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A fuzzy accident risk analysis approach for a concurrent engineering platform

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Abstract. This paper uses the fuzzy theory basics to assess accident risk that may damage a target (e.g., humans, assets, or the environment). Converting a target's position to a membership degree in a fuzzy danger zone (FDZ) helps calculate risk indices. Using FDZs normalizes the effects of different kinds of hazards, similarly visualizes them, and distinguishes the impact of a threat on various types of targets. This paper presents a related mathematical formulation. The proposed approach evaluates the accident risks by simulating industrial activities in CAD, virtual reality, and augmented reality when using a concurrent engineering platform. This approach can calculate the risk index during a human task simulation and through real-time human interaction with a virtual machine during safety analysis and training. The results also are credible to activate alarm systems according to the operator's limbs place during work. The model provides a normalized and similar scale for various risks (e.g., biological, chemical, and physical hazards) and computes the effect of danger on different target types.

Keywords: Risk analysis, concurrent engineering, fuzzy logic, virtual reality, augmented reality.

1 Introduction

Using the three digital prototypes in CAD, virtual reality, and augmented reality creates realistic visualizations, renderings, and animations of the complex systems. It plays an essential role in concurrent engineering platforms, where various disciplines use these models to predict industrial systems' behavior before constructing and employing them. The conventional risk analyses approaches are inconvenient for using these models to perform quantitative risk analyses. This research develops a fuzzy approach for doing risk analysis in a concurrent engineering context by using geometric shapes for facilitating collaboration and sharing risks information by visualizing the risk entities and preventing inconsistencies.

2 Background

Dangers are the potential of things or situations to cause harm, and "risk" is an indicator for evaluating their importance by aggregating the severity and the likelihood of their possible consequences [1], [2]. A danger creates hazards (e.g., a toxic substance that makes a toxification hazard). A danger zone (DZ) is a hypothetical area where the threat can potentially cause harm [3]. The hazard magnitude denotes the parameters to explain the potential of the hazard for harming the target. It is the value of physicals (e.g., speed and temperature), chemical (e.g., the amount and density of one or several hazardous materials), biological or conceptual parameters (e.g., the probability or risk of an accident). Figure 1 shows the hazard magnitude variation around a hypothetical hazard object indicated by a red star. The horizontal axis (x -axis) represents the locations around the danger source, and the vertical axis shows the intensity of the danger in its neighborhoods. The dashed line in this figure shows the hazard magnitude variation as a mathematical function of the one-dimensional geometric coordinates. In this figure, the traditional danger zone is shown with a red line and includes every point where the assumed intensity of the danger is more than an acceptable level (H).

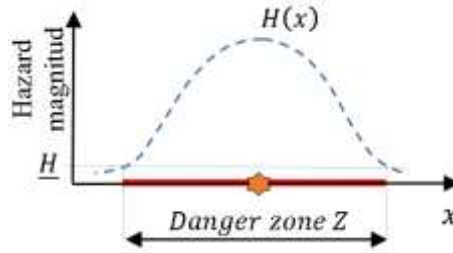


Fig 1. Representation of a mono-dimensional DZ, as a classic set of points

Some examples of hazard amplitude are the intensity of hazardous radiation around a radioactive material, the high-temperature air around a fire source, the explosion blast wave, or the toxic gas concentration during a poisonous gas leak. It can even be an understanding of the concept of collision risk around a dangerous moving object. In this way, a conventional DZ is a crisp (classic) set of points in the workplace, illustrated as follows:

$$Z = \{x | H(x) > \underline{H}\} \quad x \in X \quad (1)$$

3 The literature review

This chapter introduces the basic concepts and a review of previous applications of 3D models in risk analysis.

