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Risk information in decision-making: definitions, requirements and various functions

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ABSTRACT

Inappropriate decisions are often regarded as causes of major accidents in the process industries. To improve the quality of decisions, it is important to make the right information available at the right time. The objective of this work is to investigate what types of risk information is needed for risk-related decisions in various decision-making processes. A framework is proposed to facilitate future research for easing information deficiency. In this paper, risk information is examined through common decision-making processes, and is identified serving to 1) detect and characterize risk-related decision problems, 2) indicate the severity and urgency of decisions, 3) state requirements and constraints of workable solutions, 4) represent attributes for comparing and evaluating solutions, and 5) act as rules to maintain safety or control risk. These usages of risk information in different decision problems imply the large diversity in information needs for decision-making. An adaptive information support is thus suggested to provide targeted risk information to specific decision-makers for effective and efficient decision-making in accident prevention in the process industries.

1. Introduction

The process industries are complex and highly technological domains, where many sociotechnical systems are involved. Major accident is a critical threat for the process industries. One of the issues that investigators will focus on after major accidents are what decisions lead up to the accidents. For example, the 2010 San Bruno gas transmission pipeline rupture (Hayes and Hopkins, 2014) illustrates that a disaster can be contributed by decisions that were made independently by personnel at different levels of an organization over a long period of time. Several inappropriate decisions were made in this case, from designing inspection programs and cost cutting on maintenance and inspection, to handling specific situations during the operation. Such decisions may be called risk-related decisions.

Undesired consequences from decisions are associated with limited awareness of risk (Vaughan, 1996), poorly structured problems, unclear goals, ambiguity (Kunreuther and Meszaros, 1996) and conflicts between visible cost and uncertain benefits. Those issues are typically intensified by the complexity, ambiguity, uncertainty or insufficiency of risk-related information or knowledge which good information support can help to resolve (Zack, 2007). Even though such information is existing, it cannot be properly used before the following questions are answered, such as 1) what risk information should be provided? 2) at what time? 3) for what decision? and 4) to whom.

So called right information is expected, which can give the decision-maker an understanding of the risk so as to facilitate a good decision-making in the specific situation. The right information, or the information need, can in principle be identified from the gap between knowledge of the decision-maker and a desired state of knowledge for decision-making, including both perceived and unperceived information needs. Giving the handling of iceberg threat to an Floating Production Storage and Offloading unit (FPSO) as an example, if the hull damage is an known consequence from collision to the decision-maker while other potential damages such as damage to positioning system are not, then information about potential hull damage from iceberg collision can be a perceived need while information about other potential damage to positioning system is an unperceived need.

It is a complex issue what information a decision-maker exactly needs. Information needs have been investigated by empirical methods such as surveys, interviews and observations (Ayatollahi et al., 2013). Information-decision-action task analysis has been used to categorize tasks and to identify associated information needs (Allen et al., 1971) for

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drivers. Another approach is first to use empirical approach such as interviews or process monitoring to investigate the way of decision-making (to construct the decision ladder (Rasmussen, 1986)) and then use the constructed decision ladder to elicit the information needs (Ward, 2014) including the correct response strategies (Hassall et al., 2014). The empirical methods are restricted by the existence of observable environment and they are not capable to identify unperceived information needs. So far, we are not able to establish a standard list of information categories that will provide for all decision-makers with all the required information for all their risk-related decisions. A systematic analytical method can have potential to facilitate the identification of risk information needs. Such a method can be established in consideration of two influence factors of information need, the decision-making process and the type of decision problem. This is described in more detail in Section 4.1.

However, challenges exist in developing a systematic analytical method: 1) No clear definition of risk-related decision exists, while several terms with varied implications and scopes are used in literature. 2) The default definition of risk information is oriented by risk analysis, rather than decision-making or information processing (Rasmussen, 1983), where risk analysis is not always needed (The UK Oil and Gas Industry Association, 2014).

In this paper, we will thus focus on:

- Sociotechnical systems (Rasmussen, 1997) in the process industries, which are dynamic and involve interlinked, humans in multiple levels of organization and authority, technology and their environment.
- Decisions that influence major accident risk in such systems.
- How risk information need is dependent on the decision-making process applied.
- Investigating what type of information is required for different decision-making processes.

This paper limits itself strictly in decision-making processes, without considering psychology and personalities of decision-maker and general political mechanisms among and within organizations. Further, we do not go into the discussion of whether risk is subjective or objective (Slovic et al., 2004). Also, in the paper, no consideration will be given to the decision-making processes of teams involved in applying systematic or mathematically based methods of obtaining the best or least risky solution or generating the best ranking of options against a set of criteria in an optimum compromise. Rather, this paper is concerned with factors that support the quality of the decision of individuals participating in the process.

In risk management, whether the decision is good or not is sometimes evaluated only based on outcome, i.e. whether an accident occurs or not. However, in this paper, decision quality is analyzed and evaluated from the process perspective, namely whether the right information is used properly in the decision-making activity instead of from the outcome perspective (whether there is an accident because of the decision) by following the practice in decision analysis (Howard, 2007). This is because:

1) If we consider the outcome perspective, it becomes a retrospective learning activity instead of a prospective supporting activity. If we know the alternative will give a negative unacceptable outcome, we would not choose it;
2) The real outcome is (very often) outside the control of decision-makers once the decision is made;
3) Major accidents are seldom. If only outcomes (whether accidents occur) are evaluated, many actually poor decisions are viewed as good ones when no accidents happen. The fact is that decisions that seem good at the point of making them may not lead to good outcomes and vice versa.

The rest of the paper is organized as follows. In Section 2, the research process is described, followed by review, definitions and proposition in Section 3. Section 4 presents the analysis of information needs for decision-making processes. Possible information related conditions which may lead to mistakes are also described. Categories of risk information are summarized. A simple case study is presented to illustrate the differences in information needs also. The results are discussed in Section 5, and conclusions are in Section 6.

2. Research process

The objective of this paper is to identify information needs for risk-related decisions, considering varied decision-making process and decision problems. The research process is illustrated by Fig. 1, where bold texts highlight the research activities and the location they are described in the article and the rest of the texts are the main outputs. The shaded box is mainly a literature review.

3. Review, definitions, and proposition

3.1. Risk-related decisions

In this study, we define risk-related decisions as decisions that will influence the major accident risk for a sociotechnical system, either by decreasing or increasing the risk. They can be decisions that introduce hazards, release hazards, influence the function of barriers (Liu, 2020), impact on the occurrence probability of undesired events, mitigate undesired consequences, etc. Included in the definition are also decisions that influence risk "indirectly", such as decisions on maintenance budgets for safety equipment, manning levels for positions that manage and/or control risk, inspection and maintenance planning, etc.

It can be assumed that very few decisions are made with the intention to cause an accident, but decisions may influence risk without awareness. Normally, decision-makers try their best to maximize the benefits with respect to all objectives that they are aiming to fulfill, such as cost, scheduling, environmental performance and safety (Bofinger et al., 2015) and within the limitations in regard to time, resources, etc. It is difficult for decision-makers to measure and judge all concerns on the same scale or to have direct and correct perception of the risk of major accidents (Keeney and Raiffa, 1993; Merrick, 2011).

