Coping with System Hazards in Early Project Life Cycle

Identification and Prioritization

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***Abstract*--The rising complexity of product and systems demands further attention to potential hazards. While researchers explore tools and methods to identify hazards, their prioritization remains a challenging task in a multi-stakeholder environment. A reason for this is that the hazards are hardly quantifiable. While the accurate quantification remains a challenge, a flexible and pluralistic approach can bring the important ones on top of the list. This paper offers a methodology for ranking hazards 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 introduces the "degree of consensus" as a metric to rank the identified hazards. This metric represents the consent of stakeholders on the system of interest (SoI) concerns used for example in its architecture, design decisions, or alternative evaluation. The paper explains the mathematical formulation and presents an application example for this.**

consensus; hazards; uncertainty; prioritization; ranking.

I. Introduction

A. Hazard Identification

Hazards are the risk sources, and their proper recognition and prioritization leads to a better understanding of risk and their management. The rising complexity and cross-disciplinary nature of systems demands further development for identification of hazards [1]. Hazard is the potential source of harm [2], 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 [3] 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.

B. Early life-cycle

Designers can effectively impact a system in early design phases. In this phase, changes are often less costly and design decisions can profoundly influence the system of interest. In early design phases, proper information reduces uncertainties, increases utilities, and creates value for the system as shown in Figure 1. This is because proper information for a designer leads to better design choices that ultimately influence the rest of design including concept, detail, services, and etcetera.

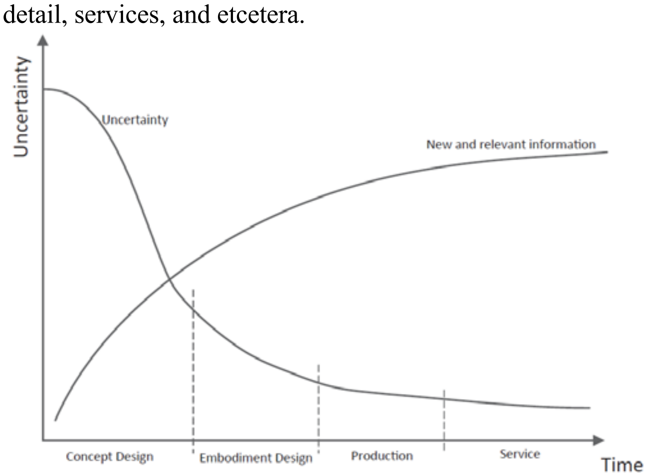

Figure 1. The information concern in the design process [4].

Yet information in the beginning of design can also be overwhelming. A design team may be exposed to a lot of information that hinders focusing on the key aspects of design. 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 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. Hazards, risks and requirements

A good understanding of hazards and risks helps to develop a proper list of requirements. The importance of requirements have been discussed in design literatures, see e.g. [5-7]. 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 2 presents the functional diagram for identifying stakeholders and communicating with them. This results in a pool of concerns with a lot of information. 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 assumes that key hazards are recognized by the stakeholders and that those key hazards can be determined 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. 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 [23]. The

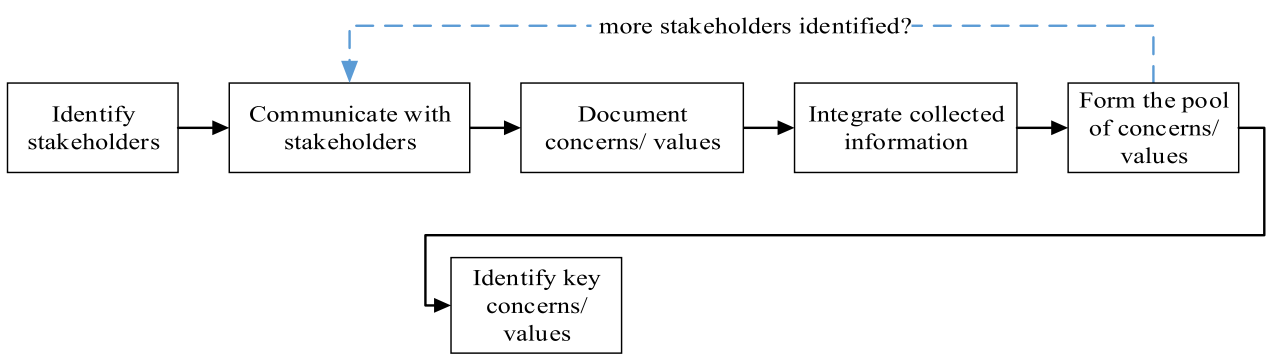

Figure 2. The process of identification of stakeholders and communication with them.

use of these methods results in a bank of information called a "pool of hazards".

