Modelling and Prioritization of System Risks in Early Project Phases

Mohammad Rajabalinejad
Faculty of Engineering Technology, University of Twente, Enschede, the Netherlands
M.Rajabalinejad@utwente.nl

***Abstract*--The rising complexity of product and systems demands further attention to potential Risks. While researchers explore tools and methods to identify system risk, its prioritization remains a challenging task in a multi-stakeholder environment. Hazard is the source of risk and causes harm. Harm may have different degree of severity. Next to the degree of severity, frequency of its occurrence is relevant to risk. These are often hardly quantifiable. While the accurate quantification remains a challenge, a flexible and pluralistic approach can bring major risks on the top of list. This paper offers a methodology for ranking risks in early phases of design with presence of a high level of uncertainty. It uses a pluralistic approach for prioritization of hazards. It adapts probability theory to embed flexibly in communication with stakeholders and process the available information. A graphical tool facilitates this communication and probabilistically utilize available information about system hazards. It suggests the "degree of consensus" as a metric to rank the identified risks. This metric represents the consent of stakeholders on the system risks used for system architecture, design decisions, or alternative evaluations. The paper explains the mathematical formulation and presents an application example for this.**

Keywords - consensus; risk; severity; occurrence; uncertainty; prioritization; ranking.

I. INTRODUCTION

A. Risk and hazard

Hazards are the risk sources, and their proper recognition and prioritization leads to a better understanding of risks and their management. The rising complexity and cross-disciplinary nature of systems demands further development for identification of hazards [1, 2]. Hazard is the potential source of harm [3], and this creates a direct link between hazard and risk. If a hazard is not identified, risks remain unattended.

The European norm on risk assessment [4] summaries the tools and methods applicable to hazard identification in categories of strongly applicable and applicable. The strongly applicable methods for risk identifications are brainstorming, Delphi, Check-lists, Primary hazard analysis, Hazard and operability studies (HAZOP), Environmental risk assessment, SWIFT, Scenario analysis (SA), Failure mode and effect analysis (FMEA), Cause-and-effect analysis, Human reliability analysis (HRA), Reliability centered maintenance (RCM), Consequence/probability matrix. The applicable methods for hazard identifications are Business impact analysis (BIA), Fault tree analysis (FTA), Event tree analysis (ETA), Cause and consequence analysis (CCA), Layer protection analysis, Sneak circuit analysis, Markov analysis, FN curves, Risk indices, cost/benefit analysis, and Multi-criteria decision analysis.

After recognition of a hazard, severity of its harm and probability of its occurrence is needed to estimate the risk as shown in the figure below.

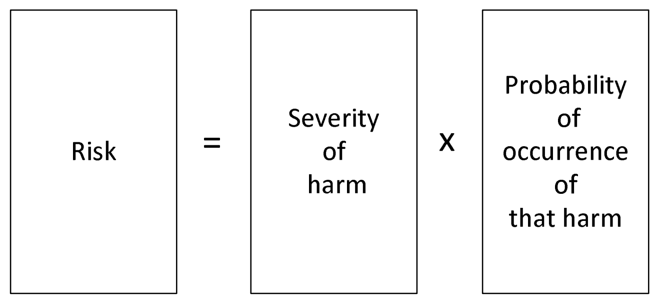


Figure 1. Risk is a function of severity of harm and probability of occurrence of that harm [4].

Next sections in the paper highlights the importance of risk and uncertainty recognition in early project phase, the involvement of stakeholders for elicitation, and the influence of hazards on system requirements. Thereafter, the paper discusses an approach for the modelling and communication for system risks. As hazard is the source of risk, terms hazards and risks are interchangeably used in the context of this paper.

B. Risk and uncertainty

There are always many factors and influences which can make it uncertain whether the project achieves its objectives. This uncertainty in early project phases is very high as discussed in details in [5]. Besides, the complexity of projects intensifies this uncertainty as shown in Figure 2. This uncertainty imposes risk on the project, and the mitigation of this risk is easier in early project phase. Figure 2 shows that the cost of risk mitigation increases as the project further develops. In order to manage this risk, the first step is its identification, then analysis, evaluation, and then taking appropriate measurements.