Some classifications of risk-related decisions have been given by Rosness (2009), The UK Oil and Gas Industry Association (2014), Bofinger et al. (2015) and Yang and Haugen (2015). Risk-related decisions vary significantly with regards to system diversity, product life cycle, accident prevention and consequence mitigation, their impacts on risk, targeted object and time span, existing knowledge and decision-making behavior etc. Even considering the same decision, the outcome could be affected by the available resources, the experience and knowledge of the decision-maker, whether there is one or more decision-makers and the perceived importance of the decision. The vast diversity in decision properties and associated contextual factors, makes it difficult to use single risk information that could meet all demands.

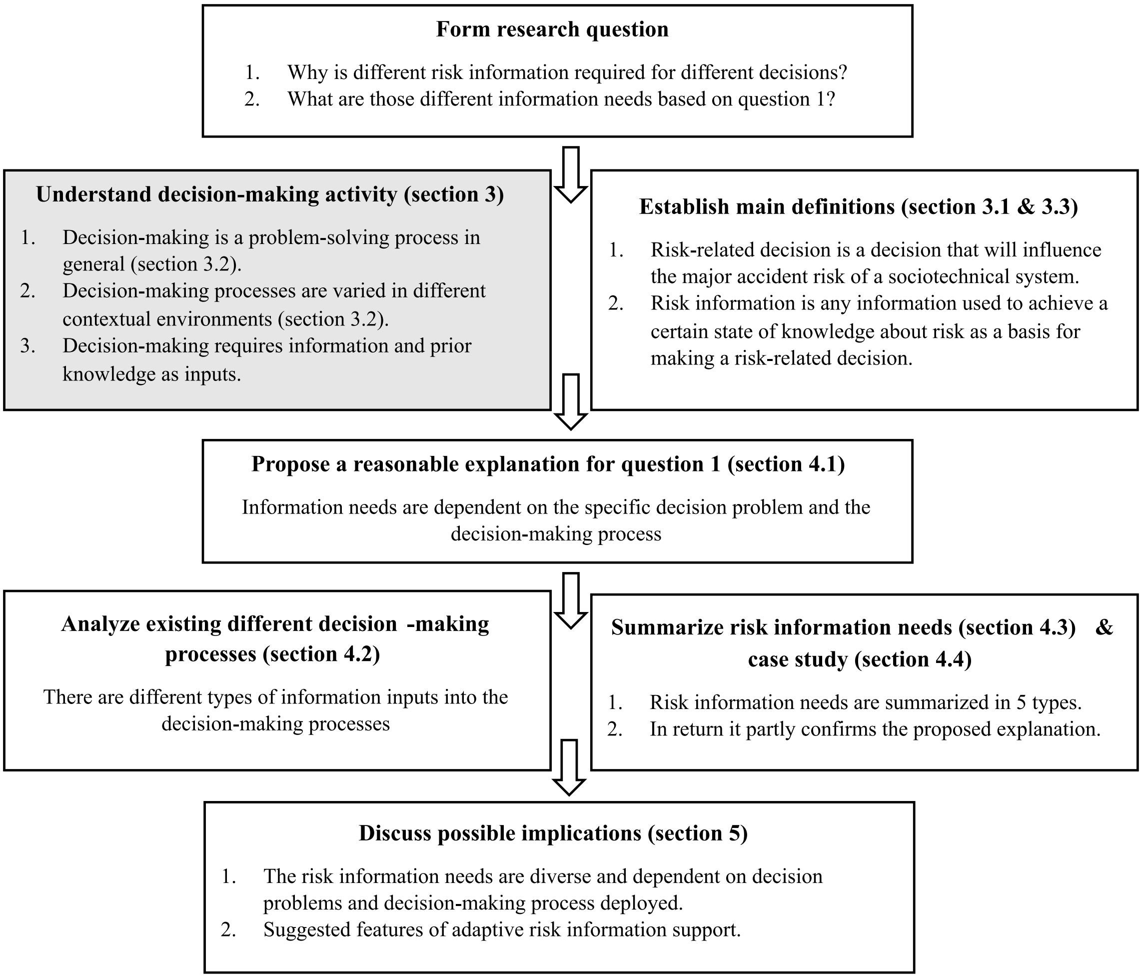

Fig. 1. Research process with activities and main outputs.

3.2. How are decisions made?

Many decision-making theories are developed for better understanding of how decision-makers make or should make decisions (Sullivan, 2009). In this paper, we adopt the opinion that decision-making follows a process from problem to solution, as shown in Fig. 2. Judgment, thinking, trade-off, making sense and reasoning are in this process. Prediction or projection is a key activity in decision-making. The existing decision-making theories and decision-making processes to a large extent show how risk-related decisions are made in different contextual environments.

There are 5 major groups of decision-making processes: bounded rational decision-making, rule-based decision-making, recognition-primed decision-making, sensemaking, and intuition. In a bounded rational decision-making process (March, 1994, 1996), decision-makers strategize and generate multiple alternatives and seek for the optimal choice or decision. Risk-informed decision-making is often studied based on the assumption of bounded rational decision-making theory (Aven, Vinnem and Wiencke, 2007; Haugen and Edwin, 2017; Zio and Pedroni, 2012).

Rule-based decision-making assumes that decision-makers know their situation by matching identities and rules and interpreting the implications of those matches. Decisions are predicated on the identity meanings that are established prior to taking actions (March, 1994, 1996). The identity meanings are usually associated with the general and self-recognized responsibilities and obligations in the organization. For example, the responsibilities and obligations for CEO, manager and front-line operators are different in risk management and accident prevention, and so are the rules they follow and the actions they take based on rule-following.

Naturalistic decision-making theories emerge in understanding how humans make decisions in certain circumstances, for example, how experts (surgeon, pilot etc.) make decisions under time pressure or in stressful situations. Under time pressure, it is more efficient to recognize patterns than to compare multiple alternatives to achieve the optimal outcome. The recognition-primed decision (RPD) model has been

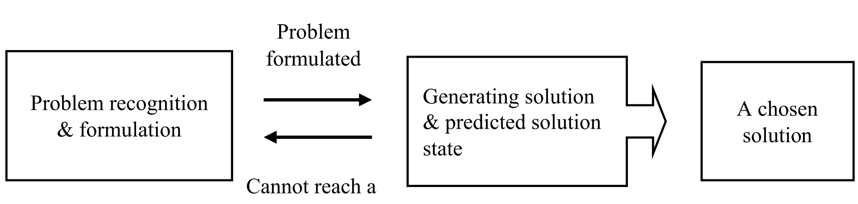

Fig. 2. Generic decision-making process from problem recognition to solution.