Bernard and Hasan considered a danger zone as one of the workplace entities, characterized by its name and origin [4]. Hasan and et al. considered DZ one of the system's safety modeling entities described by its name, nature, size, and source [5]. Pouliquen and et al. use it for estimating the severity of danger, in real-time, in the

virtual reality context for a sheet-pressing operation [6]. In recent years, very little research has been done on risk analysis in 3D using the concept of a danger zone. Alba and et al. proposed a distributed real-time anti-collision approach that uses hazardous areas to create the ability to prevent collisions with other objects on the robot, based on accurate 3D simulation of a manufacturing cell [7]. Yi-Hao and Yet-Pole construct a three-dimensional fire risk analysis technique for common building fires by simulating the thermal radiation hazards [8]. Cao and et al. studied flame propagation behaviors in explosion venting and the quantitative relationship of the maximum flame front length, and they calculated the variation of the temperature field in explosion venting [8].

4 The proposed model

According to fuzzy set theory, not only can an object be inside or outside a set, but it can also have a degree of membership.

By assigning membership between 0 and 1 to each point, Shahrokhi and Bernard introduce a "fuzzy space" to distribute risk around a hazard factor [10]. It explains how each location has a degree of belonging to the fuzzy danger set. Shahrokhi and Bernard measured instantaneous risk indices for each body part for simulation sequences by measuring body parts' membership in a Gaussian FDZ [11].

4.1 The proposed model description

This paper proposes a mathematical risk analysis model using the concept of a fuzzy danger zone to consider several types of targets with a different values. The effects of hazards vary on the different types of targets.

The proposed model is developed based on the following assumptions:

1. There is a dangerous source that produces a hazard.
2. A hazard barrier reduces some part of the hazard magnitude.
3. There are several types of targets.
4. The hazard has different effects on different kinds of targets.
5. There is a danger zone for each type of target.
6. Each target has a target protective barrier that reduces the danger for the target.
7. The exposure time is known and limited.
8. The exposure mode is known and similar for all target types.
9. The targets are immovable during the exposure time.
10. The hazard and target attributes are constant and unchanged over the exposure time.

4.2 The proposed model formulation

The model uses the following symbols:

| | |
|---------------|--|
| k | Target type index ($k \in K$) |
| J_k | Set of targets of type k |
| φ_k^h | The portion of the reduced hazard magnitude by the hazard safety barrier for the target type k |

| | |
|--------------------------------|---|
| φ_j^k | A fuzzy hedge describing the ability of the protective target barrier to reduce the magnitude of the hazard for the target t_j^k |
| t_j^k | Target j, (jth target) of target type k, ($k \in K, j \in J_k$) |
| $x_{t_j^k}$ | Coordinates of the jth target of target type k |
| X | Workplace universe of discourse |
| $H(x)$ | The magnitude of the hazard in point x |
| H_j^l | Maximum acceptable level of the hazard for target j |
| H_j^h | Minimum mortal (destructive) level of the hazard for target j |
| \tilde{Z}^k | Fuzzy danger zone produced by the hazard for the target type k |
| $\mu_{\tilde{Z}^k}^H(H(x))$ | The membership degree FDZ (Hazard severity), in point x, according to the hazard amplitude for target type k |
| $\mu_{\tilde{Z}^k}(x_{t_j^k})$ | Membership degree of presence of protected target j in the fuzzy danger zone \tilde{Z}^k , according to the target position (final hazard severity) |
| $d(\mu_{\tilde{Z}^k})$ | Target damage, the vulnerability function of the target of type k, which calculates the expected percentage target damage, based on $\mu_{\tilde{Z}^k}$ |
| $W_{t_j^k}$ | The value of the target t_j^k |
| $D_{t_j^k}(x_{t_j^k})$ | The value of damage (loss of the value) of the target t_j^k caused by accident, based on the target place |