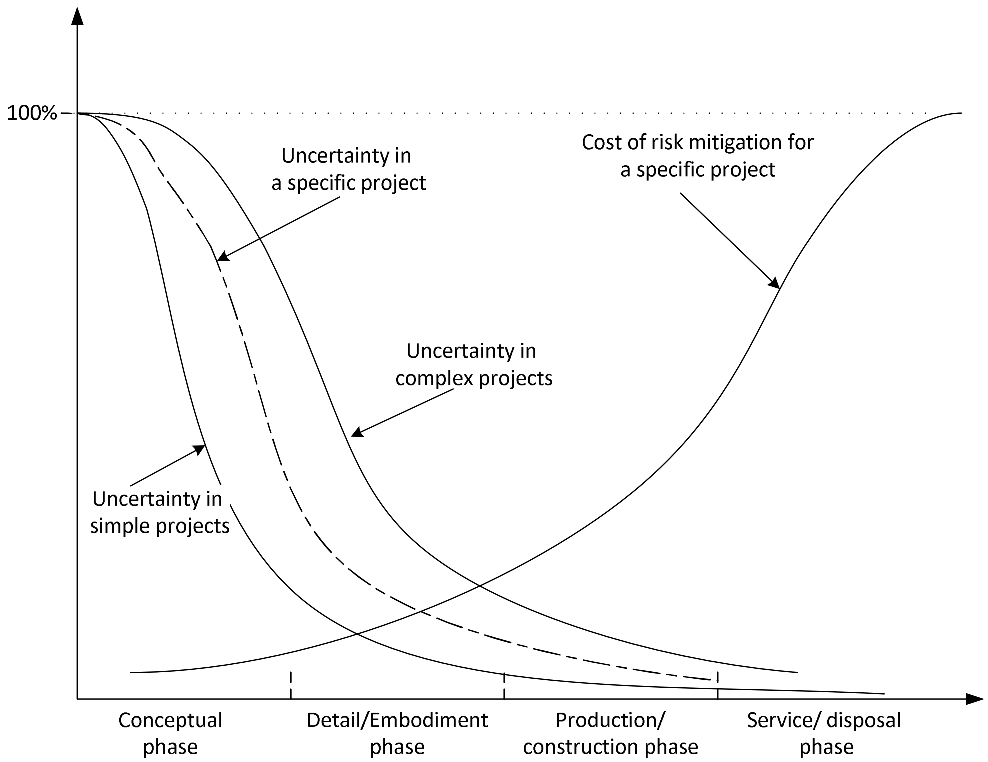


Figure 2. This figure highlights the presence of uncertainty and risk in the course of a full project life-cycle (adapted from [5]).

In early project phases, proper actions against risk factors, results in many competitor advantages including but not limited to the following (see [6]):

- higher likelihood for success
- encouraging the proactive measurements against risk factors
- higher stakeholder confidence and trust
- identification of opportunities and treats
- more effective use of resources against risk factors

To properly identify project risks and progress in the project, useful information is required. This information reduces uncertainties, increases utilities, and creates value for the system. This is because useful information for a designer leads to better design choices that ultimately influence the rest of design including concept, details, or services. This quest, however, may result in information overwhelming, and a design team may be exposed to a lot of information that hinders focusing on the key aspects. In system design with the multi-stakeholder nature of systems, divergent expectations of stakeholders can prevent a designer to focus on the key drivers for a system design.

In an interdisciplinary system, there are a lot of mono- or multi- disciplinary hazards that are hard to quantify or prioritize. Quantification of hazards in the form of frequency of occurrence or severity comes after its realization. Furthermore, this quantification may be subject to change over time.

Lack of proper hazard identification or prioritization leads to rising complexity in the risk analysis and management. Most of the currently applied hazard identification methods result in a hazard pool. In such a view, a larger system results a larger hazard pool which makes the prioritization more complex. The next section discusses this in further details.

C. *System hazards and requirements*

A good understanding of hazards and risks helps developing a proper list of (safety) requirements. The importance of requirements have been discussed in design literatures, see e.g. [7]. This study adapts a pluralistic approach for highlighting system hazards, risks or requirements.

Literatures have discussed that many engineering design methods pay attention to system risks when there is already a concept for the system. Yet proper view of main hazards helps forming an architecture that fits better to them [8, 9]. Recognition of system hazards is indeed a pluralistic approach, and the design team/ architecture need to approach different system stakeholders and explore their concerns about the system risks and hazards. Stakeholder in this paper is used as a general term that includes system shareholders, users, designers, experts and etcetera, and the concern refers to a stakeholder concern including the specific hazard.