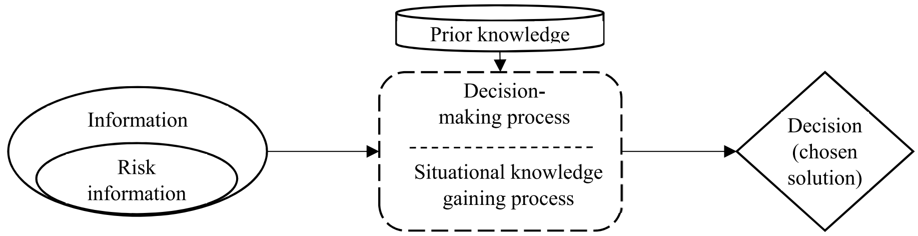

Fig. 3. Risk information, knowledge, and decision-making.

proposed from tracking the execution process of fire fighters and fire commanders (Klein, 1998). According to this model, decision-makers use prior experiences to recognize patterns and identify a single workable solution. Mental simulation might be used to see whether the solution works and determine the course of action. Situation awareness in dynamic decision-making also contributes to describe decision-making behaviors in operations of man-made systems (Endsley, 1995, 2015). Sensemaking (Bofinger et al., 2015; Choo, 2002; Klein et al., 2006a,b; Malakis and Kontogiannis, 2013; Richters et al., 2016) and intuition (Dane and Pratt, 2007; Hogarth, 2010; Kahneman, 2011; Kahneman and Klein, 2009; Salas et al., 2010) are also extensively discussed in the study of decision-making.

A mixed approach is also used in practices. For example, intuition and deliberate reasoning are combined to identify a problem or an alternative (Evans, 2010). Sensemaking is also used in problem formulation in the bounded rational decision-making process (Roth et al., 2010). In addition, Orasanu (1995) specifies a two-phase decision process model of situation assessment and response selection; pattern-matching, rule-following and comparing alternatives are the responses for selection in the two-phase model. Greitzer, Podmore, Robinson, and Ey (2010) proposed a combination model of situation awareness and mental simulation for guiding grid operator's decision-making.

In general, important factors that influence which decision-making process is applied when a decision problem occurs include:

- The decision-makers' knowledge related to the decision problem, including how much knowledge the decision-makers have and the degree of belief in the knowledge.
- Complexity and predictability of the system behavior (Snowden and Boone, 2007).
- Criticality of the problem.
- External constraints such as available time to make the decision (state of emergency) and available information sources.
- Number of decision-makers (whether there is one or several persons involved in the decision).
- Rules and norms for decision-making in the organization, such as NASA has its own risk informed decision-making procedure (Dezfuli et al., 2010).

For example, higher criticality of a decision problem will direct the decision-maker's attention to adopt a more holistic strategy, like a bounded rational decision-making process. More attention and resources in information collection will therefore be allocated. On the other hand, external constraints such as time pressure and limitation of available information will encourage an intuition-based decision-making process where less time and effort are required.

3.3. Risk information for decision-making

Provision of risk information for decision support has been a topic in areas such as risk-informed decision-making (ABS Consulting, 2001; Bofinger et al., 2015; Dezfuli et al., 2010; Office for Nuclear Regulation (ONR), 2017; The UK Oil and Gas Industry Association, 2014), operational risk analysis (Haugen and Edwin, 2017; Kongsvik et al., 2015; Sarshar and Haugen, 2018; Sarshar et al., 2018; Yang and Haugen, 2016), human-machine interface design (Abbott, 1990; Endsley, 2012 ; Rasmussen, 1983), severe accident monitoring and diagnosis (Allalou et al., 2016; Kim et al., 2015; Park and Ahn, 2010) etc. However, the majority of these studies focus on the best way of presenting risk using quantitative metrics, especially output from risk analysis, such as probability, consequences, expected utility, risk matrix. The underlying assumption is that risk information is quantitative measurements of risk that we get from risk analysis. The function of risk information is for detecting problems or presenting attributes of different alternatives, even though it may not be explicitly specified by the researchers. This utility is commonly stated as to increase risk awareness. A few studies of risk (safety) information needs has been conducted in public risk communication (Griffin et al., 2004; Huurne and Gutteling, 2008; Terpstra et al., 2014; Wiedemann et al., 1991) and risk (safety) management within the organization (Beck and Feldman, 1983; Nwagwu and Igwe, 2015; Sarshar et al., 2018).

The focus of this paper is risk information, and it is useful to distinguish between "information" and "knowledge". A good way of distinguishing is the statement by Machlup and Mansfield (1983); "information is acquired by being told, whereas knowledge can be acquired by thinking". Knowledge is information that have been sifted, organized, and understood by a human brain (Case, 2012). Information implies transfer, while knowledge is a state ("knowing"). We can create new knowledge without taking in new information from the external environment. In this paper, the definition of knowledge is adopted as "a fluid mix of framed experience, values, contextual information, and expert insight that provides a framework for evaluating and incorporating new experiences and information" (Davenport and Prusak, 1998). In decision-making, information and prior knowledge of the decision-makers are the inputs and a chosen solution is the output, as illustrated in Fig. 3. Here, the decision-making process is also a situational knowledge gaining process because the knowledge of decision-makers changes from initial state to a new state with information acquisition. Situational knowledge means all forms of knowledge about a particular event or practice. Therefore, the study of information need is also a study of situational knowledge requirement.

In this paper, we define risk information as any information that is used to achieve an improved state of knowledge about risk as a basis for making a risk-related decision. Such a definition is much wider than plain risk numbers or risk matrixes or other direct expressions of risk. Risk information should be able to describe the real situation and be understood by decision-makers in communications. Risk information can be distributed across the physical, digital and social environment. Risk information includes at least the following categories:

- Direct expressions of risk, including risk measurements, expected values, probability distributions, consequences, hazardous scenarios, risk indicators, qualitative descriptions.
- Indirect expression of risk, for example, factors which influence risk, stop criteria, constraints, distance to the stop criteria and constraints.
- Information about how risk is interpreted and estimated, including the input data, assumptions and the process.
- Information that represent the validation, limitation and accuracy of the information mentioned above. This category expresses the uncertainty of the information, also named as meta-information.

4. Framework for information needs in risk-related decision-making

4.1. Two dimensions influencing information needs

It is reasonable to assume that two dimensions of factors influence the information needs in decision-making: the problem dimension and the decision-making process dimension, as illustrated in Fig. 4. More specific factors can be identified in these two dimensions: 1) identity (tasks and job responsibilities), 2) changes of problem due to development of situation, or decision-maker's definition of risk and values, 3) feature of problems (complex, poor-structured, unclear instructions, frequency), 4) knowledge (bias, experience improving or skill degradation, training, awareness), 5) environmental factors (attention, distraction, time constraints, organization's information environment, established interaction patterns). Fig. 4 is a simple and conceptual representation for the analytical purpose, while in reality these factors can be interlinked in some degree. For example, a certain task may have some specific features (whether it is complex, etc.) and the environmental factors (time constraints, distractions, etc.). In addition, some problems may demand a certain type of decision-making process.

