Conceptual Model for Managing Sources of Danger in the Event of an Earthquake

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Abstract

Safety is defined as a state in which human activities are conducted in such a way that the realization of potential dangers is excluded with a certain probability. However, there is an established axiom: all human activities inherently carry some degree of danger. The criterion for assessing this danger is risk, which provides a quantitative measure of potential threats. Experience has shown that the previous concept of safety, which sought to eliminate all risks entirely (known as the "zero risk" concept), is not practical. Today, the prevailing safety approach is the concept of justified risk—the idea that certain levels of risk are deemed acceptable, based on current economic capabilities and social conditions, for the average citizen. This study presents the development of a conceptual model—a model of communication channels—created through system analysis. This model captures the dynamics of information flows regarding the status of danger sources within a potential earthquake zone. The conceptual model is composed of functional operators: B1, B2, B3, B4, B5, B6, and B7. One key area of this research is the mathematical modeling of emergencies and the forecasting of their potential consequences. Such modeling is crucial for enhancing the effectiveness of protective measures and improving disaster response strategies.

Keywords: Conceptual model; earthquake; Risk evaluation; Seismic risk; Urban risk.

1. Introduction

For management purposes, risk can be defined as the potential outcomes, encompassing economic, social, and environmental dimensions, that may arise from hazardous events within a specified timeframe. Historically, risk has often been addressed in a fragmented manner, with each scientific discipline contributing its own definition (Cardona, 2004). Over the past few decades, various methodologies for risk evaluation have emerged, expanding upon the concept of disaster risk initially established by UNDRO (1980). A comprehensive understanding of risk requires a multi-dimensional approach that goes beyond assessing physical damage, casualties, or financial losses (primary impacts). It must also account for societal vulnerabilities and lack of resilience, which contribute to secondary consequences (indirect impacts) when a seismic event occurs in an urban area (Cardona & Hurtado, 2000; Masure, 2003; Carreño et al., 2007a, b).

Traditionally, risk has been predominantly evaluated in physical terms due to the challenge of quantifying social vulnerability. However, it is possible to analyze vulnerability relatively, through indicators and indices, enabling the concept of "relative risk." This approach informs decision-making and helps prioritize prevention and mitigation measures. Risk indices should incorporate both physical risk factors and non-physical factors such as economic capacity, the population's ability to self-protect, social structures, levels of organization, and governance (Cardona et al., 2003).

Several methods exist for integrating data and modeling both risk and vulnerability. Approaches based on fuzzy logic and expert systems offer the advantage of assigning quantitative values. A comprehensive risk assessment, which includes geophysical, structural, economic, social, and institutional variables, is referred to as a holistic or integral approach. This method addresses all aspects of risk, including potential physical damage scenarios, which result from the interaction between hazards and the physical vulnerability of buildings and infrastructure.

The holistic approach to risk assessment may be debated when viewed through narrow, specialized lenses. However, given the complexities of socio-technical systems required to model urban risk, it is preferable to provide an approximate solution to a well-framed problem rather than a precise solution to a poorly formulated one. The uncertainty inherent in a holistic approach is generally preferable to the narrow precision often associated with reductionist views (Cardona, 2001).

In conclusion, while both reductionist and holistic approaches have their merits, the latter is more suitable for the context of urban risk management. The goal of such analyses is to promote comprehensive risk management, taking into account not only physical vulnerability but also vulnerabilities in areas like urban planning, education, and emergency preparedness.

Cardona (2001) developed a conceptual framework and model for comprehensive urban risk analysis, taking a holistic view of seismic risk by employing indices. This model includes both "hard" (physical) and "soft" (socio-economic) risk factors, such as exposure, the socio-economic characteristics of different neighborhoods, and their resilience. The primary objective of this model is to aid in decision-making by identifying critical areas in the city and evaluating their vulnerabilities across various professional disciplines. The model relies on a relative normalization of indicators to ensure a standardized basis for comparison.

