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Title: Classification of Risk to Support Decision-making in Hazardous Processes

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Abstract: Application of risk assessments developed for the design phase to support decision-making in operational settings has exposed weaknesses in how risk is analysed and expressed in an operational context. The purpose of this paper is to clarify what we actually need to express when we use risk information to support various decision scenarios. We distinguish decision scenarios into strategic decisions, operational decisions, instantaneous decisions and emergency decisions. This forms a basis for discussing the different role risk and risk assessment plays in these decisions. Five categories of risk information (average risk, site-specific average risk, activity risk (activity performance risk and activity consequence risk), period risk and time-dependent action risk) are proposed and applications for different types of decisions are discussed. An example illustrates the use of the proposed risk types. The classification has novel aspects in providing a structure that should help in understanding how we need different aspects of risk and different ways of expressing risk in different situations. In addition, it improves communication among decision-makers by clarifying what aspects we are addressing when we use the term "risk".

Suggested Reviewers: Andrew Hale Ph.D
Chairman, Hastam, UK
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Professor Andrew Hale is a senior expert in the field of safety management, behavioral safety, riskperception and situational awareness, etc. We believe Professor Andrew Hale can provide an objectiveassessment of our manuscript. He did not publish with any of the authors of our submitted manuscriptwith the past five years and is not a member of the same research institution.

Jan Hayes Ph.D
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Dr Jan Hayes is an expert in safety and risk management who has over 30 years of experience. She is also particularly interested in operational decision making, which are quite relevant to our study. We believe Dr Jan Hayes can provide an objective assessment of our manuscript.And she did not publish with any of the authors of our submitted manuscript within the past five years and is not a member of the same research institution.

Response to Reviewers: No. 1
The links between the sections are somewhat jerky or in some cases missing - for example section 2 simply stops after brief descriptions of two schools of decision making theory without drawing any conclusions or flagging where the paper is going next. The same comment applies to Section 3. Section 5 has no introductory paragraph explaining what this section is about and no wrap up. The paper would be improved if the first and last paragraphs of each section were checked to ensure that the overall framing of each one is included (What is being addressed in this section and why? What are the key messages for the reader?).

Response to reviewer comment No.1
All sections have been looked at again, and we have tried to improve the "flow" in the paper.

No. 2
It is unclear how the authors classify engineering decisions made in support of operational plant in their proposed scheme. Section 4.2.1 says that decisions such as replacing equipment (or upgrading?) or implementing a revised maintenance regime are operational decisions. These are unlikely to be made without professional engineering input and yet Figure 2 suggests that operational decisions are made only by operational managers.

Response to reviewer comment No.2
Good comment, and we have tried to address this with a new paragraph in Section 3.

No.3

Section 4.1.3 describes the role of QRA in strategic decision making. Whilst I don't take exception to the description of typical practice, it should be acknowledged that QRA has limitations and has been criticised by many authors. It might also be important to consider if/how these criticisms apply to risk used in other ways as the rest of the paper is suggesting. Or the authors may wish to acknowledge limits to technical risk assessment in the intro and say that the proposed new system is aiming to be at least as robust as other uses of QRA (if that is the intention). This is especially important when the authors seem to be claiming in section 6.3 that quantification is the most desirable option.

Response to reviewer comment No.3
Again, a highly relevant comment to make and we agree that it is worth mentioning in the paper. This has been commented in Section 4 and in Section 6.3.

No. 4
In a similar vein, there are strategic decisions made that impact safety that are not amenable to a QRA approach - eg project execution strategies linked to contracting, defining competency and training standards for personnel and many similar issues. Again, the paper would benefit from putting some context on this. It appears that the authors are intending to cover decisions linked to physical plant and equipment only ie not management systems in general and not organisational issues. This should also be clarified in the introduction.

Response to reviewer comment No.4
Ref above. Commented in Section 1, 4 and 6.3.

No. 5

The authors might give some consideration as to how they are expecting decision makers to use risk to make a decision in the new classifications. What is the role of cost in this scheme? Cost is alluded to in the example in section 5 where the first option in the table is described as 'costly and time consuming'. Is there a plan to develop decision risk criteria to go with the various classifications of risk?

Response to reviewer comment No.5
We have discussed this briefly in Section 6.2, mainly to acknowledge that there may be implications of this but not going into the discussion in much detail.

No.6
Regarding risk types and quantification (section 6.3), the authors may wish to refer to the Risk Related Decision Support Framework published by UKOOA in 1999. It addresses just this issue.

Response to reviewer comment No.6
Included reference.

No.7

In the paragraph below Table 1 the authors state that "This trigger a change in plant risk level". In fact, the test reveals new knowledge about the risk. The risk level may have been higher than estimated a since the safety critical equipment failed.

Response to reviewer comment No.7
Agree, the wording has been modified.

No.8

Consider to include a section/paragraph in the discussion including some reflections of the link to the decision theory in Section 2.

Response to reviewer comment No.8

Good point, and some comments have been included.

Xue Yang

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Dear Editor

We hereby resubmit the manuscript “Classification of Risk to Support Decision-making in Hazardous Processes” for consideration by *Safety Science*. We confirm the originality of this manuscript and that the work has not been published nor currently is under consideration for publication elsewhere.

The manuscript has been revised according to the comments received. Generally we would like to thank the reviewers for their highly relevant and good comments again. The comments have been responded in the latest version.