The problem dimension deals with the exact decision issue that the decision-maker tries to resolve. A problem is formed as a gap between the true state and desired states (Jonassen, 2000), e.g. a deviation from a norm, standard, or objectives. Concerning all relevant decision-makers (who are the relevant controllers of risk), their problems are defined

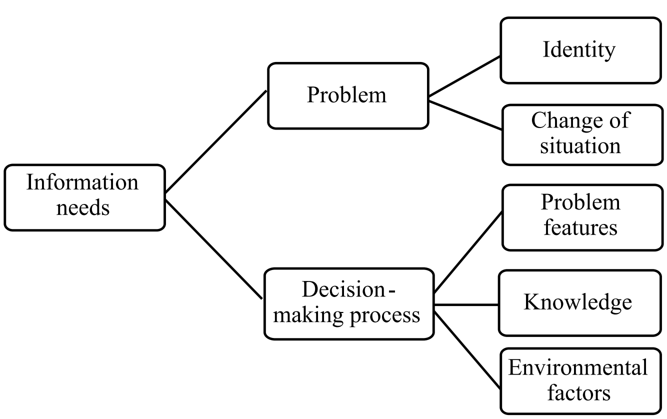

Fig. 4. Two dimensions for identifying information needs.

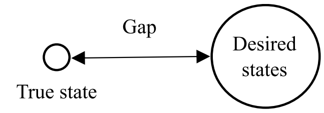

Fig. 5. Illustration of problem definition.

as the gap between their production objectives, safety objectives and other objectives, and the actual state of the system, see Fig. 5 for illustration. In the figure, we use the size of the circle to indicate the number of states. The true state is represented by a small circle, while there may be many desired future states (a large circle). The whole problem space consists of objectives related to the decision issue, background, and circumstances of the problem, which activity or system function & component or interaction or work procedure. In this regard, a decision-making process presents the way that the decision-maker engages in. Such a process can be analyzed to evaluate the information needs at each stage of the process for reaching the correct state of knowledge required. For example, Jenkins et al. (2017) use the decision ladder (Rasmussen, 1986) to elicit information requirements to support interface design of radiotherapy.

In this paper, only decision-making processes are studied for information needs. Different decision-making processes are analyzed in the next section to understand their information requirements.

4.2. Information needs for different decision-making processes

4.2.1. Bounded rational decision-making process

When a decision-maker is facing a critical and complex decision with little knowledge, the rational decision-making process is likely to be engaged. This process requires much effort from the decision-maker in both information collection, reasoning and deliberation. What alternative will be chosen heavily relies on the predicted consequences of all proposed alternatives and preferences. The environment in predecisions and outputs from the implementation of decisions are included in the decision-making process (Harrison, 1996). Table 1 summarizes the proposed information elements that could be used a bounded rational decision-making process.

Table 1
Role of information in (bounded) rational decision-making process.

Process element	Information element required to support the process
Intelligence: Identifying and structuring the problem and defining the context of the problem	1) Information to identify and structure the problem. 2) Information about the context in which the problem has occurred.
Design: Searching for alternatives	Information needed to generate or infer alternatives for decision-making if alternatives are not defined already. If alternatives already exist, information about these alternatives is required.
Choice: Screening and evaluating	Information about preferences (values that are derived from objectives), attributes of each alternative, suitable decision rules.
Monitor	Feedback information about outputs from the implementation of the decision.

Table 2
Information element in rule-based decision-making process.

Process element	Information element required to support the process
Situation	Cues which characterize the situation which is stated as the "if-conditions" in the existing rule.
Identity	Information about responsibility, positions of the decision-maker to judge the obligations and diagnose rules.
Rule	Information about existing rules which apply to the identity in such a situation.

4.2.2. *Rule-based decision-making process*

Rules are commonly applied as safety controls to constrain individual and organizational behaviors. In a rule-based decision-making process as a logic of appropriateness, the decision-maker needs to recognize the scenario for which rules exist (Rasmussen, 1983). Three questions need to be answered (March, 1994); 1. the question of recognition: what kind of situation is this? 2. The question of identity: What kind of person am I? Or what kind of organization is this? 3. The question of rules: What does a person such as I, or an organization such as this, do in a situation such as this?" The goal of the process is to establish identities and to match rules to situations. The rules may be formal, as in procedures or operation instructions, but may also be informal and rooted in culture, such as norms and established practices. Applying rules is a proper way to constrain behavior if there is high predictability in the system or severe consequence of misconducting. In new and emergent areas, there may not be enough time or experience to form good practice and therefore form rules. Table 2 summarizes the proposed information elements that is required in a rule-based decision-making process.

There are many causes of mistakes in rule-based decision-making, even though rule violation is not necessarily equivalent to decision failure (Reason et al., 1998). The following situations could be considered relevant to information deficiency: 1) not knowing the rule exists, especially for new employees, cross-organization supervision, 2) not informed of change in rule, 3) not clear or ambiguous instructions and texts, 4) incorrect perception of the situation by the decision-maker, 5) conflicting rules (multi-rules) exist for the situation, and 6) not evoking the right identity in the situation, e.g. the appointed on-site emergency team do not realize that they have to respond.

4.2.3. *Recognition-primed decision-making process*

The recognition-primed decision (RPD) model, as shown in Fig. 6, is proposed by Klein (1993a) to describe how experienced (skilled) decision-makers make sound decisions under time pressure. They do not compare different options but do pattern matching, mental simulation of the action course to find a solution that works and then implement the first workable solution. This represents a different kind of problem-solving strategy that demands specialized training where real-time, high-pressure decisions must be made. Their rich experience and knowledge let them "understand what types of goals make sense (so the priorities are set), which cues are important (so there is not an overload of information), what to expect next (so they can prepare themselves and notice surprises), and typical ways of responding in a given situation". And "the decision-makers do not start with the goals or expectancies and figure out the nature of situation" (Klein, 1993a, 2008). Table 3 summarizes the information elements required to support an RPD process.

Mistakes happen in experienced, knowledge-based decisions, where memory may be wrong during cue recognition and mental simulation, or just due to lack of confidence (Klein, 1993b). In this case, to ensure the right decision in those critical situations, situation shaping cues and information about constraints of action should be provided. In addition,

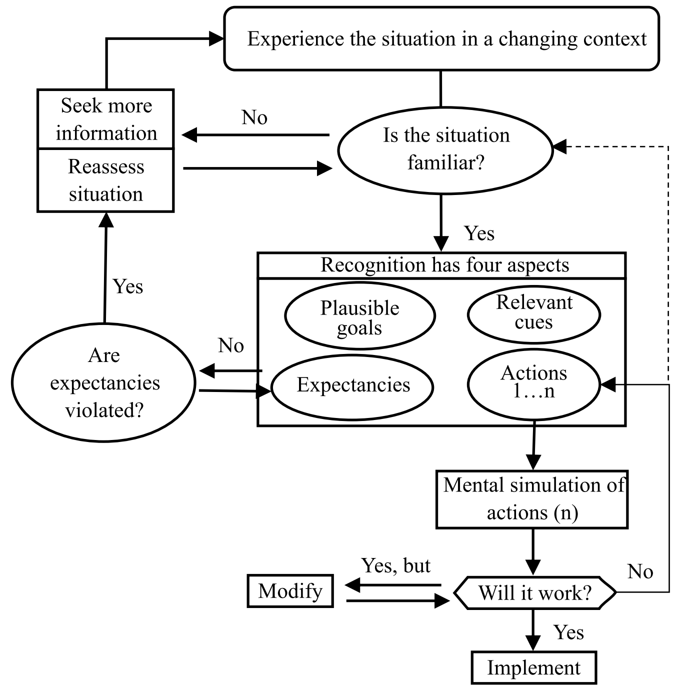

Fig. 6. Recognition primed decision-making process (Klein, 1993a).