Carreño (2006) proposed an alternative approach to urban risk evaluation, building on the foundations of Cardona's model (Cardona, 2001; Barbat & Cardona, 2003). This method uses composite indicators or indices to evaluate urban risk, particularly focusing on the physical risk index for each unit of analysis based on expected building and infrastructure damage (Carreño et al., 2007a). Carreño's method enhances the normalization process and calculates risk indices in an absolute manner, allowing for risk comparisons between different urban centers. Exposure and seismic hazard are now integrated into the calculation of physical risk, while population density, once considered an exposure variable in Cardona's model, has been repurposed as an indicator of social fragility. This method continues to use indicators, fuzzy sets, and membership functions, as originally proposed by Cardona (2001), though with certain refinements. Some descriptors are normalized relative to population size rather than the area of study (Carreño et al., 2007a).

Marulanda et al. (2009) evaluated the robustness of the methodology proposed by Carreño (2006) and Carreño et al. (2007a). In addition, this paper proposes an alternative method that utilizes fuzzy set theory, offering greater flexibility for situations where data is incomplete or unavailable. This approach preserves the conceptual framework of earlier methodologies while providing greater adaptability in handling data limitations.

2. Results and Discussion

The conceptual model represents a system of communication channels developed through system analysis, which reflects the dynamics of information flows related to the state of danger sources within a potential earthquake zone. This model is composed of several functional operators, designated as B1, B2, B3, B4, B5, B6, and B7.

Operator B1 outlines the procedure for collecting and analyzing information about a production facility and its surrounding industrial area located within an earthquake zone. This involves the identification of vulnerable components of the facility, assessing the structural integrity, and determining potential risks posed by seismic activity. The operator also specifies methods for gathering real-time data from sensors, monitoring seismic activity, and analyzing the potential impact on the facility's operations and safety.

$$B_1 : T \times X \times \Pi \times \theta_1 \rightarrow U_1$$

The conceptual model includes the following key elements:

T: A set representing the operating time of the operators, which refers to the duration or schedule under which the system functions and monitors.

X: A set that defines the state of the sources of danger, characterizing the current condition and potential hazards within the monitored area.

Π: Represents the monitoring regulations, outlining the procedures and protocols for observing and assessing the facility and industrial territory.

Staff errors: This element accounts for human errors, which may influence the effectiveness of monitoring and response actions.

U1: Generalized characteristics of the state of danger sources at the production facility and industrial territory, providing a summarized view of the risks posed by the environment.

Operator B2 is responsible for generating a forecast of the technical safety of the production facility and industrial territory in the earthquake zone. This involves using the data gathered by Operator B1 to predict how seismic activity could affect the facility’s integrity and operational safety. The forecast includes:

Anticipating potential structural damage.

Estimating the likelihood of hazardous material releases or other critical failures.

Assessing how well current safety measures and protocols (Π) will perform under earthquake conditions.

$$B_2 : T \times U_1 \times K_2 \times \psi \times \theta_2 \rightarrow U_2$$

In the conceptual model, additional elements are defined as:

K2: Represents the criteria and restrictions for monitoring a production facility and industrial area. This includes regulatory standards, safety thresholds, and operational limitations that must be adhered to during monitoring.

Forecast horizon: Refers to the time period over which the forecast is made. It defines how far into the future the predictions about the facility's safety and operational status are extended.

Forecast errors: This accounts for uncertainties and inaccuracies in the predictions, considering the limitations of the data or model used for forecasting.

U2: Describes the state of technical safety of the production facility and industrial territory within the earthquake zone for the specified forecast horizon. It provides an updated assessment of the facility’s condition based on the forecast and potential risks.

Operator B3 is responsible for generating management decisions:

$$B_3 : T \times U_1 \times U_2 \times K_3 \times \psi \times \theta_3 \rightarrow U$$

K3: Represents the limitations in making managerial decisions. These could include resource constraints, regulatory requirements, technical limitations, or external factors that restrict the range of possible actions.

Mistakes in making managerial decisions: Refers to potential errors or misjudgments in the decision-making process, which could arise from incomplete information, human factors, or incorrect interpretation of data.

