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A Concept of Information-based Strategy for Accident Prevention

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With the increasing use of sensor technology, it has become common practice to use collected data to reduce uncertainty and ensure safety. This paper presents the concept of an information-based strategy for accident prevention that puts more weight on hazard detection and monitoring and makes use of data obtained. The information-based strategy can be considered as a new barrier for safety management. The functionality of this strategy is neither to reduce the probability of an undesired event nor to reduce its consequence directly but to create a state of knowing for decision-making. The proposed concept can provide theoretical support for remote safety management of e.g., offshore installations. In addition, it can promote investigation about safety information environment in the organization and information behavior in resolving risk-related problems. In this article, some existing accident causation theories to provide the rationale for the proposed concept are elaborated. In addition, it gives an overview of typical types of information needs and measures to facilitate the information-based strategy. At the end, some challenges and problems which need to be solved to promote the application of the proposed concept are discussed.

Key words: Information, accident prevention, safety, accident, risk, decision-making

1. Introduction

According to ISO 31000:2009, risk refers to the impact of uncertainty on safety objectives, while uncertainty denotes the state of inadequate or incomplete information related to an event, its likelihood, or its consequences. This definition suggests that risk is a result of information deficiency concerning safety objectives, implying that more meaningful information can reduce risk and prevent accidents.

Currently, there are many accident prevention measures originated from different accident causation theories or daily practice; among them, the popular one is “defense in depth” which aims to reduce the probability or consequences of undesired events. Still, accidents happen; new strategies which can reduce risk as reasonably practicable are needed. This article presents the concept of an information-based strategy for accident prevention. The functionality of this strategy is neither to reduce the probability of an undesired event nor to reduce its consequence directly, but to create a state of knowing for relevant stakeholders and decision-makers. The proposed strategy focuses on generation and utilization of information for accident prognosis, prediction, and decision-making. The strategy acknowledges 1) the importance of hazard diagnosis, fault detection and monitoring, system status monitoring and timely response to early warnings and precursors of risk, and 2) the differences in lack of knowledge and information accessibility, and the bias due to simplified information processing strategies when addressing complex issues, etc.

With the advancement of sensor technology, data mining algorithms, and digitalization, data availability has been improved, making it more feasible and cost effective to implement information-based strategies. The information-based strategies can be attractive for the safety management of remotely operated facilities and infrastructures, e.g., offshore installations. It can also be attractive in remote regions, e.g., the Arctic, where accessibility is limited.

The aims of this article are to present rationales and measures of the concept of information-based strategy, and to promote further discussion and research. The rest of the paper is structured as: 1) elaboration of the rationale of the proposed concept, 2) an overview of typical information demands from existing research, 3) a brief description of measures stemming from the information-based accident prevention concept; 4) discussions, and 5) concluding remarks.

2. Rationales

The theoretical foundations for the information-based strategy concept can be found from the existing discussions about risk and uncertainty, and the existing accident causation theories.

2.1. Risk, uncertainty, and information deficiency

Uncertainty is a threat to safety, a source of risk, while it arises from information deficiency (ISO 31000 2009, Aven et al. 2018), as illustrated by Figure 1. Reducing information deficiency can help ensuring safety and reduce risk. Information deficiency can be due to the impossibility to know (e.g., variations, sophisticated sociologic, natural and human behavior) or due to incomplete or inaccurate information, resulting from e.g., missing, misinterpreted, unreliable, internally contradictory or inaccessible data (ISO/TR 31004 2013).

Figure 1. Information deficiency, uncertainty and risk (Zhu 2022)

However, obtaining information alone does not reduce risk or prevent accidents. Information provides value when it is used for decision-making. Thus, a more precise interpretation of the reduced risk is "decision risk". Actions (including no actions) from decision-making can reduce consequences or likelihood of undesired events, thus risk. In other words, information-based strategies reduce consequences and likelihood of undesired events by improving decision-making. ISO/TR 31004:2013 also states that risk is created or altered when decisions are made. Managing decisions or decision-making is an integral part of the risk management process, meaning that managing information is critical to managing risk.