By using fuzzy sets notifications, an FDZ is an ordinary fuzzy set such as \tilde{Z} , defined by its domain (x) and membership function $\mu_{\tilde{Z}}(x)$ as [12]:

$$\tilde{Z} = \int_x \frac{\mu_{\tilde{Z}}(x)}{x} \quad (2)$$

In this way, the value of the membership function $\mu_{\tilde{Z}}(x)$ is a continuous function that indicates the degree of membership of point x in a fuzzy set \tilde{Z} , which can take any value between 0 and 1, as follows:

$$\mu_{\tilde{Z}}: x \rightarrow [0,1] \quad x \in X \quad (3)$$

In the above formula, X is the universe of discourse of variable x. The classic DZ is a α -cut of the FDZ, as follows:

$$DZ = \{x | \mu_{\tilde{Z}}(x) > \alpha, x \in X\} \quad (4)$$

Fig. 2 shows how increasing the value of α from α_1 (Fig. 8 .a) to α_2 (Fig. 8 .b) leads to a decrease in the recognized area of the danger zone.

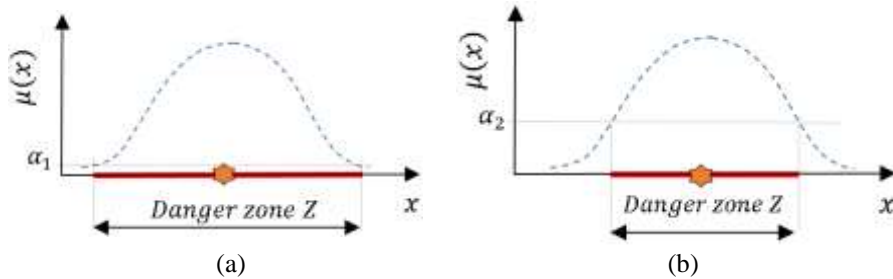


Fig 2. A demonstration of a mono-dimensional DZ, as an α -cuts of an FDZ

By considering attributes of the hazard and the target, $\mu_{Z^k}^H(H)$ assigns a danger membership degree to each hazard magnitude, for each target type k, as follows:

$$\mu_{Z^k}^H: H(x) \rightarrow [0,1] \quad \forall H(x) \in \mathbb{R}^+ \quad (5)$$

Fig. 3 shows a schematic diagram of the general form of the relationship between the degree of membership in the FDZ for target type k and the magnitude of the hazard.

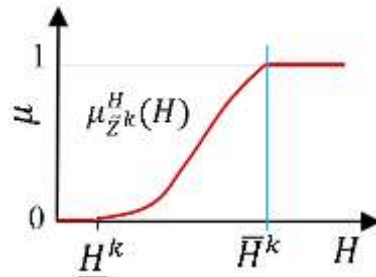


Fig 3. The relationship between the hazard magnitude and the membership degree of the FDZ for a specific target type

For example, table 1 illustrates the physiological tolerance time for various carbon dioxide concentrations (percent by Volume (% V/)) :

Table 1. Physiological tolerance time for different carbon dioxide concentration

| The concentration of Carbon Dioxide in Air (% V/V) ($H(x)$) | Maximum Exposure Limit (Minutes) |
|---|----------------------------------|
| 0.5 | Undefined |
| 1.0 | Undefined |
| 2.0 | 480 |
| 1.5 | 60 |
| 3.0 | 20 |
| 4.0 | 10 |
| 5.0 | 7 |
| 6.0 | 5 |
| 7.0 | Less than 3 |

Fig. 4 may present the relationship between the concentration of carbon dioxide in the air and the degree of membership in the FDZ for 10 minutes' exposure of target type k:

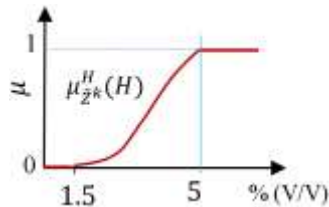


Fig 4. The degree of membership in the FDZ for the exemplified scenario

By changing the variable $\mu_{\tilde{Z}_j^k}(x_{t_j^k}) = \mu_{\tilde{Z}^k}^H(H(x_{t_j^k}))$, the result will be:

$$\mu_{\tilde{Z}_j^k}: (x_{t_j^k} \in X) \rightarrow [0,1] \quad \forall j \in J \quad (6)$$

Thus the following fuzzy set defines FDZ for the target t_j^k :

$$\tilde{Z}_j^k = \{(x, \mu) | x \in X, \mu = \mu_{\tilde{Z}_j^k}(x)\} \quad \forall k \in K, j \in J_k \quad (7)$$

For example, Fig. 5 shows an FDZ that assigns a membership degree to each point's coordinates in mono-dimensional space.