Table 3
Information elements in the RPD model.

Process element	Information element required to support the process
Situation recognition	Cues, plausible goal, expectancies, actions which characterizing the situation or pattern which is familiar to the decision maker.
Mental simulation	Mental models from memory that present the course of action and corresponding consequences of the action (whether the action will work to achieve the goals). Constraints that limit action course.
Action modification (occasional)	Information about the physical situation.
Action judgment	Confirmation that the action will work.

information that confirms the situational knowledge will be helpful. Action course generated from decision support aids that represent the dynamic physical situation can reduce imagination errors during mental simulation. Rapid feedback information from operator's action can enforce learning and pattern recognition in the future.

4.2.4. *Sensemaking in decision-making process*

The definition of sensemaking is adopted as "a motivated, continuous effort to understand connections (which can be among people, places, and events) in order to anticipate their trajectories and act effectively" (Klein et al., 2006a). There are other interpretations of sensemaking, from generic definitions to specific application fields (Chater and Loewenstein, 2016; Linderman et al., 2015; Sandberg and Tsoukas, 2015; Weick, 1995). Sensemaking is the deliberate effort to understand events and begins when someone experiences a surprise or perceives an inadequacy in the existing frame (process-driven) and the existing perception of relevant information (information-driven) (Klein et al., 2007). Sensemaking needs cues as triggers, such as surprises that can be interpreted as a lack of preparation, vigilance, control, or discipline in an organization. The cues can be issues, events, or situations

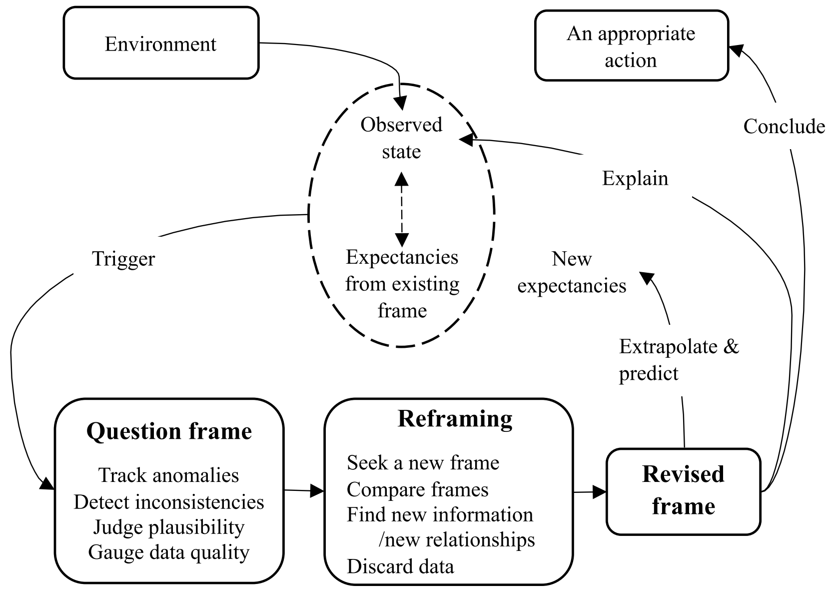

Fig. 7. Modified sensemaking process from Klein et al. (2007).

with ambiguous meanings and/or uncertainties. Examples are applying new technologies during operation, changes of rules or operation instructions, and other changes that create dynamic and less predictable environment where existing frameworks for solving problems repeatedly and maintaining safety do not work (Maitlis and Christianson, 2014). Unexpected events do not necessarily trigger sensemaking, which only occurs when the discrepancy between the expected state and observed state is large enough, and important enough, to cause individuals or groups to ask what is going on and what they should do next. Actions to find more information for explanation might be part of sensemaking. For example, astronauts react to a crisis situation by trying to make sense of the situation by making checks and running through procedures carefully and systematically to see whether they could establish what had happened (Stein, 2004). Klein et al. (2007) present a data/frame model of sensemaking which describe sensemaking as the process of fitting data into a frame and fitting a frame around data to explain prior events and anticipate future events. Certainly, the accumulation and enrichment of information is part of sensemaking – the synthesis of data into higher-order inference. The sensemaking process is shown in Fig. 7.

The process of sensemaking requires:

1) Information which triggers the process;
2) Information (cues) which indicates and confirms plausible explanations.

Sensemaking is retrospective, decision-makers build up their own story/frame in a cyclic and iterative manner to assemble the information they received. Sensemaking depends on the interaction between people, situation, and knowledge (Klein et al., 2006a). Those characteristics of sensemaking are relevant to information support. For where sensemaking is required, the system should be designed to be flexible and allow information searching, action and exploration in it. Errors of sensemaking occurs when the wrong frame is adapted. For example, when decisions are made in a narrow frame which makes the solution seem satisfactory or most beneficial while it ignores some important but not easily visible consquences. Such occurrences may be due to several reasons: 1) not enough knowledge to interpret information and identify new frame, 2) important cues have not been observed or recognized, and 3) information indicates several possible frames and competes for plausibility.

4.2.5. *Intuitional decision-making process*

Intuition is one of human's basic cognitive activities and it goes on unconsciously. A definition of intuition is that "they knew without knowing how they knew" (Kahneman, 2011). Decision-making relying on intuition is fast and effective. In real life, intuition is extensively applied (Dane and Pratt, 2007; Khatri and Ng, 2000). In the decision-making process, intuition can have two functions. First, intuition serves as input to deliberative processes. For example, in highly regular environments, decision-makers can use intuition to sense the irregularities. Second, when facing a regular decision task, decision-makers can intuitively generate a workable solution automatically (Çizgen and Ulusu Uraz, 2019; Rasmussen, 1983). Intuition seems similar to pattern-matching in recognition-primed decision-making model, but it is not the same thing because pattern-matching is a conscious activity.

It is necessary to differentiate immature (general) intuition and educated (expertise-based) intuition with regards to the accuracy (Salas et al., 2010). Expertise-based intuition is where the decision-makers have developed a deep and rich knowledge base from extensive domain experience (Salas et al., 2010), therefore can be accurate. As clarified by Hogarth (2010), errors in intuitive thought are essentially 1) those of bias induced from past experience (e.g., using an inappropriate anchor in judgment) or 2) personal transient impacts from emotions and salience of some information. Expertise-based intuition is likely to be relevant to use in regular decisions in predictable system environments but not valid for emergent situations. It takes time to develop intuition, which means that it is not possible for decision-makers when facing an unfamiliar, unpracticed condition or issue (Kahneman, 2011; Kahneman and Klein, 2009). To maintain and make use of expertise-based intuition, information inputs from the system and its environment should be regular and directly sensible even without attention or conscious awareness. The same information items as experienced or learned in the past should be present.