2.2. Relevant accident causation theories

Accident causation theories do not only explain why certain types of accidents occur, but also provide a scientific basis for predicting and preventing them. Over the years, several accident causation theories have been proposed (Rosness et al. 2010), among which the Swiss Cheese Model (SCM) is the most well-known. The SCM model has been further developed into the "defense in depth" and the barrier concept (Larouzee and Le Coze 2020). The following theories explain accident causations from different perspectives:

- An information perspective.
- A decision-making perspective.
- A control perspective.
- A risk perception and awareness perspective.

2.2.1.The information perspective

The information perspective of accident causation theory posits that accidents result from lack of information (Rosness et al. 2010, Choo 2005). This theory finds it origin in Turner's man-made disaster theory (Turner 1978), which asserts that an accident is the result of both physical failures, and failure of communication and interpretation of hazard signals and information. According to Turner, signals and information necessary for anticipating an accident are either unknown, or ignored, allowing hazardous scenarios to continue until an accident occurs. Choo (2005) extends this perspective by proposing that an organization's ability to recognize and respond to signals and events that presage failure can be hindered by epistemic blind spots, risk denial, and structural impediment. To prevent accidents, relevant but unnoticed or ignored information must be recognized and appreciated as early as possible. Organizations should also establish an information culture that balances the need for efficient operations with attentiveness to the abnormal and surprising.

2.2.2.The decision-making perspective

The decision-making perspective of accident causation theory posits that accidents occur due to a series of “wrong” or “no” decisions (Rosness et al. 2010, Bofinger et al. 2015, Endsley 1995). This perspective is a collection of understandings regarding organizational behavior, human behavior, human interaction, human-system interaction both in temporal and spatial spaces. Strategies for preventing accidents from this perspective include conducting decision analysis (Keeney and Raiffa 1993), risk-informed decision-making (Zio and Pedroni 2012), and improving decision-making skills (Hayes et al. 2021).

It is impossible to decide without information about the situation, the goals, and the available options. The absence of information may delay the moment of making a choice, and limit opportunities severely. The quality and quantity of information accessible may indirectly favor one option over another. Misinformation or lack of information can lead to an accident through the chain of unsafe perception, decision-making and unsafe execution (Chen et al. 2021).

2.2.3. The control perspective

The control perspective of accident causation theory says that accidents occur due to inadequate control or enforcement of safety-related constraints (Leveson 2004). The strategy to prevent accidents is to eliminate, mitigate, or control hazards. It also involves the continuous monitoring of a system's safety constraints and taking appropriate action when necessary.

Control is primarily about information. Effective control requires the efficient communication of information to the relevant stakeholders, such as the system's operators or controllers. To control a hazard, one must 1) obtain sensory information about hazard status and/or status about the enforcement of safety-related constraints, 2) process the information to make it interpretable either to controllers, and 3) use the information to make decisions to initiate a satisfiable control action, thus avoiding unacceptable losses.

2.2.4. The risk perception and awareness perspective

The risk perception and awareness perspective proposes that accidents occur due to lack of correct perception and awareness (Slovic 2000). The term risk perception implies that risk can be sensed, either technically or psychologically, through perceived danger, threats or pure unknown. Risk perception can be stimulus driven, relying on information input (Liu et al. 1998), and/or can involve thoughts, beliefs, and constructs (Sjöber 1979). Thus, it can be subjective and be a combined result of sense of hazard, imagination, or knowledge about future outcomes of such hazards. Accidents prevention measures following this perspective include safety education, training, interface design, display, the use of safety labels and signs.

The relevance of information for accident prevention from the risk perception and awareness perspective lies in the facts that 1) risk perception is stimulus-driven, e.g., interface and display design are to make necessary information supply handy and easily accessible. and 2) safety education and training provide knowledge for the decision maker to recognize risk from surroundings and conduct safe operation.

2.2.5. Information in the loop of decision-making and accident causation

As discussed above, information impairments and deficiency play a critical role in the many proposed accident causation theories. Figure 2 illustrates the position of information in the loop of decision-making and accident causation in sociotechnical systems.

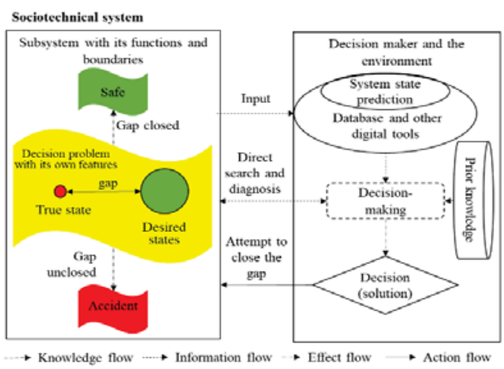

Figure 2. Information in an accident causation loop.