E. Pool of hazards

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 3 schematically shows a set of hazards recognized for a system.

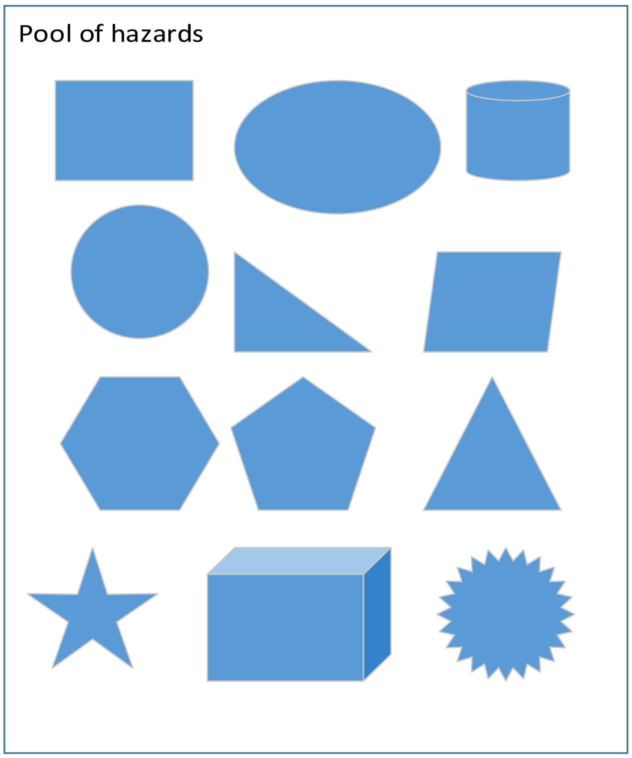

Figure 3. A schematic view for the pool of hazards.

II. COMMUNICATON OF HAZARDS

There are obstacles in communication with system stakeholders who can be individuals, corporations, organizations and authorities, with different fields/ levels of knowledge and experience [4]. They all have their interests and expectations. This study uses uncertainty to allow a human solution in terms of preferred alternatives [24, 25]. The uncertainty in importance of design concerns is also of human nature which should be reflected in the process [26]. The principle of the method is described elsewhere in [7] and discussed in further details through this next section.

A. Presentation

The method aims at a realistic and intuitive approach that can communicate to stakeholders with different fields of knowledge and expertise. The method must be transparent, easy to implement and readily adaptable by different users. For this purpose, graphs are used to effectively communicate with different users. The format presented in Figure 4 is used to identify and register the importance of a concern according to a stakeholder. It shows that the linguistic scale may replace the numeric scale for the ease of communication, and one can assign a range of possible importance to a certain concern. For illustration, Figure 4(b) shows that the i-th concern, C_i, may have the importance somewhere from 0.6 to 0.8 according to one of the stakeholders in 0 to 1 grading scale, where 0 indicates no importance at all and 1 represents the absolute importance. Then, probability distribution function (PDF) is assigned to this recorded data. Symmetric opinions are assumed here in this paper as described in [27, 28] and the collected data is treated as a random variable with a Gaussian distribution.

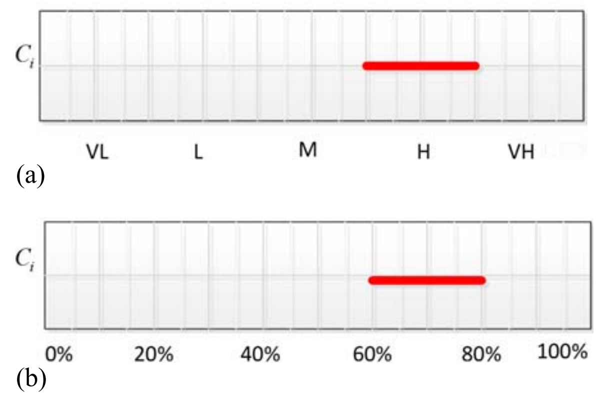

Figure 4. An example of a stakeholder's opinion about the importance of the i-th concern C_i.