Please address all correspondence concerning this manuscript to xue.yang@ntnu.no.

Thank you for your consideration of this manuscript.

Sincerely,

Xue Yang

	Comments from reviewers	**Response**
No.	**Reviewer #1:**	
1	The links between the sections are somewhat jerky or in some cases missing - for example section 2 simply stops after brief descriptions of two schools of decision making theory without drawing any conclusions or flagging where the paper is going next. The same comment applies to Section 3. Section 5 has no introductory paragraph explaining what this section is about and no wrap up. The paper would be improved if the first and last paragraphs of each section were checked to ensure that the overall framing of each one is included (What is being addressed in this section and why? What are the key messages for the reader?).	All sections have been looked at again, and we have tried to improve the "flow" in the paper. 1. A new paragraph at the end of section 2.2 2. A new paragraph at the end of section 3. 3. A new paragraph at the beginning of section 5.
2	It is unclear how the authors classify engineering decisions made in support of operational plant in their proposed scheme. Section 4.2.1 says that decisions such as replacing equipment (or upgrading?) or implementing a revised maintenance regime are operational decisions. These are unlikely to be made without professional engineering input and yet Figure 2 suggests that operational decisions are made only by operational managers.	Good comment, and we have tried to address this with a new paragraph in Section 3. - "In the figure, different decision-makers are shown…"
3	Section 4.1.3 describes the role of QRA in strategic decision making. Whilst I don't take exception to the description of typical practice, it should be acknowledged that QRA has limitations and has been criticised by many authors. It might also be important to consider if/how these criticisms apply to risk used in other ways as the rest of the paper is suggesting. Or the authors may wish to acknowledge limits to technical risk assessment in the intro and say that the proposed new system is aiming to be at least as robust as other uses of QRA (if that is the intention). This is especially important when the authors seem to be claiming in section 6.3 that quantification is the most desirable option.	Again, a highly relevant comment to make and we agree that it is worth mentioning in the paper. This has been commented in Section 4 and in Section 6.3. - A new paragraph in section 4. "In addition to the issue of how risk is presented to decision-maker…" - Addressed also in section 6.3 "As pointed out, there may also be modelling issues (e.g. in QRA) which means that…has not been explored further in this paper"
4	In a similar vein, there are strategic decisions made that impact safety that are not amenable to a QRA approach - eg project execution strategies linked to contracting, defining competency and training standards for personnel and many similar issues. Again, the paper would benefit from putting some context on this. It appears that the authors are intending to cover decisions linked to physical plant and equipment only ie not management systems in general and not organisational issues. This should also be clarified in the introduction.	Ref above. Commented in Section 1, 4 and 6.3.

5	The authors might give some consideration as to how they are expecting decision makers to use risk to make a decision in the new classifications. What is the role of cost in this scheme? Cost is alluded to in the example in section 5 where the first option in the table is described as 'costly and time consuming'. Is there a plan to develop decision risk criteria to go with the various classifications of risk?	We have discussed this briefly in Section 6.2, mainly to acknowledge that there may be implications of this but not going into the discussion in much detail. - “This is shown in section 5 and as a result, a specific risk picture can be constructed as an input to risk-informed decision making (RIDM) for each decision context.”
6	Regarding risk types and quantification (section 6.3), the authors may wish to refer to the Risk Related Decision Support Framework published by UKOOA in 1999. It addresses just this issue.	Included reference.
	Reviewer #2:	
7	In the paragraph below Table 1 the authors state that "This trigger a change in plant risk level". In fact, the test reveals new knowledge about the risk. The risk level may have been higher than estimated a since the safety critical equipment failed.	Agree, the wording has been modified. - Change to “This indicates that the plant risk level has changed and triggers a need to update”
8	Consider to include a section/paragraph in the discussion including some reflections of the link to the decision theory in Section 2.	Good point, and some comments have been included. - “Even though the planning horizon is…, with proper risk information as input” - “As illustrated in section 3, NDM provides… these two types of decisions” - “Therefore, systematic processing… by rational decision making theory”

Highlights:

- Classification of decision situations to target different aspects of risk that need to be expressed
- Five types of risk information for supporting decisions from general to context-specific
- Application of classification scheme to a case related to leaking Emergency Shutdown Valves in a process plant

Classification of Risk to Support Decision-making in Hazardous Processes

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Classification of Risk to Support Decision-making in Hazardous Processes

Abstract:

Application of risk assessments developed for the design phase to support decision-making in operational settings has exposed weaknesses in how risk is analysed and expressed in an operational context. The purpose of this paper is to clarify what we actually need to express when we use risk information to support various decision scenarios. We distinguish decision scenarios into strategic decisions, operational decisions, instantaneous decisions and emergency decisions. This forms a basis for discussing the different role risk and risk assessment plays in these decisions. Five categories of risk information (average risk, site-specific average risk, activity risk (activity performance risk and activity consequence risk), period risk and time-dependent action risk) are proposed and applications for different types of decisions are discussed. An example illustrates the use of the proposed risk types. The classification has novel aspects in providing a structure that should help in understanding how we need different aspects of risk and different ways of expressing risk in different situations. In addition, it improves communication among decision-makers by clarifying what aspects we are addressing when we use the term "risk".