In a sociotechnical system, decision-makers have specific objectives and aim to bridge the gap between the current and/or future situation and their goals. The technical and functional aspects of a system are controlled by the decisions (solutions). These decisions may create new gaps, which may require further decision-making. Unclosed gaps may cause accidents.

Information is vital for creating a state of knowing and reducing uncertainty. It is an essential input for risk-related decision-making activities. Additionally, information is necessary for risk analysis and accident prediction; their outputs are used for decision-making enabling timely execution of proper actions to close gaps and prevent accidents. Reducing information impairments and deficiencies can contribute to risk reduction and accident prevention.

3. Typical Information Needs

The purpose of information-based strategy is to ensure that relevant stakeholders, including risk analysts, decision-makers and other stakeholders, have a good knowledge state. While information demand is personal, temporal, and situational, it is still possible to categorize some typical information demands based on existing research.

From the angle of uncertainty and information used for uncertainty reduction, information needs depend on the uncertainties that exist, what is not known or not accurate enough, the knowledge gap between existing state of knowledge and desired state of knowledge (Zhu et al. 2021). For risk prediction, an accepted categorization of uncertainty is model uncertainty, parameter uncertainty, and completeness uncertainty (NUREG - 1855 2017). The information needs include information about better models, more accuracy parameters, and hazards/failures. Information needs for risk estimation also depend on the methods used for risk estimation.

Uncertainty is also classified into epistemic uncertainty and stochastic uncertainty. Epistemic uncertainty is due to lack of knowledge and while stochastic uncertainty is due to variability (Hoffman and Hammonds 1994). Epistemic uncertainty can be reduced by gaining more knowledge while stochastic uncertainty is unreducible. The value of a stochastic variable can be expressed by a probability distribution. The effort of uncertainty reduction is therefore to obtain a better approximation of the probability distribution.

Knowledge are also classified into how and what, why, know with (Chen 2010) types of knowledge. This classification may also apply to information demand when resolving risk-related decision problems. For example, risk managers would like to have knowledge about what hazards exist, why such hazards exist, how to control or eliminate them, and other elements related to the hazards. In process operation, operators would like to know the functions of system, what actions to achieve the functions, how to execute the actions, and why they work (Rasmussen 1986).

In situations where hazardous or near hazardous event occur, emergency management requires three types of information: incident identification information, impact information, and action recommendations. Incident identification information describes the current situation, impact information describes the evolution and impacts of different scenarios, and action information advises on how to prevent or minimize harm (Hernández and Serrano 2001).

In high-risk industrial facilities or operations, where there is a risk associated with a task, task planners need information about the task, such as resources required, procedures, hazards and risk associated with the task, and information about the system that task is acted on, such as status, process, and instrumentation diagrams (Sarshar et al. 2018).

For decision making, information is required to generate knowledge about the decision problem, contextual factors, possible solutions, predicted consequences of those possible solutions, constraints, rules, goals and objectives, as well as identity and responsibilities of decision-makers (Zhu et al. 2021).

4. Measures in the Information-Based Strategy

This section presents measures to operationalize the information-based strategy and elaborates some of them in detail. Overall, the concept of information-based strategy embraces means to:

- Create a proactive information culture and environment that 1) acknowledges rare events and avoids risk denial; 2) encourage active communication, information exchange, seeking, and knowledge maintenance; 3) establish decision premises, rules, and routines to structure information search and evaluation (Choo 1996).
- Identify critical safety objectives, decision problems, decision makers, their information need and decision-making patterns.
- Establish and improve system model.
- Establish diagnosis and detection schemes for abnormal, hazards and faults, and response protocols.
- Establish information acquisition and processing, storage scheme to obtain and store historical data, real-time data and/or artificial data from simulations.

- Develop and implement a knowledge-based system/information system.
- Promote communication, information sharing, and smooth information flow through the organizational hierarchy or work process.
- Enforce information utilization, such as by display and visualization, particularly for human decision makers, using ecological interfaces (Vicente 2002, Stanton et al. 2021).
- And other means to support the objectives of the information-based strategy.