Literatures confirm that an incomplete set of stakeholders may lead to incomplete results since there are problems arising from the scope, understanding and validation of needs, concerns or concern [10, 11] in the course of communication with stakeholders. Therefore, identification of stakeholders and elicitation of information are considered as prerequisites for understanding the system hazards. Systems often involves a large number of stakeholders [12]. Figure 3 presents the functional diagram for identifying stakeholders and communicating with them. This results in a pool of hazards with a lot of information [see [1]]. Ranking of this information helps the designer to keep her focus on the key aspects. Recognition of key hazards is likely to be seen subjectively as different stakeholders tend to focus on their areas of interest and pay more attention to the hazards that influence their interest.

This study builds on the previous study [1] on ranking system hazards and suggests ranking of system risks based on two measures of severity and occurrence through a pluralistic approach. It therefore focuses to offer a pluralistic approach that communicates well with stakeholders, provides freedom for presenting the opinions, and embraces doubts or uncertainties in their information.

D. *Ranking of system hazards*

This study builds on the assumption that key hazards in design are recognized by the consensus of stakeholders, and they can be rated systematically through a ranking process. In general, ranking of parameters (hazards) based on their importance is well discussed in decision models. The use of multi criteria decision models typically involves a systematic ranking process as for instance indicated in [13, 14]. The influence of the ranking process on final decisions is for example explained in [15]. A review of subjective ranking methods shows that different methods cannot guarantee accurate results. This inconsistency in judgment explains difficulty of assigning reliable and subjective weights to the requirements. A systematic approach for ranking is described in [16] that is a generalization of Saaty's pairwise structure [17]. Given the presence of subjectivity in the ranking process, sensitivity analysis of the design criteria is used to study the influence of variation and the ranking process on the decisions made [18]. Furthermore, some approaches e.g. the task-oriented weighing approach is effectively used. This approach is meant to limit the subjectivity of criteria weighting [19]. It suggests an algorithm to rank criteria objectively while considering the uncertainty in criteria weight [20]. The approach is based on introducing fuzzy numbers that imposes specified membership functions, which has been also used in [21, 22].

The methods used to identify the system hazards are mentioned earlier in this paper. The outlines of these methods are available elsewhere in for example [6]. The use of these methods results in a bank of information called a "pool of hazards".

E. *Pool of hazards; severity, occurrence and risk*

The so called pool of hazards integrates the identified hazards that threaten the system. This pool includes all the system hazards recognized by stakeholders. As the pool can become of enormous size, a method is required for listing them based on their priorities. Figure 4 schematically shows a set of hazards recognized for a system. For ranking the system hazards, this study uses two metrics of frequency of occurrence and degree of severity. These metrics are further described in the next sections.

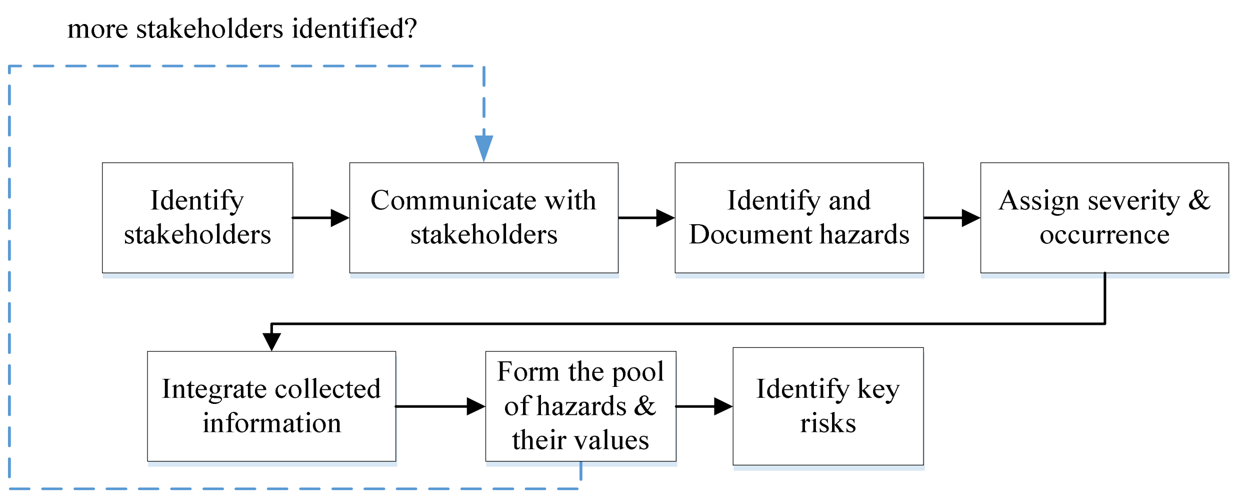


Figure 3. The process of identification of system stakeholders and system hazards.