4.3. *Types of risk information needed for risk-related decisions*

By considering the information needs of the various decision-making processes in the previous section, we can conclude that the needs for risk information in decision-making can be classified into types listed below. Each type represents a specific function and content of risk information in decision-making.

Type 1: information reflecting potential existence of safety problems for problem detection and identification. Such information can be a direct expression of the safety problem or an indirect expression but sufficient for the decision-makers' inference of the problem, such as results from risk evaluation showing a gap between risk analysis output and risk acceptance criteria. Examples of direct expression are a) the estimated worst consequence is unacceptable, b) the estimated probability of explosion during the mining operation is far higher than the acceptable criterion, or c) the plane is likely to crash before it reaches the planned destination. Examples of indirect expression from scenario parameters, are a) the altitude deviation from terrain is very close to the separation threshold, or b) fuel quantity may not be sufficient to reach the planned destination for the flight. In addition, it also includes information which forms the if-conditions of a certain rule in rule-based decision-making process. For example, considering an existing procedure: "Shut down the process if process parameters a, b, or c are exceeded. In such a situation, information about the process parameters a, b, and c is critical for the decision-maker to judge whether to take the specified action in accordance with the rule.

Type 1 information is not necessarily a simple number. It could be a set of situation features and safety value and objectives which formulate the problem. It would be impossible to detect a safety problem without considering safety as valuable, such as the mistake in Challenger lunch decision (Vaughan, 1996).

Type 2: information of contextual factors. This could be e.g. information about the severity and urgency to make the decision. This information helps the decision-maker evaluate the relative importance of the decision problem compared to other tasks at hand and judge how much effort should be put into resolving the decision problem and how fast the action should be implemented.

Type 3: information about constraints, system boundaries, specifications, and requirements of workable solution. Examples are operating limits, critical operating parameters, safety margins, guidelines, availability of required resources and cause-effect relationships. This group of information is used to generate solutions in the bounded rational decision-making process and mental simulation in the RPD process. Type 3 information can be classified into three subtypes according to their functions.

Subtype 3.1: safety margins and operating limits. Typical examples are 1) minimum operational level of redundancy of safety-critical equipment must have at least three of five pumps operating or available and 2) the distance between two cars on the highway should be at least 100m if the speed is greater than 100 km/h.

Subtype 3.2: information about requirements for workable solutions and availability of required resources, such as money, time, space, a special skill, or a certain system/subsystem condition that is required for an action to be feasible.

Subtype 3.3: cause-effect relationship between a proposed solution and possible outcomes, such as "sand can be used to cover chemical substances" therefore "sand can separate chemical and air" therefore "sand can be used to extinguish chemical fire". There is a strong causal link between the proposed solutions and possible outcomes. This information is important for generating a solution to achieve the desired objectives.

Type 4: attributes or features of alternatives for comparing and evaluating. A decision-maker needs to make a judgement based on Type 4 information on which alternative is going to achieve the maximum benefits. Typical examples are decrease/increase of risk or probability of introducing hazards/undesired events of the alternative sets.

Type 5: rules that are set to maintain safety or control risk, such as procedures, rules, and standards. These rules have a function of guiding actions under certain circumstances for certain identities in the organization. It has been accepted that some professionals set their own situation-specific rules. In this kind of circumstances, information about the rule does not need to be supplied. However, there are rules which are set by others such as designers, managers or others according to previous experiences or accidents. Those rules need to be clearly communicated and reminded when situations, where the rule applies to, show up.

4.4. *Case study for illustration*

In this part, we use the handling of iceberg threat to an offshore installation as a case to illustrate the differences in information needs when different decision-making processes are deployed. We consider several similar scenarios related to the handling of iceberg threat and avoid serious collision between iceberg and FPSO (Floating Production Storage and Offloading unit). The basic scenario is that an FPSO is in production during the season when iceberg collision may occur. The offshore installation manager (OIM) is the one in charge of handling situation where an iceberg threatens the FPSO. The relevant objectives of the OIM is to keep the FPSO in operation and to keep it safe (no serious damage from collision).

4.4.1. *Scenario A (sensemaking)*

Iceberg season is coming. So far there is no visible iceberg coming toward the installation. However, another FPSO in the same area suddenly sails away. The OIM hears about this (abnormal observed from the environment) and wonders why this is happening. FPSO sails away only on few occasions and something serious might be happening. There may be several reasons for moving off location. One possibility is to avoid severe environmental conditions/loads. Another one is being taken off location for dry-docking, repair, or maintenance work. Then the OIM possibly starts to search for relevant news and make some calls to those who possibly know what is happening. At the same time, the manager gets informed that some big icebergs are coming towards the field (additional information to confirm the hypothesis) and realizes that very likely the other FPSO is moved off from the location to avoid iceberg collision and disconnection is necessary to avoid iceberg collision for the FPSO of which he is in charge (confirms the threat and chooses corresponding strategy to handle it).

4.4.2. *Scenario B (bounded rational)*

An iceberg is detected by radar. The iceberg can damage the hull structure and positioning system if a collision occurs. The forecasted drift Closest Point of Approach (CPA) is about 0.4 NM from the FPSO and Time to Closest Point of Approach (TCPA) is 4–9 h. There are several ways to handle icebergs: 1) disconnect the FPSO and sail away, 2) change the direction of iceberg by towing or use of water cannon, 3) fragment iceberg by explosive techniques such as shooting or implanting slow-burning explosives Thermite, 4) closely monitoring the iceberg to get a more accurate assessment of the threat including load dynamics and trajectory prediction; if the iceberg is not threatening the FPSO, then it can be ignored; if the iceberg is threatening, then disconnection should be conducted. The costs, requirements, constraints, and success chance of each solution should be considered when deciding which one to choose. After a thoroughly deliberation, the OIM concludes that option 4) is the best.

4.4.3. *Scenario C (rule-based)*

A detailed procedure has been made to guide how to handle this problem. A zone-based guideline has been provided in the ice management procedure. Different response actions are given based on the FPSO serviceability criteria related to iceberg size and significant wave height, zone of the iceberg and forecasted drift CPA. The manager finds this procedure and compares current iceberg situation (threat level of the iceberg, location of the iceberg, and zone location of the forecasted drift CPA of the iceberg) with the requirements in the procedure. The comparison indicates that the FPSO should be disconnected at the current stage. The OIM decides to disconnect the FPSO and sail away.

4.4.4. *Scenario D (recognition-primed)*

Iceberg season is coming again. The OIM has experienced such ice season for many years and has had formed a series of strategy. First, she/

Table 4
Information required for the four scenarios about iceberg handling.