4.1. Investigating decision makers, their safety objectives, and decision-making activities

Information contributes to accident prevention when it is used in decision-making. In a sociotechnical system, there are different decision-makers with distinct safety objectives and decision-making tasks. Moreover, their decision-making behaviors and information needs vary depending on their knowledge background and working environment (Rasmussen 1986). Naturally, it is essential to understand the relevant decision-makers, their safety objectives, and possible decision-making activities to develop adaptive information and decision-support measures.

4.2. System modelling, accident/abnormal diagnosis, prediction, and response

Effective decision-making requires the ability to diagnose current conditions, predict future outcomes and determine appropriate actions. Accident or hazards prediction can provide input for problem detection so that control action can be taken in advance (Klein et al. 2005). This prediction also provides time constraints in accident mitigation, up-to-date safety margins for operation and produces information about fault for corrective or predictive measure (Mosier et al. 2007).

Since the future cannot be directly observed, system modelling, in form of computational, mathematical, or mental representations (i.e., knowledge residing within an individual's brain), is necessary to represent the system of interest. Model quality determines the accuracy of abnormal diagnosis and system behavior prediction, and ultimately the success of chosen actions.

4.3. Establish information acquisition schemes

Information acquisition can be established after an understanding of information needs. There are various ways for information acquisition, including direct inquiry to experts, searching in databases, recording raw data using sensors, obtaining abstractive data from analysis and predictive information using simulations, etc.

Incidents/accidents reports and database are used to obtain information on system level safety and accident causation and consequences, along with statistical and other data mining algorithms (Fayyad et al. 1996).

Real-time information acquisition is also essential for timely problem identification and decision-making to avoid "no decisions''. This can be achieved by allocating sensors and algorithms for hazard/abnormal detection, fault discovery, alarm generation (Us et al. 2014).

To obtain predictive information about future system behavior, physical models and simulations are commonly used. Additionally, data fusion methods that combine real-time information and system behavior knowledge (system model based on physics, statistics) can be used together for hazard, accident prognosis and prediction, including degradation prediction (Li et al. 2023).

4.4. Communication

Information also implies communication. Information could not be used if the message is not conveyed to relevant users. Keeping a smooth communication flow in organizations and pay attention to means of communication can increase the likelihood of information use.

Risk communication practitioners need to understand how different audiences and audience segments seek and process risk information. As holders of information, risk assessors also appreciate and present the broader context of the decision, and they must convey how uncertainties and weaknesses in the assessment may influence stakeholder perceptions of risk and the effectiveness of different risk management options (Thompson and Bloom 2000).

5. Discussions

5.1. Some general questions

Currently, risk is evaluated from the likelihood and undesired consequence of an event or activity. A pertinent question to ask is whether risk can be assessed directly from uncertainty, thus information deficiency of which information availability and quality are factors. This would shift the focus of risk analysis to identify and evaluate unknowns, and information deficiency. Such a change in risk evaluation could potentially offer new perspectives and solutions to existing problems in risk management and accident prevention.

Another critical question to ask is whether information always contributes to accident prevention or risk reduction. The preliminary answer is “No”. Information is neutral, and has a quality issue, i.e., whether it describes facts. Inaccurate information can be misleading and thus contribute to accidents or increase risk. Even if information is accurate enough, it may not contribute to risk reduction if it is not accessible to the relevant decision-makers. It is, therefore, crucial to ensure the right information is available at the right time in a format that facilitates risk-related decision-making, while information noise does not hinder, and information overloading is avoided.

5.2. Risk-related decision problems

In a complex hierarchical sociotechnical system, decision problems are diversified and distributed (Rasmussen 1997); decision-making processes vary based on decision-maker’s knowledge, environmental factors, and decision problem features. Such diversity impacts decision-makers’ information needs. However, there is a lack of methods to investigate risk-related decision problems and the preferred decision-making processes.

Another important question is how to allocate and frame decision problems so that decision-making is simplified while still achieving safety objectives. Leveraging the environment and expertise of decision makers may help. Despite ongoing discussions, evaluating decision-making quality and determining when a decision problem is deemed solved remain unclear.

5.3. Knowledge engineering

Efforts are required for knowledge engineering, including creating a state of knowing of decision-makers and generating information for this purpose. Decision-making quality can be improved as a result. Extract, model and exploit knowledge from field experience is one way to generate knowledge (Studer et al. 1998), because humans are skilled at handling uncertain and risky situations. Such knowledge can be used to supplement the information gained from risk analysis, which is also a knowledge engineering activity.