Keywords: Risk classification; Decision classification; Decision support; Operational risk assessment

1. INTRODUCTION

Risk assessment was first introduced to the Norwegian oil and gas industry when the Concept Safety Evaluation Guidelines were established by the Norwegian Petroleum Directorate in 1980. These guidelines required risk assessment to be performed for all new oil and gas installations to be installed on the Norwegian Continental Shelf.

In the first years after this, risk assessment was performed mainly to support high-level design decisions, typically issues such as layout of equipment and main areas, escape ways and evacuation means and also to establish performance criteria for safety systems.

Since then, the regulatory requirements have been revised several times and with them, the application area for risk assessment has widened continuously. Today, the situation is that risk assessment is being used to support a wide range of decisions, from the high-level decisions mentioned above to very detailed technical decisions. Similarly, the scope has also been widened to cover not just technical issues, but also operational and organizational issues. In addition, risk assessment is increasingly being used not just for design purposes, but also in an operational setting, to make detailed decisions about how to operate an installation, what activities to perform, whether operation can continue and so on.

This widening of the scope has led to the realization that the "risk" that is relevant to consider in one decision situation not necessarily is the same as we need in other situations. The risk that we consider when we are making a decision about some long-term *strategic decisions* will not be the same as the risk we consider when deciding to complete a short duration operation, even if a safety system has stopped functioning. This is the background for the present paper, where we are aiming at distinguishing between different decision scenarios and what we actually need to express when we use risk information to support the decision.

When preparing this paper, we have had mainly "technical" decisions in mind. Typical examples are decisions relating to maintenance/repair of equipment, how to operate the plant, how to perform a specific piece of work etc. Decisions that primarily are "organizational" in nature have not been specifically considered. One reason for this is that such decisions often are more of a *strategic* than *operational* type. This issue may require further exploration, but we have not gone into this.

The first part of the paper briefly reviews decision theory and describes types of decisions that need risk information as input. This is followed by a description of the types of risk information that is required in different situations and examples of how these can be applied in different scenarios and situations.

In the oil and gas industry, it is common to consider three main types of consequences; consequence to personnel, which include fatalities and injuries, consequences to the environment, and consequences to assets (Vinnem, 2014). Personnel risk is the main concern in this paper, although the principles outlined would be relevant and could also be applied for environmental risk and asset risk. This work was further performed with major accidents in mind. This means that some of the descriptions may not be relevant for occupational accidents, but it is still considered that the overall principles are applicable also for occupational accidents.

2. DECISION THEORY

Decision theory is a wide field in itself, and the paper does not attempt to go into details of the theoretical approaches. However, some basic descriptions of decision theory are provided, as a background to how risk information may play a role in the decision-making processes.

2.1 Rational Choice and Bounded Rationality

In the rational choice theory, a decision (δ) is considered as a choice between two or more actions a_i. To make a decision means to choose an action. The process starts by identifying the set of possible actions $A = \{a_1, a_{2,\dots} a_n\}$, where A is called the action-space. Each action is evaluated against consequences, preferences and decision rules (March, 1994). The underlying assumption is that we can identify all possible actions in advance, and that we have “perfect” information about all actions.

Rational choice theory is criticized by organizational decision-making (Cyert and March, 1963; March and Simon, 1958; Simon, 1976), pointing out that most decision-making in real-life is better described as outcomes of bounded rationality. This means that not all alternatives are known, not all preferences are taken into consideration, and not all consequences are considered. The decision (i.e., choice) is actually based on the available knowledge K which results in the action a_i. As a consequence, only a few of all possible alternatives are considered and the choice is a “good enough” solution, not necessarily the “best” (Almklov et al., 2014). It is worth noting that under bounded rationality, the current available knowledge K may change over time, so the decision made today may be different from a decision made tomorrow.

2.2 Naturalistic Decision-Making

Naturalistic decision-making (NDM) goes one step further compared to bounded rationality theory. It claims that rational decision-making promotes better decisions only when time is available to make a choice, the problem is clear, essential information is distributed, and uncertainty around details is low. More typical, situations that we are facing are characterized by ill-defined goals and ill-structured tasks; uncertainty, ambiguity, and missing data; shifting and competing goals, dynamic and continually changing conditions, action-feedback loops (real-time reactions to changed conditions), time stress, high stakes, multiple players, organizational goals and norms, and experienced decision makers (Klein and Klinger, 1991).

The goal of NDM is to understand the cognitive work of decision-making, especially when performed in complex sociotechnical contexts (Schraagen et al., 2008). Lipshitz (1993) reviewed nine models of naturalistic decision-making and identified six common themes: diversity of form; situation assessment; use of mental imagery (i.e. construction of scenarios); dynamics processes; context dependence; and description-based prescription. The key concepts can be summarized as follows:

1) Recognition-Primed Decision (RPD) model highlights pattern matching which combines intuition with analysis (Klein, 2009); that the pattern recognition from the cues that sharp-end personnel recognize from the situation, suggests an effective course of action, and then people use a mental simulation to make sure it would work (Figure 1).
2) NDM shifts focus from selection of alternatives to initial stages of observing phenomena and developing descriptive accounts. This is elaborated under the concept of *situation awareness* proposed by Endsley and Jones (2012) into three levels: "*perception of the elements in the environment; comprehension of the current situation; and projection of future status*".
3) NDM adhere to empirical-based prescription, based on how experts describe and assess the situation. (Almklov et al., 2014).