U: Denotes the actual management decisions that are made. These decisions aim to mitigate risk, improve safety, and ensure the operational stability of the production facility and industrial area in the earthquake zone.

Operator B4 is responsible for describing the forecast of the state of the production facility and industrial area within the earthquake zone after the management decision (U) has been made and implemented. This operator assesses the potential impact of the decision on the facility's safety and operational stability, based on the following aspects:

$$B_4 : T \times U \times X \ \times \psi \ \times \theta_4 \rightarrow P$$

Θ_4- staff errors;

P – represents the state of the production facility and industrial territory after the implementation of a management decision, evaluated over the selected forecast horizon. This reflects the condition of the facility following the actions taken to mitigate risks in the earthquake zone.

Operator B5 is responsible for conducting the assessment of the forecast of the facility's and industrial area's state within the earthquake zone. This operator evaluates how accurately the predicted outcomes (from Operator B4) align with the actual state (R) after the management decision has been implemented:

$$B_5 : T \times P \times U_2 \times \psi \ \times \theta_5 \rightarrow M$$

Θ_5- Errors in the analysis of the situation refer to potential inaccuracies or misjudgments during the assessment of the facility’s condition and the forecast of risks. These errors can result from incomplete data, incorrect assumptions, or unforeseen variables that affect the reliability of the analysis and subsequent decision-making.

M represents the characteristics and assessment of the forecast of the state of the production facility and industrial territory in the earthquake zone. This includes a detailed evaluation of the forecasted outcomes, considering both the accuracy of the predictions and the effectiveness of the management decisions made to mitigate risks.

Operator B6 is responsible for conducting the safety assessment of the production facility and industrial area within the earthquake zone. This operator evaluates the overall safety and resilience of the facility and surrounding area after the implementation of management decisions, using the results of the previous operators and forecasts.

$$B_6 : T \times U \times P \times M \times \psi \ \times \theta_6 \rightarrow B$$

θ_6 - errors in risk assessment;

C – safety assessment at the production facility and industrial territory;

Operator B7 describes the procedure for forming a management decision, taking into account the safety assessment at this production facility in the earthquake zone:

$$B_7 : T \times P \times M \times B \times \psi \ \times \theta_7 \rightarrow U'$$

θ_7 - mistakes in making managerial decisions;

U' – management decision;

In a comprehensive risk assessment using indices, the determination of risk outcomes involves integrating various contextual factors, such as socio-economic fragility and lack of resilience, which can significantly amplify physical risks. These factors contribute to a more nuanced understanding of the overall risk landscape, as they highlight the vulnerabilities that exacerbate the direct physical impacts of hazards like earthquakes.

To effectively implement this approach, it is crucial to collect and analyze input data on these socio-economic and resilience-related conditions at the urban level. This data allows for a detailed assessment of how a city's socio-economic structures, governance, infrastructure, and population dynamics might influence its ability to withstand and recover from a disaster.