Although probabilities or model results from risk analysis cannot be entirely accurate, the knowledge generated is still the best knowledge available to the world or to decision-makers. Efforts are required to maximize the utility of the knowledge generated, e.g., the results from scenario analysis of rare events can be used for training in hazard control and emergency responses.

5.4. Accident prediction and prognosis by information accumulation and integration

It is challenging to foresee a accident during its incubation period (Turner 1978). Severe accidents usually are not due to a single event or condition but an effect of interaction of many conditions and events (Saleh et al. 2010). It is necessary to integrate a lot of evidence or input, possibly from multiple actors, to make a prediction, e.g., the prediction of occurrence probability, of an accident of interest. To determine the occurrence probability of a major accident, a capable accident model and available input data are required.

Another challenge is the diagnosis of unknow faults. Still, some accidents might be easier to predict. Some predictions may not need to be very accurate. Short-term prediction is likely to be more accurate than long-term prediction. Combining both predictions can be a way forward.

5.5. Information behavior and factors that impact information behavior

Information behavior refers to the patterns of behavior that individuals recognize their information needs, make choices about where and how to look for information, and reflect or act on the information they see. Conceptually, information behavior consists of (1) information needs, (2) information seeking, and (3) information use.

Given the diverse decision-making environment and decision problems, it is necessary to understand the information behavior of decision-makers to facilitate better understanding of how information is utilized to minimize risks and prevent accidents. Research is needed on professionals’ information needs, how they seek for and use information, the impact of their information behavior on task their performance (task effects, context effects, and managerial heuristics and biases and their influence on decision effectiveness), other factors (such as information holder, its relevance, quality, credibility and the means of communication etc.) that impact information behavior, accident prediction and decision-making quality.

Information load is defined as the variety of stimuli. Questions arise, such as “how much information is sufficient to create proper risk perception?” “How much information leads to a risk reducing action?”, “How do decision-makers decide where and when to look for information?”, and “how does decision-makers’ knowledge affect information utilization?” Methods to evaluate information sufficiency and adequacy of information environment may be needed. Behavioral study and information value evaluation are likely to yield some answers.

5.6. Measures and theory development

There is limited understanding of the potential of information-based strategies. While practices such as hazard detection and monitoring, accident prognosis and prediction (such as earthquake, hurricane, nuclear core damage) have been applied in some domains, a comprehensive and systematic explanation of contributions of information to accident prevention is still lacking. Understanding when more information does not contribute is also important to avoid information over-seeking and over-reliance. Furthermore, it is unclear to what extent this strategy could contribute to accident prevention or to reduce undesired consequences. Answering these questions can facilitate more effective measures.

To advance in this field, there is a pressing need for case development and validation. By developing cases and validation, researchers and practitioners can uncover further problems and identify factors that impact the practicability and feasibility of the information-based strategy.

5.7. Performance evaluation

It can be worth to address 1) the cost, feasibility, and effectiveness for measure implementation, comparing with existing accident prevention strategies such as level of protection, barrier concept; 2) whether risk can be further reduced if combining information-based strategies with the level of protection and barrier concept. However, it can be challenging to evaluate performance because 1) the many ways to evaluate safety and 2) the many factors which impacts the effect from control groups and case groups(van Kampen et al. 2023). To address the feasibility, effectiveness and cost, a way to model and evaluate the strategy needs to be established.

5.8. Residual risk

With an information-based strategy, the risk of accidents may be reduced but residual risk remains. The residual risk arises from factors such as unpredictability, complexity, unknown unknowns, mishap in practice, a lack of resources for information collection. The challenge is how to handle the residual risk. Precautionary principles, error-tolerant system, and resilient design may help to create safety margins (North 2011).

6. Concluding Remarks

This article proposes an information-based strategy for accident prevention, which is based on the relation between risk, uncertainty, and information, as well as the role of information in the existing accident causation theories. The information-based strategy can promote investigation about information environment and information behavior in organizations, including how decision makers seek and use information. A brief list of measures is provided for strategy implementation, but challenges still exist, such as the unclear information behavior of decision-makers, a vast number of accidental and hazardous scenarios, difficulties in predicting accidents/abnormal events, unknown unknowns, and evaluation of the strategy’s effectiveness.

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