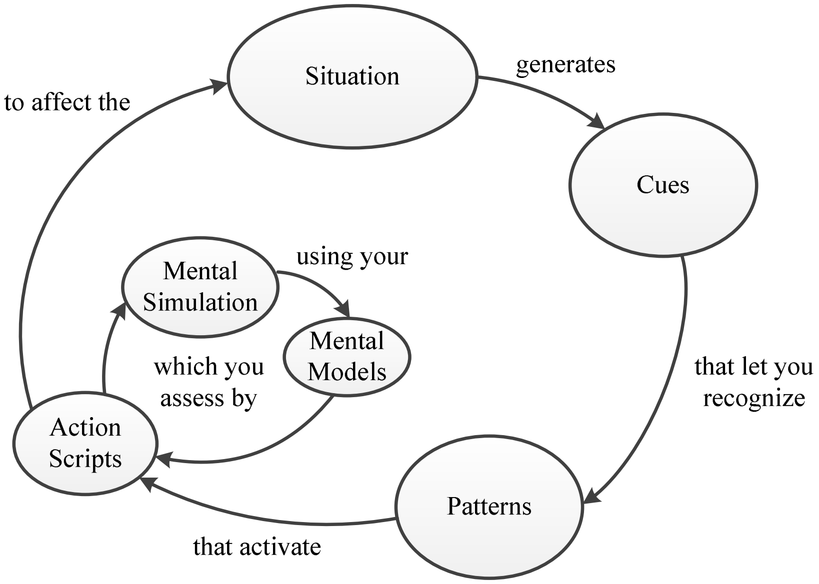

Figure 1 The Recognition-Primed Decision (RPD) model (Klein, 2009)

Rational choice theory and NDM give two quite different descriptions of decision processes that require different information. The information includes risk, which is one of the important dimensions for decision-making to avoid major accidents. It is important to recognize the role of risk in different decision scenarios with these two schools of decision theory as basis, to develop different ways of presenting/providing information and corresponding risk assessment methods to help with searching for risk reduction measures and effective risk control measure. In the next section, categories of decision types that are faced by different levels of decision-makers are looked into to see the expected role of risk in decision-making and further explore types of risk information that are needed.

3. CL.ASSIFICATION OF DECISIONS FROM A RISK ASSESSMENT PERSPECTIVE

In this paper, we have chosen to classify decisions into four categories (Figure 2). First, we differentiate between *planning decisions* and *execution decisions*. *Planning decisions* are characterized by a (relatively long) time lag between the decision and action. The time lag is long enough to systematically identify and evaluate different alternatives. *Execution decisions* are made by sharp-end personnel (personnel who monitor or control on-going operation and/or emergency response teams) with much less time lag between action and decision and will be characterized by minimal or no planning (although decisions may be taken based on "generic planning", such as emergency response plans). Examples of decisions are execution of an intervention and reacting upon deviations.

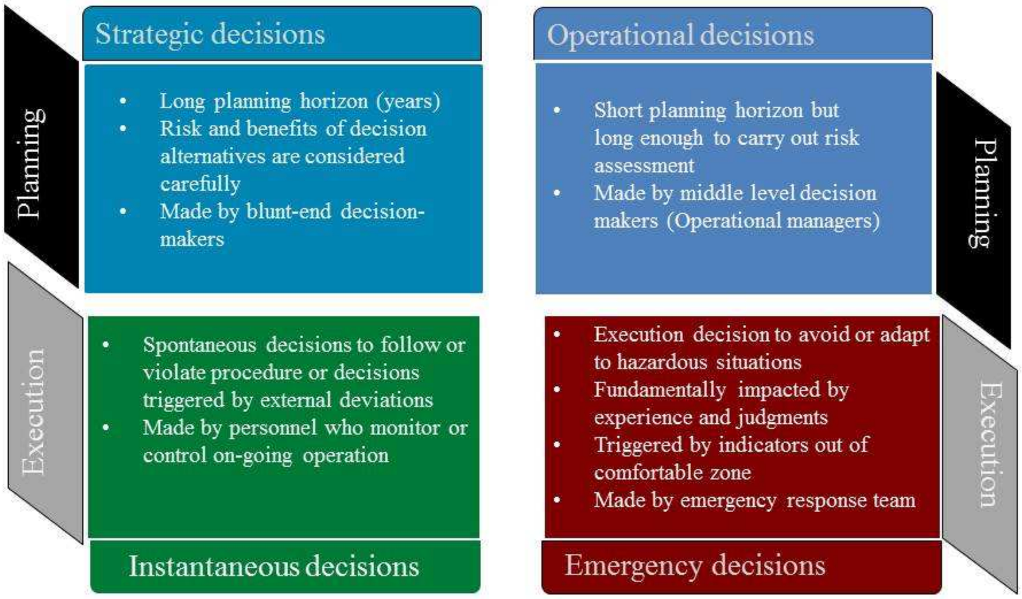

Figure 2 Four decision types that use information about risk as input

Planning decisions are further divided into two categories: *strategic decisions* and *operational decisions*.