B. Formulation

Having m stakeholders, their opinions for the i-th design concern C_i is presented by stochastic variables $c_{i_1}, c_{i_2}, \ldots, c_{i_m}$, where v_{i_k} presents the k-th stakeholder's opinion over the importance of the i-th concern. The mean and standard deviation of these variables are respectively shown as $\mu_{i_1}, \mu_{i_2}, \ldots, \mu_{i_m}$ and $\sigma_{i_1}, \sigma_{i_2}, \ldots, \sigma_{i_m}$. As a result, the overall mean and standard deviation of opinions over the i-th concern are formulated by Equations (1) and (2), respectively.

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

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

Where α_k represents the assigned weight to the k-th stakeholder. If the stakeholders are evenly graded (which is not very likely in the context of complex systems), Equations (1) and (2) transform to the following.

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

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$$\sigma_i^2 = \sum_{k=1}^{m} \frac{\sigma_{i_k}^2}{m^2} \quad (4)$$

After normalization, the following equations are concluded.

$$\lambda_i = \frac{\mu_i}{\sum_{i=1}^{n} \mu_i} \quad (5)$$

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

$$\phi_i^2 = \frac{\sigma_i^2}{\sum_{i=1}^{n} \sigma_i^2} \quad (7)$$

Where λ_i, σ_{λ_i} and ϕ_i are respectively the weight factor, its standard deviation and the relative uncertainty for the i-th concern. Relative weight λ_i is often used as the criteria for ranking parameters or concerns. Under uncertain situation, however, λ_i is not the only parameter to rank data, and its uncertainty σ_{λ_i} can play an important role in the ranking process. High uncertainty can lead to high risk, and one may prefer a concern with more certainty but lower λ_i. On the basis of discussion above, we use "the reliability index" as an estimated measure of reliability of each concern. Therefore, the reliability index of each concern is estimated as

$$\beta_i = \frac{\lambda_i}{\sigma_{\lambda_i}} \quad (8)$$

The equation above indicates the relative standard error (RSE) for the importance of i-th estimated concern, which also can be referred to as reliability of the i-th concern [29]. It represents the degree of stakeholders' consensus on the i-th concern. The algorithm for applying this method is described next and an example application of it is presented in the next section.

C. Algorithm

Here, we describe the steps needed for ranking the requirements. A summary of this process is shown in Figure 5.

- List m stakeholders and n concerns for SoI. Determine the weight of stakeholders' opinions if they are not evenly graded.
- Draw tables and list concerns $(C_1, C_2, ..., C_n)$ using the numeric or verbal format shown in Figure 4.
- Ask the stakeholders to fill the tables. This step concludes m series of tables. Use c_{i_k} format to label the collected information for each table, where k is the number of stakeholders.
- Calculate the expected concern and standard deviation (μ_{i_k} and σ_{i_k}) for each c_{i_k}.
- Calculate the mean and standard deviation for each concern (μ_i and σ_i) for the i-th concern. Use Equations (1) and (2). If the stakeholders are evenly graded, use Equations (3) and (4).
- Use Equations (5) to (7) to calculate the normalized weight of each concern, its standard deviation, and relative uncertainty.
- If new stakeholders or concerns are realized, reiterate from the first step. Otherwise use Equation (8) to calculate the degree of consensus on each concern and rank the concerns.

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.

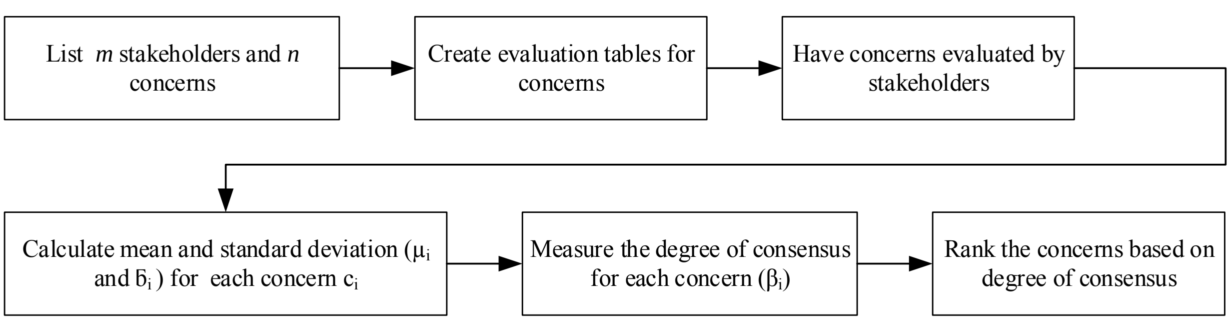

Figure 5. The process for ranking concerns.

