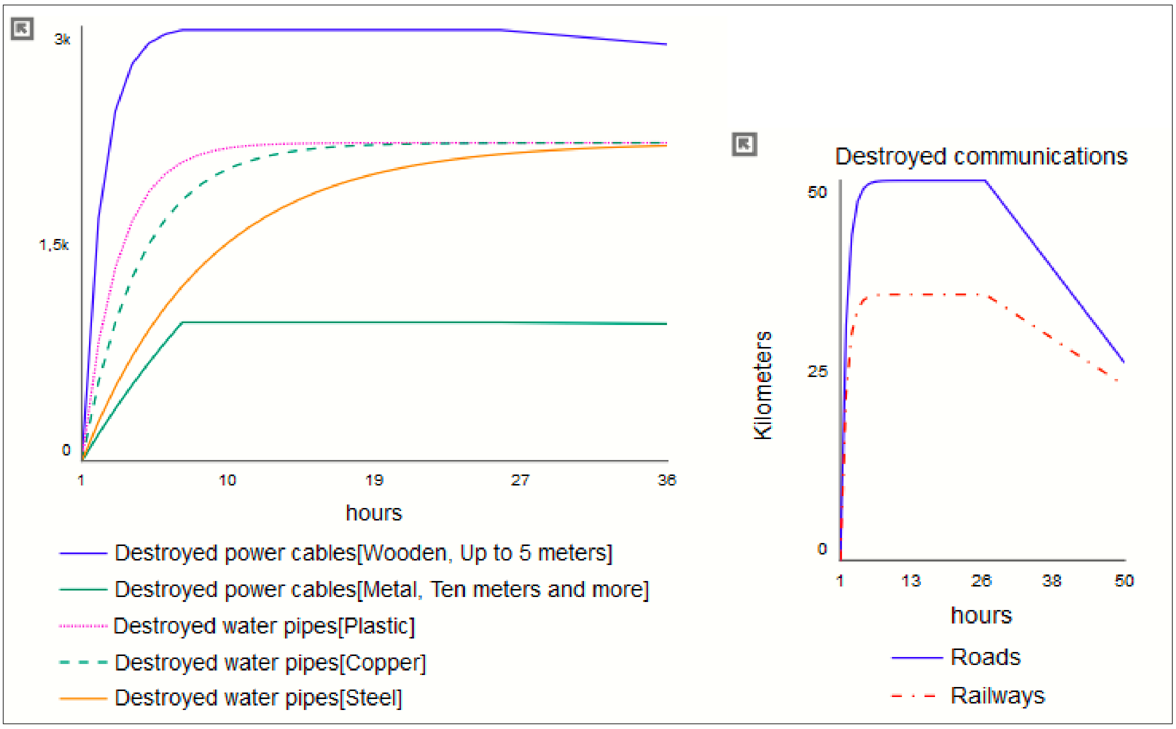


Figure 4. Simulation in the Infrastructure module – Communication and Infrastructure

## 5. Sensitivity Analysis and Robustness Test

The most significant variables for the sensitivity analysis can be identified mainly in the Tsunami module, as this module is the source of the whole event and dramatically influences the other modules. However, for the purpose of the sensitivity analysis, the Inclination of the module water surface converter from the Tsunami module and the Population density converter from the People module were identified.

The values of the variable Inclination of the water surface show that if the slope of the water surface increases even slightly, then the wave onset speed will be much higher, affecting the impact rate in the area and the mortality rate. From the provided example, it is possible to find out that after increasing the slope of the water surface from 0.00021025 to 0.0004 radians, casualties increase by 10,000 people. Due to the interconnectedness of the model, this also has a secondary effect on the Finance module, because the more casualties, the more finance resources will be allocated to the affected area. Population density represents another variable to which the model is sensitive. This is quite obvious because the higher the population density in the affected area, the more dead and injured will be. In the validation example, when the population density increases from 0.116 people/m$^2$ to 0.5 people/m$^2$, the number of disaster victims increases by 5,000.

We can look for the most suitable variables for the robustness test in the Tsunami module again. The goal of this test is to prove that the model works as expected under extreme conditions. The simulation of the model will not take place at all, for example, if the Inundation depth is zero, because at that moment, the tsunami wave did not occur at all, and there will be no casualties or injuries. Another example where the model will not work is when the Tsunami starts at a depth of 200 (variable Water depth). In this case, the place of the source of the tsunami would be too close to the coast and there would not be enough space to gain height and speed. All settings of the robustness test support the validity of the model.

## 6. Conclusions

This work emphasizes the need for the development of emergency management and, above all, the possibility of application of simulation models employing system dynamics methodology. Although the model replicates historical data, it does not mean that the model could not be created in another way. In fact, the model has to be considered immature and able to provide initial demonstrations. For example, one of the possibilities for further development is the linking of the Tsunami module and other modules using the Imammura variable Lida magnitude scale, described in the relevant literature. Another possible extension could be to create a module focused on defence mechanisms and tools. Each organization has different conditions, the spatial layout of buildings, the concentration of workers in different premises or financial possibilities to implement existing ways to slow down the tsunami wave and thus reduce the subsequent loss of life and damage. Conditions are already prepared for this module that considers finances, namely at the level where finances are allocated into particular areas. One of the areas where the money can be spent is implementing defence elements. This statement can, of course, be generalized to any type of disaster, not just the example of tsunamis. If the model is extended in this way, it could serve as a tool for EM in preparing for a disaster. It would be possible to determine which types of defense tools are the best solution for a given area and, at the same time, to which extent it must be implemented. An extension can also consist of connecting to automated data processing or analytical tools that are commonly used in other areas, e.g. reporting tools or ambient intelligence and smart environment methods and technologies (Mikulecký et al., 2011) or developing easily searchable and properly organized corporate web pages (Bartuskova & Soukal, 2016) presenting related information to all employees in the organization. However, this path of development is strongly associated with technological readiness and ICT investments (Svobodova & Hedvicakova, 2017). Finally, an extension of the source module with other types of tsunamis, such as meteotsunami, would be beneficial. The existence of elements for which the end state of the simulation is not determined represents one of the existing shortcomings of the model. In other words, the simulation of the given element continues, but after some time, the values no longer correspond to reality. Therefore, it is significant to consider how long we set the simulation time. Overall, in each module, it is essential to set the simulation time to suit the module, as the results are visible after a different period of time each time. For example, when a wave strikes, we see the value of injured people right away, but the value of repaired buildings will be apparent only after a long time. One of the possible solutions could be based on the separation of modules into separated modules providing data which can be exported to a model with longer simulation time periods. Furthermore, values of various variables have to be estimated as actual data are not available. However, it is anticipated that data would be at hand in case of implementation in particular organizations.

The model shows the effects of a disaster on an organization's life in the affected area. Therefore, it could be used as a helpful tool for the crisis manager in all phases of the emergency situation, i.e. preparation and prevention, response and subsequently in dealing with the consequences of a disaster that has already taken place, specifically for the distribution of resources and aftermath. It can support managers in making complex and significant decisions in emergency situations.

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Conflict of interest: none.

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