Scenario	Information
A (sensemaking)	1. Information about another FPSO is disconnected and sailed away. 2. Information about severe iceberg presence.
B (bounded rational)	1. Information about the iceberg presence. 2. Information about collision risk prediction of the iceberg, including the potential consequences of collision, the likelihood of collision, the range CPA and range of TCPA. 3. Information regarding the costs, requirements, constraints, and overall successful chance of each solution. 4. Information about the algorithm to determine which one is the best.
C (rule-based)	1. Information about iceberg presence 2. Iceberg handling procedure. 3. Current condition of the iceberg corresponding to the procedure statement, including threat level of the iceberg, location of the iceberg, and zone location of the forecasted drift CPA of the iceberg.
D (recognition-primed)	1. Information about iceberg presence 2. Information of the size of the iceberg, distance from the FPSO, estimated CPA and TCPA. 3. Information about specific requirements and environmental constraints for chosen solutions. Such as: time and tools required, weather conditions to conduct towing successfully.

he monitors the iceberg movement closely and get an accurate estimation of the threat and determine what to do next. If the iceberg size is medium, towing and cannon shooting would be applied to change the direction. If there are many icebergs and the sizes of some icebergs are not easy to estimate, the manager will order to disconnect the FPSO and sail away, etc. In this case, a series of patterns and corresponding measures have been established. When a medium size iceberg is detected close to the FPSO, the estimated Closest Point of Contact is less than 0.1 NM, and Time to reach the Closest Point of Contact is 2–2.5 h. The manager decides to tow the iceberg first which is often the most used iceberg handling technique. However, the time required to establish a successful towing is 4 h. The available time is not enough to conduct a tow; eventually, the manager decides to disconnect the FPSO (which requires about 40 min).

Comparing the four scenarios above, we can see that sensemaking happens in an unclear environment so that the decision-maker needs to collect information and form her/his own judgment about what is happening and take actions based on the causes of the scenario. While for the other three scenarios, there are clear signals about the problem. In the process of bounded-rational decision-making, the decision-maker needs to spend quite much time to collect information compare different known solutions and find out the best in terms of safety and operational limits and cost. In the opposite, rule-following is much simpler. When it comes to recognition-primed decision-making process, much experience and knowledge is required about when should do what and how. For sensemaking, good information collection is required for the decision-maker to find out what is truly happening combining prior knowledge. For rule-following, information is required to know the match of current condition and demanded condition in the rule. For recognition-primed decision-making process, the decision-maker relies on the signals she/he gets and environment constraints for chosen solution to judge whether the chosen solution will be successful or not. Therefore, we can conclude that which decision-making process will be applied is context-based, and information needs will be different, as showed in Table 4. However, information available to the decision-maker might also change the decision-making process. For example, if the decision-maker finds out that there is a rule regarding iceberg handling which should be followed and the real iceberg threat, then the other three theoretical processes might not occur either.

5. Discussion

In this section, we want to expand a bit our observations and insights further on 1) decision-making process, 2) information for uncertainty reduction in decision-making, and 3) possible implementations in decision support.

5.1. Decision-making process

Any process has its own background, specific environment, and requirements to lead to a good decision. For example, if a procedure or norm exists for specific types of decisions in the organization, using work permit approval or action approval as an example, the information support system should be designed to ensure the required information elements are effectively supplied. The diversity of information needs is part of the fact. Therefore, risk information categories summarized in this paper are not necessarily required in every case of risk-related decision-making.

As mentioned earlier, predictability and state of knowledge, criticality and external constraints influence the decision-making strategy that a decision-maker may deploy. From the analysis of decision-making processes, we can see that the higher the predictability of the system behavior, the simpler, more efficient decision-making processes can be applied to achieve the same decision quality. Predictability is influenced by several system properties including complexity, inherent uncertainty of system behavior and available knowledge about the system. When it comes to external constraints including available time, accuracy and availability of risk analysis methods, information sources etc., the shorter time available, the more efficient process will be engaged. When available information resources are limited, general intuition might be applied. However, the less prior knowledge the decision-makers have about the situation, more deliberate effort will be put into it and there will be a higher demand for information. In addition, it is obvious that the bounded rational decision-making process is not constrained by working memory as much as RPD or sensemaking. The capacity limitation of working memory implies that certain information-mapping tools might be needed for RPD or sensemaking for resolving complicated issues.

There are two basic predictions required across the entire decision-making process. The first is the prediction of what is going to happen if no action is taken. This is part of the problem formulation and is what many risk analyses do in risk management and online accident diagnosis and prognosis (Ahn and Park, 2009; Allalou et al., 2016). In order to formulate a problem, safety objectives must be well understood (Merrick et al., 2005) and a safety criterion must be established (can also be called boundary or constraints) (Merrick, 2011). The second prediction is what will happen, conditional on alternative courses of action.

However, decision-makers do not necessarily explicitly conduct these two predictions. The common definition of "choice-based" bounded rational decision-making focus on the second prediction. Situation awareness emphasize the first prediction about what is going to happen based on the current situation (what is going on right now). Mental simulation in RPD use imagination to predict whether the course of action will work. Moreover, sensemaking is about using actions, checking and reasoning to test out connections in order to project and act further. As for the rule-based decision-making process, the two predictions were made when setting up the rule. Therefore, decision-makers who follow the rule do not need to make any extra effort to make predictions.

Another important prediction is the objective prediction because it directs changes in the problem. The objective might change when time goes, or the risk perception changes. This is more critical when it comes to long-term (across years) decisions than short-term ones. This is applicable to the case when production objectives are overrated in early phases of projects while later, risk is of more concern. An earlier problem may be not a problem anymore or the other way around because of changes of objectives. In organizations, objectives need to be communicated as information, so does the change of objectives.

In real organizational decision-making, sensemaking may be part of normal decision-making activities in daily operation in situations where decision-makers reactively respond to unfamiliar system changes, external disruptions, malfunctions etc., for example, the decision-making process in emergency and crisis handling (Baber and McMaster, 2016; Kefalidou et al., 2018; Richters et al., 2016). Therefore, facing rapidly changing technology and society, sensemaking is likely to be an important element in decision-making for risk management, because sensemaking provide a way of handling uncertain environments which is inherent to the circumstances of risk-related issues. The design of sociotechnical systems should support efficient and accurate sensemaking towards the establishment of resilient systems.

5.2. Information to reduce uncertainties in the decision-making process

Uncertainty that is understood as limited knowledge is often discussed in decision-making (Apostolakis, 1990; Aven and Reniers, 2013; Lipshitz and Strauss, 1997). Knowledge increases when more information is taken in and perceived through the whole decision-making process, as explicit knowledge is likely to be elicited from information in a very short time. The perception of uncertainty will also trigger active information seeking. The requisition of information in turn reduces the uncertainty (increase the amount of relevant knowledge and increase the belief of the knowledge) of the decision-maker. We can assume if knowledge (what the decision-maker already knows) is not enough for a sound decision, then extra information is required and should be supplied by the organization or system. Therefore, we may need to differentiate what information we need to retrieve from outside and what we have. On the ther hand, uncertainty also affects our ability to interpret the received information and to make predictions about the future. In addition, what the decision-maker already know also matters. It directs the decision-maker's attention by relevance, links the decision-maker to a fact, and allows the decision-maker to take in new information from the environment (Nagel, 2014).