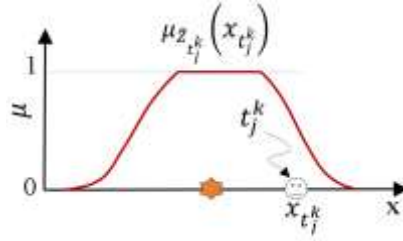


Fig 5. A demonstration of a fuzzy mono-dimensional DZ

Assigning 0 membership to a point means that the hazard magnitude is equal to or less than the maximum hazard acceptable level. Setting 1 to a place indicates that the danger for the target in that place is equal to or greater than a fatal or destructive threshold level. The effect of protective barriers describes their power to neutralize the danger as the proportion of reduction of the danger amplitude (φ). The values 0 and 1 for φ indicate an unprotected and a fully protected target, respectively. The values between 0 and 1 concern a protective barrier that diminishes some part of the hazard. Therefore, the FDZ for a protected target is defined as follows:

$$\mu_{\tilde{Z}_j^k}(x_{t_j^k}) = \begin{cases} 0, & (1 - \varphi_j^k)H(x_{t_j^k}) \leq \underline{H}_j^k \\ h_j\left((1 - \varphi_j^k)H(x_{t_j^k})\right), & \underline{H}_j^k < (1 - \varphi_j^k)H(x_{t_j^k}) \leq \bar{H}_j^k \\ 1, & (1 - \varphi_j^k)H(x_{t_j^k}) \geq \bar{H}_j^k \end{cases} \quad (8)$$

Where $h_j(H)$ maps the hazard magnitude (or other hazard attributes) to its harmfulness for the protected target on a scale between 0 and 1.

If it would be possible to define target vulnerability function $d(\mu_{\tilde{Z}_j^k})$ for calculating the expected damage, based on $\mu_{\tilde{Z}_j^k}$, then, by defining function D as follows, we can directly estimate the target damage based on the target location:

$$D_{t_j^k}(x_{t_j^k}) = d\left(\varphi_j^k\left(\mu_{\tilde{Z}_j^k}(x_{t_j^k})\right)\right) \quad x_{t_j^k} \in X \quad (9)$$

Where φ_j^k apply the effect of the target barrier on the fuzzy danger zone.

4.3 Numerical example

Here, an accident scenario is presented in a one-dimensional workplace space to illustrate the model application. The objective is to assess the degree of inhalation damage of 4 targets of two types exposed to the toxic cloud of carbon dioxide for 10 minutes. Before the exposure, the ventilation system reduces 15% of the leaked gas concentration ($\varphi_k^h = 0.15$). The following table presents the CO₂ concentration in different workplace locations before and after ventilation operation.

Table 2. Reduction of the CO₂ concentration by using the hazard barrier, in the exemplified scenario

| Coordinates of the place(x) | $H(x)$ (percent by Volume) | |
|-----------------------------------|-----------------------------------|--------------------------|
| | Immediately after the accident | After air ventilation |
| | 4 | 8.05 |
| 5 | 6.9 | 6 |
| 8 | 5.75 | 5 |

Suppose two different types of targets exposing to high CO₂ concentrations. Table 3 illustrates the accident analysis process and results according to the exemplified scenario.