- *Strategic decisions* are characterized by a long planning horizon (with time to consider risks and benefits of choices carefully), low decision frequency, and long-term effects. The disadvantage is that few details often are available, limiting the available information or making it uncertain. Blunt-end decision-makers make these decisions. Examples are approval of major projects, choosing from alternative designs/technology, and deciding on maintenance strategy before operation starts.
- *Operational decisions* are related to actions that will be taken and implemented within a shorter period. The planning period is relatively short, however, long enough to carry out formal risk assessments. Middle-level decision makers, such as operational managers, typically make these decisions. Approval of medium term operational plans, e.g. for a 1-3 month period, approval for initiating projects, and approval of shorter term operational plans (1-2 weeks) are examples of *operational decisions* which require risk assessment to understand both short term and long term effects on risk. Another type of *operational decisions* is made on a daily basis, such as approving work permits and daily plans.

In the figure, different decision-makers are shown. It may be worth mentioning that in many of the decisions, different personnel groups will provide important input to the decision process, and may in fact also be directly involved in the decision. In operational decisions where technical issues are involved (as is very often the case), engineering support personnel will provide input. Often, sharp end personnel from operations will also be involved. The total picture of how decisions are made is therefore more complex than indicated by the figure.

Planning decisions is a typical arena for rational choice decision-making, with bounded rationality. For the decision situations we are considering, risk is an important dimension of the decision in rational decision-making (Rausand, 2011). The results from risk assessment are used as direct or indirect input to decisions. Risk acts as one of the decision rules (through use of e.g. ALARP principle, societal risk criteria) to assist evaluating alternatives. On the other hand, formal risk assessment may also be translated into rule-compliance for decision-makers. This can range from safety related regulations to rules that are expected to be followed by sharp-end workers (Hopkins, 2011).

Execution decisions are made by sharp-end personnel with minimal or no planning, typically during the implementation/execution of different work activities. These may well have been planned in advance, but not necessarily in all detail and not necessarily to cover all situations which may arise during performance of the work. This is an arena where decision-making best can be described by naturalistic decision-making theory. Sharp-end operators need to make rapid decisions. It is common to use their mental model to simulate and imagine what might happen next, to look for the first workable option, instead of the best option (Klein, 2008). In naturalistic decision-making, risk assessment is normally invisible during the decision-making process and an informal assessment process is concealed in the mental models and the experience of professionals (Hopkins, 2011).

Depending on the degree of urgency of the situation that the sharp-end personnel are facing, we divide *execution decisions* into *instantaneous decisions* and *emergency decisions*.

- *Instantaneous decisions* are taken spontaneously by sharp-end operators, e.g. to follow or deviate from procedures; ignore or react upon deviations in normal working conditions. The decision-making emphasizes situation assessment and pattern matching, and “when action is the central focus, interpretation, not choice, is the core phenomenon” (Weick et al., 2005). Decisions are typically taken quickly, although not necessarily because there is a need to do so.
- *Emergency decisions* are the decisions taken in emergencies to avoid or adapt to hazardous situations. Time dynamic is often so fast that pattern matching may not catch the development of the situation.

The risk that we consider when we are making *planning decisions* will not be the same as the risk we consider for *execution decisions*. Different characteristics of *strategic decisions* and *operational decisions* result in different risk expressions that are required as input to make rational choice. Furthermore, risk information that is required by sharp-end personnel under different levels of urgency to make *execution decisions* also varies. This is further explored in next section by looking into how we need different aspects of risk to better support these decisions.

4. RISK INFORMATION INPUT to DIFFERENT DECISION TYPES

There is no universally accepted definition of risk. In this paper, we have adopted the definition from Kaplan and Garrick (1981), who define risk as the answer to following three questions:

1. What can happen?
2. How likely is it that will happen?
3. If it does happen, what are the consequences?

As a result, we get a set of scenarios with corresponding probability and consequences $\{< s_i, \phi_i, x_i >\}$. Commonly, this is expressed as statistically expected loss, by multiplying the probability of a scenario and the consequences of that scenario, and adding the products over all possible scenarios. This is the basis for Quantitative Risk Assessment (QRA) or Total Risk Analysis (TRA), which is a standard practice in the Norwegian oil and gas industry to determine the overall level of risk to personnel and to improve safety aspects of the design (Vatn and Haugen, 2013).

Another common way to express risk is to employ predefined scales of probability and consequence as the two axes in a risk matrix and then plotting the scenarios in this matrix. The scales can be either quantitative or qualitative, depending on whether probabilities/frequencies and consequences can be quantified or not. Both QRA and risk matrix express risk explicitly, by specifying scenarios, probabilities/frequencies and consequences.

Information about risk is an important dimension in a risk-informed decision-making context. For *strategic decisions* like how the layout of a facility should be or how to design the safety systems of a facility, expressing risk explicitly (as above) provides useful information. In such situations we are interested to find the solution that gives the minimum expected loss over a long period of time.

However, expected loss is not necessarily similarly useful for decisions such as whether a single activity can be carried out or not. Then it is more interesting to know if this activity can be performed without an accident occurring or not. This can e.g. be monitored by considering whether or not safety critical parameters (e.g. availability of safety system, work permit, procedure) are within acceptable limits, and whether possible interactions between the activity and surroundings are controlled. An example could be an operator who has to decide whether or not isolation is required before executing maintenance work. Presence of flammable gas is then a safety critical factor that will influence the decision.

In addition to the issue of how risk is presented to decision-maker, quantification in itself is not necessarily the solution in all situations. QRAs have limitations in what is modelled and how well in particular organizational influences are reflected in the results. This clearly means as well that QRAs will not necessarily give the good answers in all situations. Since it is mainly the more “technical” type of decisions that we have chosen to focus on in this paper, the issue is less pressing. For practical applications, this is however clearly an issue that needs to be taken into account.