Information need is a knowledge gap between what is already known and what should be known. This means that there is a recognized anomaly in the user's state of knowledge concerning some topics or situations. The collection of information in all categories can reduce uncertainty, increase the robustness to handle remaining uncertainty, and increase the knowledge or confidence in knowledge. It is a continuous process by which information is interpreted at each step of the decision-making process. The proposed categories of information can be used to further explain how lack of information and uncertainty impact decision-making and lead to poor decisions. For future application, uncertainties of the required information in the decision-making process should be presented together with the information itself or lack of information. As for uncertainty reduction, at least four strategies can be applied: 1) searching for existing information, 2) confirming or discarding information by using other information sources, 3) using existing information to form new information by analogy or inference, 4) testing and interacting with the system environment to get new information.

Uncertainty reduction is a key process in decision-making because decision-making involves prediction in which uncertainty plays a large role. When it comes to predicting the future, we should not assume that we could have perfect information. However, it is easier to achieve a more accurate prediction when the time span of prediction is short and influencing variables are few. In order to get relatively more accurate risk estimations for different time horizons and system complexity levels, we need to choose the right risk analysis methods and carefully define the system under concern. The results of risk prediction will impact risk control actions, and again influence risk, back and forth. The loop of risk prediction and risk control action also demands simulation in risk estimation and control.

5.3. Adaptive risk information support

In any large organization, many decision-makers are involved in risk-related decisions in operation. However, those decision-makers face different risk-related decisions due to their distinct positions and responsibilities. The link between decision-makers from different levels are made by the objective hierarchy, shared values and preferences, and organizational structures. For example, outcomes of high-level strategic decisions will constrain lower level planning and execution decisions. Those constraints can be spatial, temporal, technical, resources or objective related. Planning decisions are commonly constrained optimization problems, which are to allocate the planned activities within the constraints. The information needs for these decisions will be different. Decision-makers will require different information when the decision they face changes and when their way of resolving the problem changes with increased experience and knowledge.

The most difficult part of information support is when contingent but critical situations show up, for example the Fukushima Daiichi nuclear disaster (The National Diet of Japan, 2013). Situations that indicate the occurrence of a major accident do not repeat often. Decision-makers do not have enough experience to conduct mental simulation correctly or to generate workable actions. Very likely, rules such as instructions will not exist. Sensemaking has a high potential in such situations. However, sensemaking is directed by plausibility and not necessary accuracy, which means that the perception can be wrong. Such may imply that we cannot rely on intuition, sensemaking, RPD or rules for decision-making about major accidents. Bounded rational decision-making process usually takes a long time, which may not be acceptable in emergency situations when a major accident is developing. The possible solutions can be 1) direct an accuracy guided sensemaking in decision support or 2) make a fast analytical tool to project the future and tell the operators the requirements of workable solutions (for example, how long time until the critical thresholds are exceeded) and this fast analytical tool must have been prepared and available all the time.

To manage the risk-related decision-making across different decision-makers in the organization, constructing an adaptive information supply system will be helpful. Such a system should have the following features:

1. It provides targeted risk information to specific decisions and decision-makers.
2. The supplied risk information first helps the decision-makers detect potential risk issues.
3. The supplied risk information not only fits the needs of the decision, but also supports the decision-makers' strategy for resolving the issue to ensure effective utility. This means it should meet the situational needs and match the experience and knowledge of the decision-makers. This can also reduce information overload and save time as every piece of information retrieval takes effort.
4. It provides warnings about mismatch of deployed decision-making process and decision-maker's knowledge base and resources, which are required by the decision-making process, to avoid decision failures.
5. It is able to provide physical accident causation models for the decision-makers to deduct inferences when they encounter unfamiliar situations or surprises to get a more accurate understanding of the development of the accident.
6. The supplied risk information changes when the risk-related decisions change.
7. It is able to give a rate about the importance of a risk-related problem (not necessary to quantitatively evaluate the importance, but more like scenario-oriented, qualitatively) for resource allocation such as attention and time because any person in the organization usually need to handle many tasks at the same time.
8. It provides feedback about the outcome of the decision for monitoring effectiveness and learning.

It may be difficult to achieve those features listed above (at least some of them). However, we think that the difficulty does not necessarily influence them working as principal design guidelines. Designers should strive to get as close as possible for the decision problems of concern. Information system for routinely responsive tasks is the easiest (Howard, Hulbert and Farley, 1975). Therefore, designers of information system can perhaps classify decisions into different categories and design varied functions for each of them.

The study of information needs is meaningful due to the very normal contextual factors that constrain our access to infinite information or infinite time to search for information or creating the proper knowledge. Even though decision-makers are actual information seekers, who is continuously looking for what is missing. When it comes to information acquisition, balancing the accuracy, cost and efficiency in information retrieval can be further discussed during implementation. We emphasize again that training is important to prepare knowledge that the decision-makers need (Orasanu, 1995). The better training, the more efficient strategies can be adopted for decision-making. In addition, sufficient information supply does not necessarily lead to good decisions. It also depends on the decision-maker's perception of the information.

6. Conclusion

There is a wide range of risk-related decisions across the whole operation period of any major socio-technical systemin the process industries. To provide targeted risk information to the distributed decision-makers and support an effective and efficient decision-making activity and eventually contribute to accident prevention, their decision tasks and way of making decisions should be analyzed and considered, especially when designing decision support tools.

In this work, we have proposed a definition of risk-related decisions that influence major accident risk in sociotechnical systems and a wider definition of risk information. Those definitions/terms could raise the attention and potentials in both academia and industry in managing risk-related decisions from the angle of information support and promote further research in this topic. By analyzing commonly applied decision-making processes for risk-related decisions, risk information is found to 1) detect and characterize risk-related decision problems, 2) indicate the severity and urgency of a decision, 3) state requirements of workable solutions and environment constraints to design solutions, 4) represent attributes that are used for comparing and evaluating alternatives or solutions, such as predicted possible consequences of the set of potential options, and 5) act as rules which are set to maintain safety or control risk. The actual function the risk information is dependent on the actual decision-making process. The information categories based on decision-making processes also put the decision issues in a structured manner and make the problem solvable. The framework of information needs proposed in this paper can facilitate future research that intend to ease the problem of information deficiency in decision-making by designing improved information system. Moreover, the study of information needs can further direct the risk information distribution to different decision-makers and related knowledge management in the organization and increase our understanding about how organizational factors contribute to the occurrence of accidents.

However, there is no detailed exploration of specific risk-related decisions in this paper. It would be interesting to investigate decisions in the perspective of accident prevention from the life cycle span of system development by employing a causation model (for example, by investigating decisions which shape risk influence factors) and responsibility distribution in the sociotechnical system. In addition, it is interesting to enhance the combined advantages of different decision-making processes, such as further exploring and facilitating accuracy guided sensemaking in handling contingent and safety-critical situations. The dependence on the knowledge of decision-makers also reminds us about the need to call for further research on the knowledge requirement of decision-making activities and further on how to enhance training for risk-related decision-making, such as 1) training which improves the causal-reasoning capability of decision-makers, 2) including accident causation models in the training material which give the operator predictive meaning of system parameters and cues (by training programs, learning from experience, storytelling).

Author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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