Table 3. The accident analysis process and results, according to the exemplified scenario

| Target t_j^k | Target type k | Target value (\$) $W_{t_j^k}$ | Target place $x_{t_j^k}$ | Hazard magnitude $H(x)$ | Hazard severity $\mu_{z_j^k}^H(H)$ | The target safety barrier effect of $\varphi_j^k(\mu)$ | Final hazard severity $\mu_{z_j^k}(x_{t_j^k})$ | Target vulnerability function (%) $d(\mu_{z_j^k})$ | Target damage | |
|-------------------|--------------------|-------------------------------------|-----------------------------|-------------------------------|--|---|--|---|------------------|--------------------|
| | | | | | | | | | (%) | Monetary unit |
| t_1^1 | 1 | 10^6 | 4 | 7 | 1 | $(\mu)^{1.2}$ | 1 | $100\mu_{z_1^1}$ | 100 | 10^6 |
| t_2^1 | | 10^8 | 5 | 6 | 0.9 | $(\mu)^{1.4}$ | 0.86 | $100\mu_{z_2^1}$ | 86 | 8.6×10^7 |
| t_1^2 | 2 | 10^6 | 5 | 6 | 0.9 | $(\mu)^2$ | 0.81 | $70\mu_{z_1^2}$ | 56.7 | 5.67×10^5 |
| t_2^2 | | 10^7 | 8 | 5 | 0.7 | $(\mu)^{1.5}$ | 0.59 | $70\mu_{z_2^2}$ | 41.3 | 4.13×10^6 |

5 Discussion and Limitations

This paper aims to integrate risk analysis into a 3D design platform based on using geometric profiles to illustrate the spatial risk distribution. Using an FDZ in a CAD model visualizes the normalizing effects of different kinds of hazards. For example,

while simulating a toxic spill accident, each FDZ gives a typical picture of a gradual decrease in the mass concentration as the cloud moves away from the epicenter of the evaporation, which can be compared with created FDZ from an explosion accident, at another point, at the same time. It can be applied to calculate the risk index during a human task simulation and through real-time human interaction with a virtual machine during safety analysis and training. The results also are credible to activate alarm systems according to the operator's limbs place during work. The use of fuzzy danger zone has the following advantages:

1. Visualize a representative danger zone in 3D platforms and calculate the membership degree in an FDZ as a hazard index using computerized calculation methods during a simulation.
2. Create a normalized and similar scale for various risks (e.g., biological, chemical, and physical hazards).
3. Compute the effect of danger on different types of targets.
4. Calculate a momentary risk index for each specific target (e.g., different human limbs) according to their type and location.

Also, the following limits the application of the model."

1. The model lacks validation.
2. Using this approach requires developing more complex risk analysis applications.
3. Model development requires a lot of data on the nature of risk, the effect of distance on reducing it, and the effect of risk on the various types of targets expressed by mathematical formulas.
4. The model ignores the effect of the time mode of exposure of the target to the danger.
5. The model assumes that the risk factor and a goal location remain constant during the exposure.
6. The model applies to hazards whose severity depends on the target distance from them.

More efforts are necessary to integrate complementary risk analysis methods such as FMEA and fault trees into CAD platforms. Supposing a linear effect of barrier on the hazard magnitude assumes that it neutralizes a part of the hazard. Using a more realistic function for the actual impact of the safety measures improves the model. This approach is only applicable to dangers with known spatial effects. The model supposes that danger zone attributes and the target location are fixed and recognized during the exposure. Further research can discuss combining the probability and fuzzy danger zone concepts and combining several FDZs.

6 Conclusion

This paper provides an overview of definitions of a DZ as an essential risk analysis concept. It supports applying the fuzzy set theory for modeling DZs as a meter of spatial danger variation. It presents a mathematical model to calculate a real-time risk index during three-dimensional simulations of activities. Using this approach helps perform the risk and design analyses concurrently and improves multidisciplinary

communication. Future research may consider the effects of multiple dangers, variations of the target exposure time and place.

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