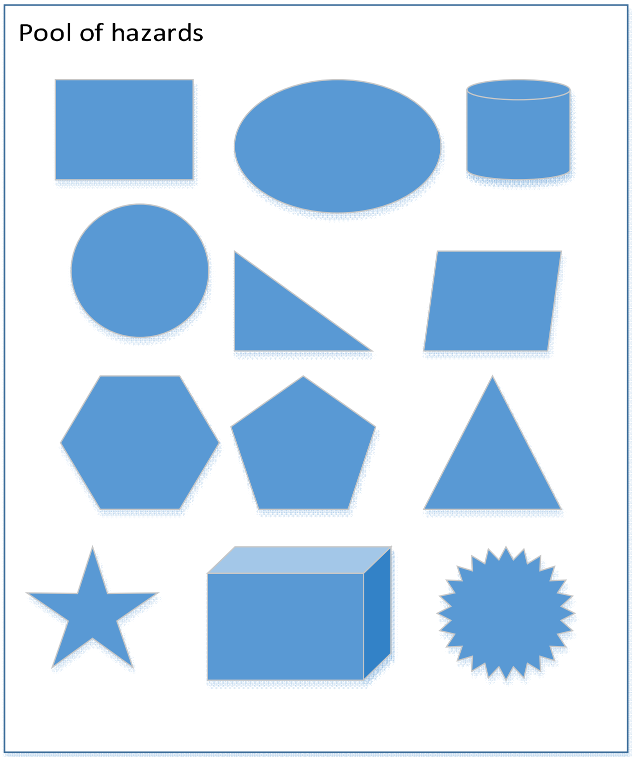


Figure 4. A schematic view for the pool of hazards. Every shape in this pool stands for a hazard.

1) *Severity of harm*

Harm is defined as physical injury or damage to persons, property, and livestock [23]. A Systems Engineer or designer is advised to define the severity of harm and communicate it with the stakeholders. For example, IEC (see [23]) defines three categories for severity of harms. This reference defines three categories of harm which are slight, high and serious as explained below.

- Slight harm which is normally reversible or reparable in short term
- High harm which is normally reversible or reparable in longer term
- Serious harm which is normally irreversible and irreparable or death.

The issue with this approach is that the user has to choose one single category, and different harms inside one category do not make differences. To overcome this and provide freedom to the user, these categories are presented in the following table and communicated with the system stakeholders. This enables the stakeholders to freely present their opinion and include their lack of certainties.

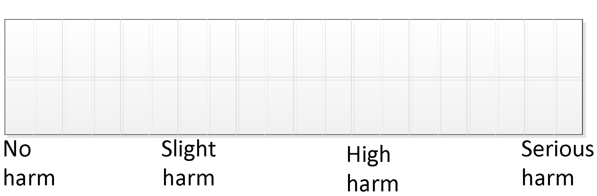


Figure 5. An example table for different categories of harm.

2) *Frequency of occurrence*

Likewise, there is a need for a standard table for communication of the frequency of occurrence for each hazard. Figure 6 presents an example table for this purpose. This table is based on the advice of [23] which suggests considering the occurrence or exposure time as a criterion for this estimation.

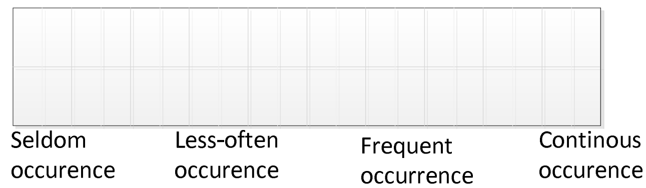


Figure 6. An example table for different frequency of occurrence.

II. METRICS FOR RISKS AND HAZARDS

In order to facilitate communication with system stakeholders, it is important to note that system has stakeholders who can be individuals, corporations, organizations and authorities, with different fields/ levels of knowledge and experience [5]. They all have their interests and expectations. Their interest may overlap, interfere or compete. This paper uses uncertainty to embed flexibility and allow a human solution in terms of preferred alternatives [24, 25]. This uncertainty is of human nature described elsewhere e.g. in [26], and its formulation will be discussed in further details through next section.

A. *Formulation of system hazard*

Having *m* stakeholders for a system, their opinions for the i-th hazard H_i is presented by stochastic variables $h_{i_1}, h_{i_2}, \ldots, h_{i_m}$, where h_{i_k} presents the k-th stakeholder's opinion over the importance of the i-th hazard. To analyze and rank system hazards according to expert opinion, two measures of severity and occurrence are needed for each hazard. These are further explained in the next sections.