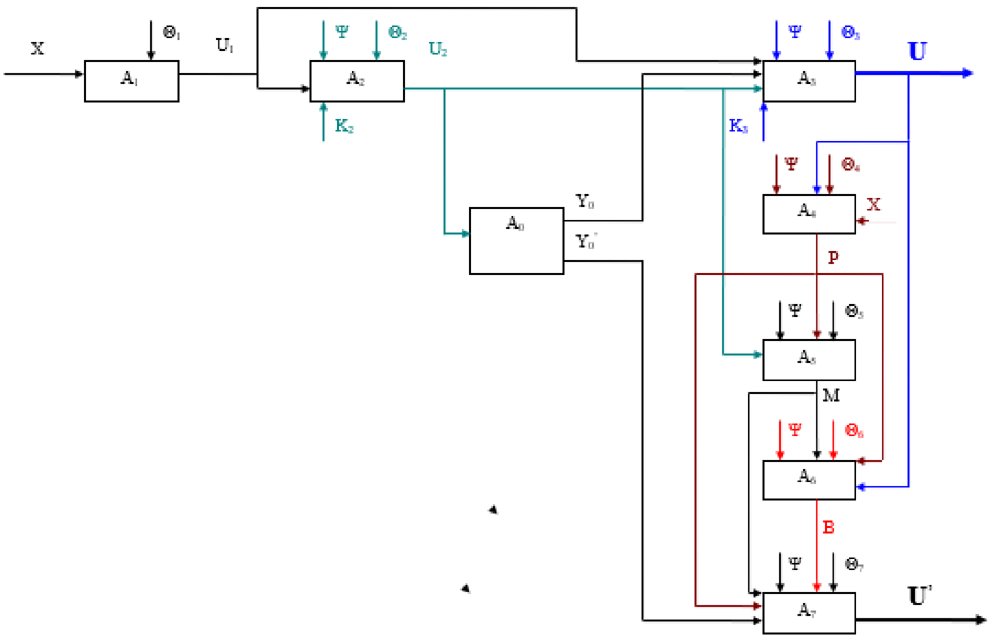

Figure 1. is a diagram of a conceptual model for managing sources of danger.

Operator B1: This operator manages the collection and analysis of information regarding the state of a production facility and the surrounding industrial area in a potential earthquake zone. It considers factors such as time (T), the state of danger sources (X), monitoring regulations (N), and personnel errors (E). The outcome is a generalized assessment of the hazard sources' condition (U1) in these locations.

Operator B2: This operator handles the forecasting of the technical safety of the production facility and the industrial area in the earthquake zone. It takes into account monitoring criteria and limitations (K2), the forecast horizon, potential forecast errors, and provides the predicted state of technical safety (U2) for the selected forecast period.

Operator B3: This operator is responsible for forming management decisions. It factors in decision-making limitations (K3), potential errors in decision-making, and ultimately issues the management decisions (U).

Operator B4: After management decisions have been made, this operator forecasts the state of the production facility and the surrounding area in the earthquake zone. It considers staff errors (Θ4) and the state of the facility (P) after implementing the decisions for the chosen forecast horizon.

Operator B5: This operator evaluates the forecasted condition of the production facility and industrial area in the earthquake zone. It accounts for errors in situation analysis (Θ5) and provides a characterization and assessment (M) of the forecast.

Operator B6: This operator is tasked with evaluating the safety of the production facility and industrial area within the earthquake zone. It considers errors in risk assessment (Θ6) and delivers a safety assessment (B).

Operator B7: This operator describes the process of formulating a final management decision based on the safety assessment at the production facility within the earthquake zone. It considers errors in decision-making (Θ7) and issues the final management decision (U').

This conceptual model allows for the systematization of information and processes involved in risk management within earthquake-prone areas. Each operator fulfills a distinct role, considering various aspects such as monitoring, forecasting, decision-making, and safety evaluation. The model offers a structured approach to enhance the effectiveness of risk management, ensuring that all key factors are accounted for, and that decisions are based on comprehensive and updated information.

3. Conclusions

A simplified conceptual model for managing earthquake-related risks is proposed, utilizing parametric variables to capture different dimensions of risk. The model is designed to be highly adaptable and practical, leveraging fuzzy sets to allow for flexible adjustments and alternative configurations. By focusing on physical factors, it constructs a physical risk index, which is based on seismic scenarios and measures physical damage (direct effects). Additionally, another index is developed to assess indirect effects, which are influenced by social fragility and lack of resilience in the exposed elements.

The application of fuzzy sets proves particularly useful when complete data is unavailable, allowing expert opinions to fill in gaps. This innovative fuzzy model for holistic risk assessment simplifies integrated risk management and enhances decision-making for stakeholders involved in risk mitigation.

The case studies illustrate the calculation of aggravating coefficients, which identify key factors that significantly impact the results. These coefficients offer valuable insights for prioritizing measures to improve socio-economic conditions in the studied areas. Notably, identical weights and aggravation coefficients are applied in both cases, though for different underlying reasons.

Future research could explore variations in membership functions and variable weights, though the results may not vary significantly, given that they are rooted in the transformation functions of the original methodology.

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