In the following sub-sections, we will explore the various decision situations defined in Section 3 and what information about risk that is required in different situations. We use this as a basis for defining different “risk types” and briefly discuss how these can be expressed and estimated.

4.1 Risk input to strategic decisions

4.1.1 Strategic decisions at society/industry level and average risk

Strategic decisions may be made at society level or industry level. An example from the societal domain could be the choice between different options for developing new energy (e.g. comparing wind energy with nuclear energy). On the industry level, examples can be what supervision activities should be prioritized by authorities, or whether the regulations need further development to enhance overall industrial safety. In such cases, risk acts as one of the decision criteria, usually in combination with many others. In this context, we are interested in average risk over a large population of relatively similar systems or operations.

This form of risk may be termed *average risk*. This is an expression of risk for an industry, a nation or an even wider scope averaging over a large group of plants, activities, areas and personnel. Risk is further averaged over a relatively long time period, typically a year or sometimes even longer periods.
Average risk is normally based on retrospective data without consideration of specific system attributes. As such, it is an expression of past performance, but this is usually combined with assumptions about future activity, changes in technology etc. Based on this, it is assumed applicable also as a prediction of future risk.

An example is the Risk Level Project (PSA, 2014) which analyses the status of major accident risk in the Norwegian offshore industry. Various data related to major accidents are collected from the industry each year. This includes precursor data (e.g. number of hydrocarbon leaks, number of well incidents, number of ships observed on a collision course with an installation) and barrier reliability data (test data for e.g. Emergency Shutdown Valves, Blowout Preventers, and Fire pumps). Based on these statistics and probability of a fatal accident if the incident happens, a total indicator for major accidents is generated to express the effects of risk management (Vinnem, 2004). This is a basis for prioritizing safety efforts in the industry and Petroleum Safety Authority Norway (PSA) supervision activities.

Some examples of databases which provide major accident related data are OGP Risk assessment data directory (OGP, 2010), eMARS (MAHB, 2014), WOAD (DNVGL, 1998), SINTEF Offshore Blowout Database, FACTS (TNO, 2014), PSID (CCPS, 2014), etc. The information contained in these databases is typically accident data. There may be very large variations between the individual elements in the population that the *average risk* does not necessarily reflect.

4.1.2 Strategic decisions at company/plant level and site-specific average risk

Strategic decisions may also be made at company level or plant level during different phases, e.g. planning phase, engineering phase or operational phase (NORSOK, 2010). Some examples can be choosing the location of a hazardous facility; decisions about how to design layout and safety systems of a facility; decisions about maintenance planning before operation starts, decisions about how the plant is operated, e.g. increasing throughput or changing operating conditions and so forth. At this level, specific characteristics of the plant need to be reflected in the risk expression. The risk expression should take into account site characteristics such as layout, safety barriers (i.e. safety systems, structural protection, and evacuation routes), personnel exposure, etc. To differentiate from *average risk*, we call this *site-specific average risk.*

Since we are still considering *strategic decisions* and long-term effects, using expected loss is appropriate. Different alternatives can be compared, and risk reduction measures can be identified and evaluated by reducing probabilities of scenarios, mitigating consequences or both, to reduce expected loss.

4.1.3 Estimation of site-specific average risk

Quantification of *site-specific average risk* based on accident scenarios is common practice in the industry. Major accidents are usually not caused by a single equipment failure or an operator error, but are a result of a chain of events initiated from equipment failures, equipment malfunctions, human errors, or deviations of process parameters. Specific information about how the scenarios develop from initial failures through the event sequence to the end consequence is reflected in the modelling to estimate *site-specific average risk*. These models usually integrate event trees and fault tree analysis to represent the cause-consequence relationship.

The input to the models is mainly based on generic databases. The types of data will more typically be information about equipment failure or activity failure rather than accident data (e.g. OREDA (OREDA, 2009), Exida (Exida, 2007)). This information is combined with information about the type and quantity of equipment and the number of various activities taking place to provide risk estimates. These generic failure data may also adjusted to take into account specific types of equipment, specific maintenance regimes, specific operational procedures, etc. There have been developments in how to adjust generic data to reflect site-specific operational and organizational features information into the risk picture, which can be summarized in three approaches:

- Update status of causal factors of basic events and update corresponding likelihood of consequences (Aven et al., 2006; Gran et al., 2012; Røed et al., 2009; Sklet et al., 2006; Vinnem et al., 2012; Øien, 2001a, 2001b). These causal factors are termed as Risk Influencing Factors (RIFs), which are defined "*as aspects of a system or an activity that affect the risk level of the object*" (Øien, 2001a).
- Updating likelihood of some consequences based on accident precursors (near miss, mishap, incident) and probability of failure of safety barriers in event trees, and finally update likelihood of the accident(Rathnayaka et al., 2011a, b);
- Map fault trees and event trees into Bayesian networks (Bobbio et al. (2001) and(Bearfield and Marsh, 2005)). The changes are then reflected in the risk picture by assigning posterior probability of events given experience data (evidence) (Khakzad et al., 2013). Principally these models have the potential to handle changing features with desired updating intervals,

whereas most of the models choose to update from 3 months to one year due to high resource requirements.