1) *Measure of severity*

Let S_i presents the severity of H_i and let variables $s_{i_1}, s_{i_2}, \ldots, s_{i_m}$ present severity of the hazard identified by system stakeholders. The mean and standard deviation of these variables are respectively shown as $\mu^s_{i_1}, \mu^s_{i_2}, \ldots, \mu^s_{i_m}$ and $\sigma^s_{i_1}, \sigma^s_{i_2}, \ldots, \sigma^s_{i_m}$. As a result, the overall mean and standard deviation of severity of the i-th hazard are formulated by Equations (1) and (2), respectively.

$$\mu_i^s = \frac{1}{\sum_{k=1}^{m} \alpha_k} \sum_{k=1}^{m} \alpha_k \mu_{i_k}^s \tag{1}$$

$$\left(\sigma_i^s\right)^2 = \sum_{j=k}^{m} \frac{\alpha_k^2 \left(\sigma_{i_k}^s\right)^2}{\left(\sum_{k=1}^{m} \alpha_k\right)^2} \tag{2}$$

Where α_k represents the assigned weight to the k-th stakeholder. If the stakeholders are evenly graded, Equations (1) and (2) transform to the following.

$$\mu_i^s = \frac{1}{m} \sum_{k=1}^{m} \mu_{i_k}^s \tag{3}$$

$$\left(\sigma_i^s\right)^2 = \sum_{k=1}^{m} \frac{\left(\sigma_{i_k}^s\right)^2}{m^2} \tag{4}$$

After normalization, the following equations are concluded.

$$\lambda_i^s = \frac{\mu_i^s}{\sum_{i=1}^{n} \mu_i^s} \tag{5}$$

$$\left(\sigma_{\lambda_i}^s\right)^2 = \left[\frac{\sigma_i^s}{\sum_{i=1}^{n} \mu_i^s}\right]^2 \tag{6}$$

Where λ_i^s and $\sigma_{\lambda_i}^s$ are respectively the weight factor and standard deviation for the i-th severity. Relative weight λ_i^s is often used as the criteria for ranking parameters. Under uncertain situation, however, λ_i^s is not the only parameter to rank severity, and its uncertainty $\sigma_{\lambda_i}^s$ can play an important role in the ranking process. High uncertainty can lead to high risk, and generally certain values are more reliable. On the basis of discussion above, we use "the reliability index for severity" as an estimated measure for the reliability of estimated severity. Therefore, the reliability index of each severity is estimated as

$$\beta_i^s = \frac{\lambda_i^s}{\sigma_{\lambda_i}^s} \tag{7}$$

The equation above indicates the relative standard error (RSE) for the estimated severity of the i-th hazard [27].

2) Measure of occurence

Let O_i presents the frequency of occurrence of the harm for H_i and let variables $o_{i_1}, o_{i_2}, ..., o_{i_m}$ present occurrence of the hazard identified by system stakeholders. The mean and standard deviation of these variables are respectively shown $\mu_{i_1}^o, \mu_{i_2}^o, ..., \mu_{i_m}^o$ and $\sigma_{i_1}^o, \sigma_{i_2}^o, ..., \sigma_{i_m}^o$. As a result, the overall mean and standard deviation of severity of the i-th hazard are formulated by Equations (1) and (2), respectively.

$$\mu_i^o = \frac{1}{\sum_{k=1}^{m} \alpha_k} \sum_{k=1}^{m} \alpha_k \mu_{i_k}^o \tag{8}$$

$$\left(\sigma_i^o\right)^2 = \sum_{j=k}^{m} \frac{\alpha_k^2 \left(\sigma_{i_k}^o\right)^2}{\left(\sum_{k=1}^{m} \alpha_k\right)^2} \tag{9}$$

Where α_k represents the assigned weight to the k-th stakeholder. After normalization, the following e After normalization, the following equations are concluded.

$$\lambda_i^o = \frac{\mu_i^o}{\sum_{i=1}^{n} \mu_i^o} \tag{10}$$

$$\left(\sigma_{\lambda_i}^o\right)^2 = \left[\frac{\sigma_i^o}{\sum_{i=1}^{n} \mu_i^o}\right]^2 \tag{11}$$

Where λ_i^o and $\sigma_{\lambda_i}^o$ are respectively the weight factor and standard deviation for occurrence of i-th hazard. The reliability index for the frequency of occurrence is estimated by

$$\beta_i^o = \frac{\lambda_i^o}{\sigma_{\lambda_i}^o} \tag{12}$$

The equation above indicates the relative standard error (RSE) for the estimated occurrence of i-th hazard, which also can be referred to as reliability of the i-th occurrence [27]. It represents the degree of stakeholders' consensus.