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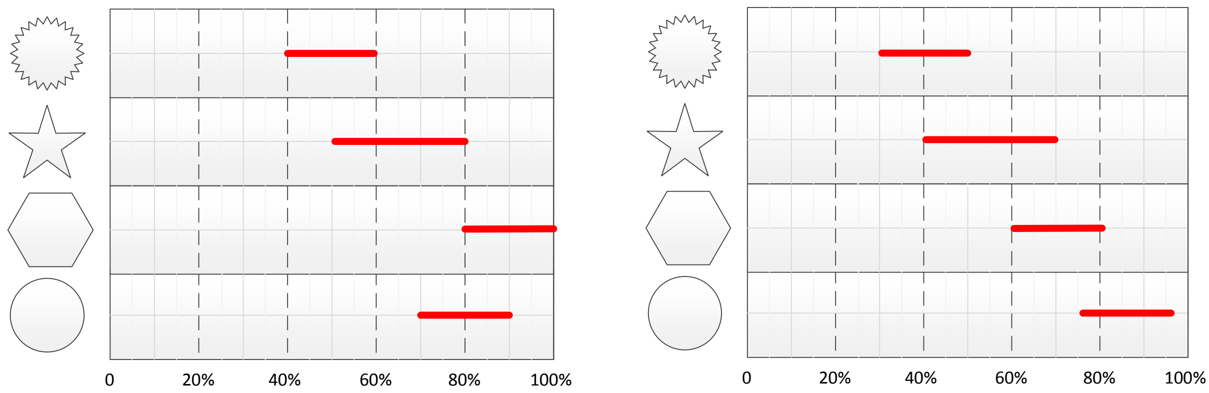


(a) (b)

Figure 6. This figure presents the opinion of two stakeholders over the importance of four concerns shown by different figures. The numerical scale is used to present the importance of each concern.

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 concerns (hazards) in the pool of concerns (hazards). These concerns have typically been shown by different geometrical shapes (see Figure 6). Two stakeholders have ranked the concerns according to their views shown in this figure. The outcome of this ranking is presented in TABLE 1. The first column of this table shows a list of design concerns which are to be ranked. The rest of the columns respectively present the mean, standard deviation, relative weight, its uncertainty and relative uncertainty for each concern. The last column, which is highlighted, shows the degree of stakeholder's consensus.

As seen in this table, there could be different results for ranking based on "relative weight" or "relative uncertainty". Here the "degree of consensus" plays an important role to set the priority of concerns as it acts as a measure of the reliability in each concern.

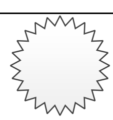
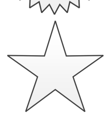
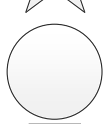
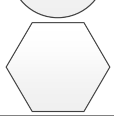
This example shows how the method is used to communicate with stakeholders, register their concerns, integrate the collected data and disclose the most important aspects. Similar results have been achieved through real-world case studies to prioritize the stakeholder consensus in terms of project requirements. See for example [6, 7].

IV. CONCLUSIONS

This study highlights the stakeholders' concerns for identification of system hazards. Realization of key concerns and their ranking can be a challenging task due to a high number of stakeholders and their competing or conflicting interest.

The paper proposes an approach that uses a graphical

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.

Concerns	Expected concern (μ_i %)	Standard deviation (σ_i %)	Relative weight (λ_i %)	Uncertainty in weight (σ_{λ_i} %)	Relative uncertainty (ϕ_i %)	Degree of Consensus (β_i %)
	45	5	10	1.1	11	9.1
	60	7.5	14	1.7	25	8.2
	80	5	18	1.1	11	16.4
	82.5	5	19	1.1	11	17.3

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tool to communicate with stakeholders, collect the information and combine it in order to rank the concerns. The "degree of consensus" is used to rank concerns. The proposed approach is based on probability theory and promotes probabilistic thinking.

The use of this outcome for triangulation of hazard identification is the next step for this research.

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