During the planning phase and engineering phase for a new facility, *site-specific average risk* is normally estimated using QRA. The QRA is based on a set of assumptions about the equipment that is to be used in the plant and the types of activities going on. In the operational phase, *site-specific average risk* is usually updated periodically (e.g. a common practice in the industry is to update QRAs every 5 years) to reflect changes in assumptions, plant configuration, operational conditions, performance of safety barriers, manning level etc.

4.2 Risk input to operational decisions

Operational decisions are made at plant level during the operational phase. *Strategic decisions* may also be made during the operational phase, e.g. related to major modifications. Some examples of *operational decisions* are approval of work orders, prioritizing corrective maintenance activities, approval of work permits, scheduling for simultaneous work activities, and so forth.

4.2.1 Operational decisions and activity risk

Compared to *strategic decisions*, *operational decisions* are made in situations where more detailed and accurate information is available about operational conditions, system status, operating personnel, weather conditions and so on. Further, the effects of *operational decisions* may be long-term (e.g. replacement of defected valves with new ones or implement more frequent maintenance) or short term (i.e. the risk related to performing the work). For some decisions, it may be necessary to consider both.

For decisions that have short-term effects (e.g. during the performance of an activity), averaging risk over a long period of time is not relevant. We are primarily interested in the work associated with the specific activity that we are considering and whether this can be completed safely or not. In this situation, we want information about what we may call *activity performance risk*. This will be an expression of the risk associated with performing an activity. For this expression of risk, expected loss is not necessarily the best measure of risk anymore; instead focus will be on avoiding accidents. The probability that we will experience negative consequences thus becomes more important than expected loss.

To illustrate this, we may look at a decision about whether to perform maintenance on a shutdown valve the next day or whether to postpone it (prioritization of corrective maintenance). The maintenance work may lead to a gas leak if not performed properly. It is then important that the gas detection system is operating properly, to ensure early detection and warning of any leaks that may occur. In a QRA, we would use the average probability of failure on demand as a measure of the unavailability of the gas detection system. However, in this specific situation we will usually have specific knowledge about the status of the system, and can use this in our decision-making rather than the average values of unavailability from the QRA. The risk associated with the situation can then be expressed implicitly, by considering what the status of the gas detection system is and using this rather than the probability of an accident as an indicator of whether risk is acceptable. In a real situation, we can usually find a number of indirect (or implicit) ways of monitoring risk.

The above focuses on risk associated with performing the work, and this risk will “disappear” once the activity has been completed. However, the activity may also have long-term effects on the risk level. From the example above, performing maintenance on a valve will most likely improve the reliability of the valve (at least for some time). In essence, this implies a change (reduction) in the *site-specific average risk*. However, we will normally not update the total risk picture for the facility but consider only the specific effect of performing the activity. To distinguish from an updated *site-specific average risk,* we may call this *activity consequence risk*. In some cases, the *activity performance risk* may be very small and *activity consequence risk* is high or vice versa.

To sum up, *activity performance risk* indicates risk level associated with performing the activity while the *average consequence risk* provides the risk level after the activity has been completed.

4.2.2 Estimation of activity performance risk

Hayes (2013) has pointed out that in practice operational managers seldom use quantitative expressions of expected loss to make decisions in specific situations. Instead, they focus on compliance with rules (operational barriers) and sufficient integrity of the technical barriers that prevent a specific hazardous event from becoming a reality.

More generally, we can say that we can predict and control the risk level by considering activity critical safety parameters. These parameters will vary from activity to activity. For instance, the parameters that influence risk involved in working above sea are different from parameters that influence risk involved in hot work. Figure 3 shows an example of safety critical parameters of hot work, which are collected from lessons learnt from hot work accidents and recommended best practices (CSB, 2010; Madsen, 2013). It is possible to use risk influence diagrams to structure *activity performance risk* to ensure critical risk factors are under control. It is worth noting that the factors considered here usually are much more specific and detailed than the factors taken into account when we estimate *site-specific average risk* on a plant level. When considering the activity only, factors that may be relevant if there is a potential for fire or explosion may be presence of flammable gas; human errors, unsafe acts; environmental condition deviations; simultaneous activities; and so forth. In a QRA, these factors will implicitly be taken into account in the data and models used.

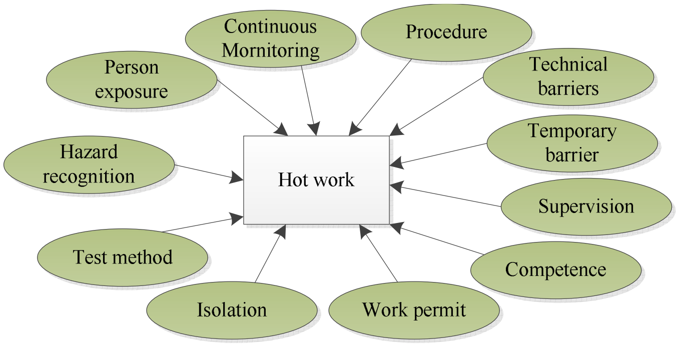

Figure 3 Safety critical parameters for hot work

4.2.3 Estimation of activity consequence risk

As was pointed out above, the *activity consequence risk* is in principle an update of the *site-specific average risk*, using specific information related to the activity that is going to be performed and what effects this activity will have on the long-term risk level for the facility. In principle, the models applied for calculating *site-specific average risk* could therefore be used. However, in practice, this is not necessarily easy to do because the models do not necessarily contain a level of detail that makes it possible to update the risk level.