3) Measure of risk

Risk is a function of severity of harm and frequency of its occurrence. In a two dimensional space of severity and occurrence, a larger distance from the origin means a larger risk. Therefore, the risk measure depends on both severity and occurrence, and it is obtained by the following formula

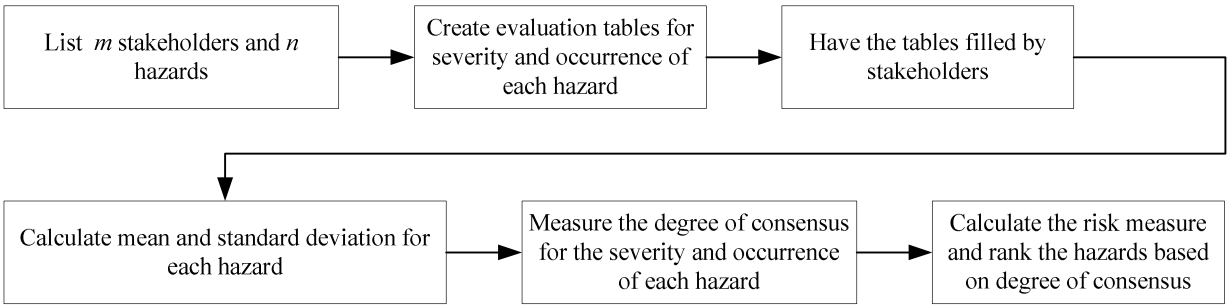


Figure 7. The process for ranking hazards.

$$R_i = \sqrt{\left(\beta_i^s\right)^2 + \left(\beta_i^o\right)^2} = \sqrt{\left(\frac{\lambda_i^s}{\sigma_{\lambda_i}^s}\right)^2 + \left(\frac{\lambda_i^o}{\sigma_{\lambda_i}^o}\right)^2} \qquad (13)$$

The algorithm for applying this method is described next in Section B and an example application is presented in Section III.

B. Algorithm

This section describes the steps needed for ranking the risks. A summary of these steps is shown in Figure 7.

1. List m stakeholders and n concerns for system of interest. Determine the weight of stakeholders' opinions if they are not evenly graded.
2. List the hazards and make tables for their severity using the numeric or verbal format shown in Figure 5 and Figure 6.
3. Ask the stakeholders to fill the tables. This step concludes m series of tables. Use s_{i_k} format to label the collected information for each table, where k refers to the k[th] stakeholders.
4. Calculate the expected value and standard deviation for each table: $\mu_{i_k}^s$ and $\sigma_{i_k}^s$ for each s_{i_k} .
5. Calculate the mean and standard deviation for the severity of each hazard μ_i^s and σ_i^s .
6. Normalize the severity of hazards and calculate the relative weight factor and its uncertainty.
7. Repeat steps 2 to 6 for the frequency of occurrence instead of the severity of hazard.
8. Use Equation 13 and estimate the risk.
9. Rank the hazards based on their risk, severity, or probability of occurrence.

This process uses the collected information and sorts the system concerns based on the stakeholders' opinion. The next section presents an example application for this.

III. EXAMPLE APPLICATION

To illustrate the application of the proposed method, a simple example is presented in this section. In the example, there are four items in the pool of hazards. These hazards have been schematically shown by geometrical shapes as shown in Figure 8. This figure presents that two stakeholders have estimated the severity and frequency of occurrence of the hazards. Figure 8 (a) and (c) respectively show opinion of the first stakeholder over the severity and occurrence of the hazards. Figure 8 (b) and (d) present the opinion of the second stakeholder. The verbal explanation of the tables is not included in this example and only the numerical scale is presented. In this example, the stakeholders are not evenly graded. The importance of stakeholder 1 and stakeholder 2 are weighted as 0.7 and 0.3, respectively.

IV. DISCUSSION

Applying the algorithm explained in Section II.B results in the outcome shown in TABLE 1. The first two columns of this table shows the hazards information. Columns 3 and 4 present the average of expert opinions over the severity and occurrence of harms associated to the hazards. Based on the uncertainty of these estimates, the degree of consensus is shown in Columns 5 and 6. A higher value in these columns represents a higher consensus on the stakeholder's agreement. Based on these, the risk metric is presented in the last column representing the stakeholders consensus on the values of risk. The conclusion may be drown from the risk values is that the second hazard is less risky than the others according to the stakeholder's opinion. As seen in this table, the hazards can be ranked based on the severity of harm or its frequency of occurrence. For illustration,

Figure 9 shows the risk area depicted in a two-dimensional space of severity and occurrence. Such a figure can summarize the information collected from the stakeholders and provide further insight about the risk priorities in early system design.

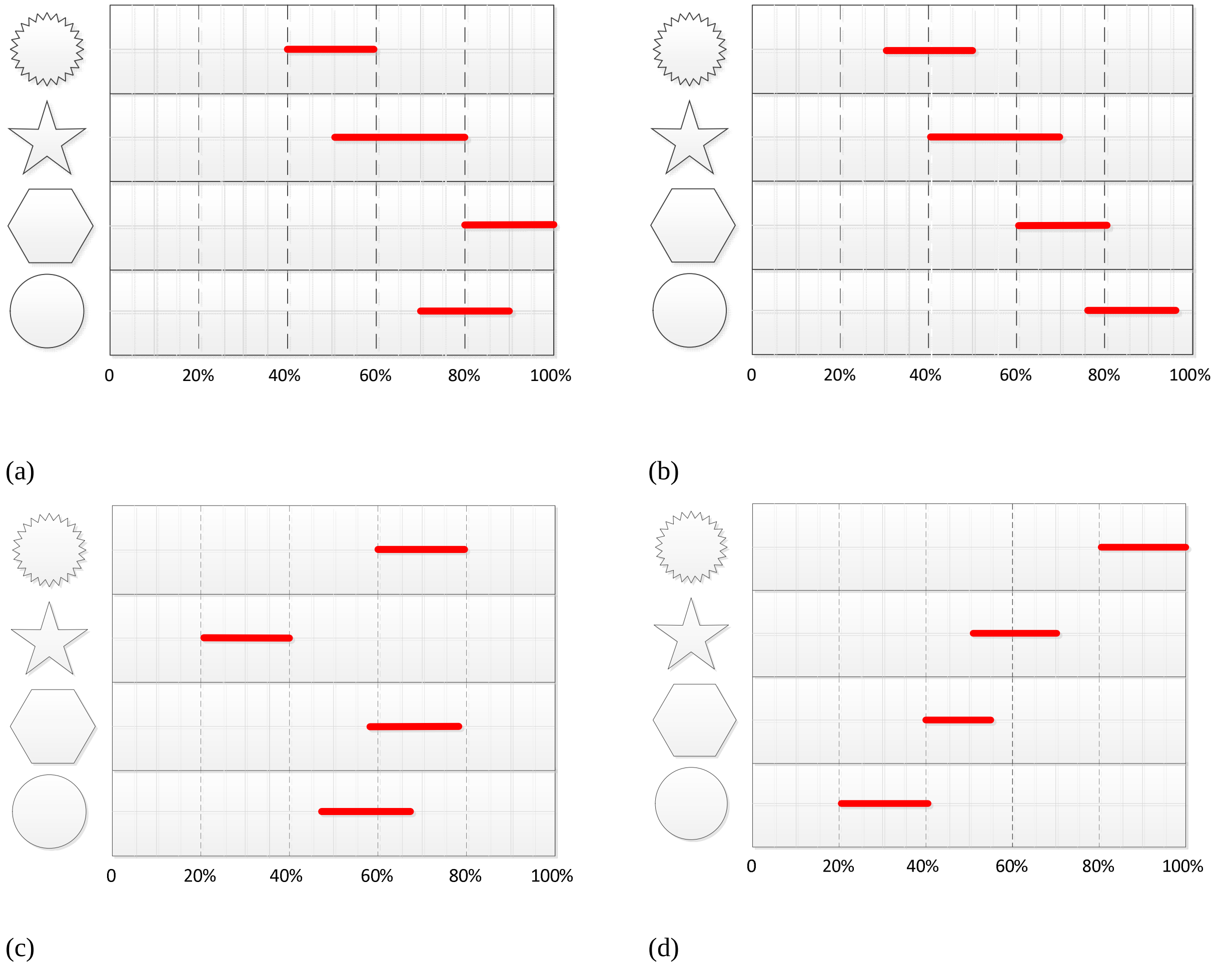
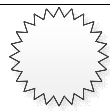
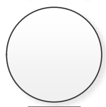
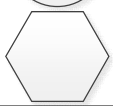


Figure 8. Figures schematically present system hazards. (a) Expert 1 presents his opinion over the severity of hazards. (b) Expert 2 presents her opinion over the severity of hazards. (c) Expert 1 presents his opinion over the frequency of occurrence of hazards. (d) Expert 2 presents her opinion over the frequency of occurrence of hazards.

This example shows how the method is used to communicate with stakeholders, register their concerns, integrate the collected data and disclose the most important aspects. Similar results have been achieved through real-world case studies to prioritize the stakeholder consensus in terms of project requirements. See for example [26, 28].

TABLE 1. THIS TABLE PRESENTS THE REQUIREMENTS AND THEIR WEIGHT FACTORS, STANDARD DEVIATIONS, RELATIVE WEIGHTS, UNCERTAINTIES IN RELATIVE WEIGHT, RELATIVE UNCERTAINTIES AND DEGREE OF CONSENSUS.

ID	Hazards	Expected severity (μ_i^s %)	Expected occurrence (μ_i^o %)	Consensus over severity β_i^s	Consensus over occurrence β_i^o	Estimated Risk (R_i %)
HZ1		40	90	3,1	6,7	10
HZ2		55	60	2,8	3,8	6
HZ3		70	48	5,6	5,5	11
HZ4		88	30	5,9	3,6	10

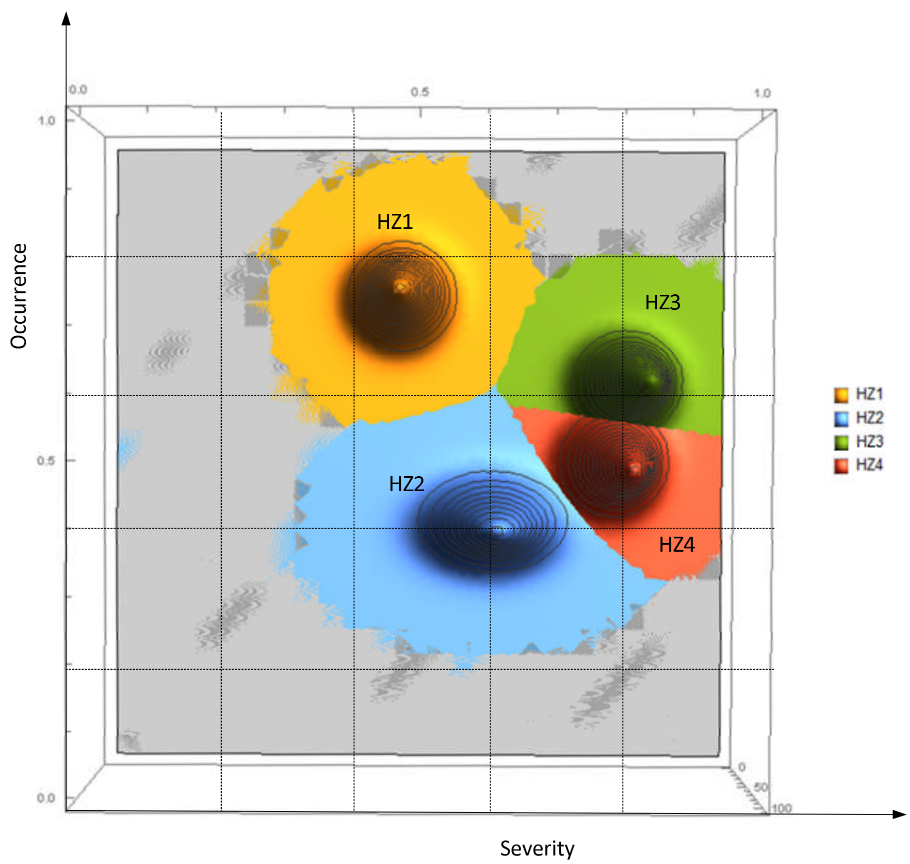


Figure 9. Two-dimensional representation of risks. Risks are presented in this picture through two categories of severity of harm and its occurrence.

V. Conclusions

The paper proposes a graphical tool to communicate with stakeholders, collect the risk information and combine it in order to prioritize the system risks. A pluralistic approach is used to probabilistically measure the severity of harm and frequency of occurrence. These metrics are used to find the degree of stakeholders' consensus over system risks and rank them. The proposed approach is based on probability theory and promotes probabilistic thinking. The use of this outcome for triangulation of risk concerns is the next step for this research.

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