This can be approached by developing a more detailed model (but more limited in scope) that can be used to estimate the *activity consequence risk* and express this in terms of probability of specific consequences or expected loss.

Another possible way to qualitatively estimate *activity consequence risk* is to assess the likelihood of certain initiating events, level of redundancy, defence-in-depth barriers that are influenced by completing the activity. This will indicate how successful the completed activity will be in influencing the likelihood of initiating events, and performance of barriers, in turn to influence the risk level over the plant. This idea originates from Plant Transient Assessment Trees (PTATs) applied in the nuclear industry (OECD, 2004). This method is actually a simplified version of updating the *site-specific average risk* described above.

4.2.4 Operational decisions and period risk

In the previous section, we considered individual activities and the risk associated with these. However, in many situations there will be decisions that have effects over a period in which multiple simultaneous activities are carried out. Figure 4 shows examples of how work orders in a two week period and work permits in 24 hours can be carried out in overlapping periods. These activities may influence each other such that the risk associated with all activities together not necessarily will be equal to adding together contributions from each activity on its own. The risk associated with this may be called *period risk*. This is an expression of risk for a plant or facility over a period of time (usually short, e.g. a day, a week or possibly a few weeks).

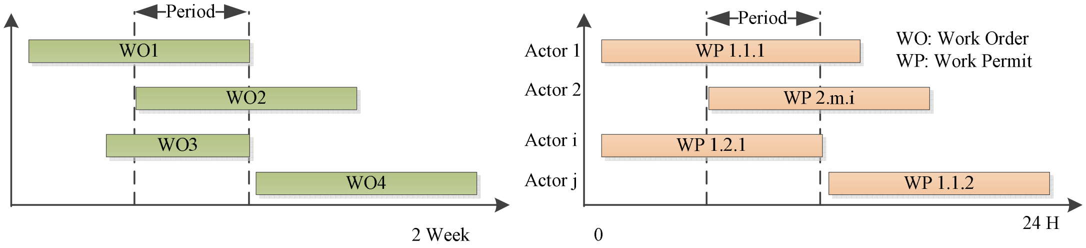

Figure 4 Illustration of schedule overlapping work orders and work permits

An example illustrating how activities may interact to increase risk is as follows. Assume that activity 1 implies replacing gas detectors, while activity 2 involves work on a gas system during the same period. Activity 1 will increase the *activity performance risk* of activity 2 because one of the technical barriers, gas detectors, is missing. Another example can be concurrent activities of hot work and work on HC system. Hot work implies increased probability of ignition while work on hydrocarbon equipment implies a possibility of release. If these two activities are carried out simultaneously, the possibility of an ignited release is not just a matter of adding together the effects.

Another type of operational decision is whether or not an action (e.g. to stop production for maintenance) should be postponed, with a particular period in between alternatives. This is a common situation, requiring consideration of both safety and economic impact. Assume that the choices are about whether the plant should be shut-down to repair a newly discovered defect on a barrier, or postpone the repair until the next scheduled shutdown, which will be 3 months later as an example. The second alternative - postpone the repair - has an effect in this 3 month period. This dilemma was faced by operators in Yerkes chemical plant in Buffalo (CSB, 2011). After a leak in a flash tank overflow line was identified, it was decided that the repair could be postponed until the next planned unit outage. This did not take into account that another repair that involved welding was scheduled during this period. The hot sparks from the welding in turn ignited the large vapour space accumulated in the slurry tanks due to the leak and led to an explosion. The accident illustrates interactions between the consequences of the decision (not to repair the leak immediately) with hazards introduced by planned activities (a source of ignition) that increased “period risk”.

It is noted that *period risk* is the same as *site-specific average risk*, if we consider a period of one year and we consider the whole plant. However, the point is that this usually not will be the type of information that we are interested in – instead we want to focus on a much shorter period with very specific activities and we may also limit the focus to only a subset of all activities taking place during a period.

4.2.5 Estimation of period risk

Interaction is a well-known topic in hazard identification and risk assessment. ISO (2000) points out that "*the interaction of activities taking place concurrently may give rise to hazards not previously considered significant (e.g. inspection activities in normally unmanned areas may be more hazardous if painting or coating is being carried out in a nearby location)*". However, the relationships are difficult to identify using traditional risk analysis logic (Dekker, 2011).

In today's practice, one way of managing this risk is to apply Simultaneity Matrixes. These show which activities cannot be performed simultaneously without compensating measures being introduced. An example would be that hot work is not allowed to be performed simultaneously with work being performed on a flammable gas system (MIRMAP, 2014). However, it is also admitted that risk is not very well covered by this matrix. The focus of the matrix is still more on avoiding resource and schedule conflicts (MIRMAP, 2014). Further, this does not explicitly evaluate *period risk*; it only identifies combinations which will lead to increased risk without considering how large the increase is.

To control *period risk* of simultaneous activities, one possible way is through Bow-tie diagrams which illustrate the route to an accident by breaching physical and procedural controls (Rausand, 2011). Figure 5 shows key elements of the bow-tie from hazards, triggers, proactive barriers, hazardous event, to reactive barriers, exposure and consequences. How concurrent activities may influence multiple elements in the bow-tie diagram should be identified and compensated for, to reduce the additional risk caused by interactions.

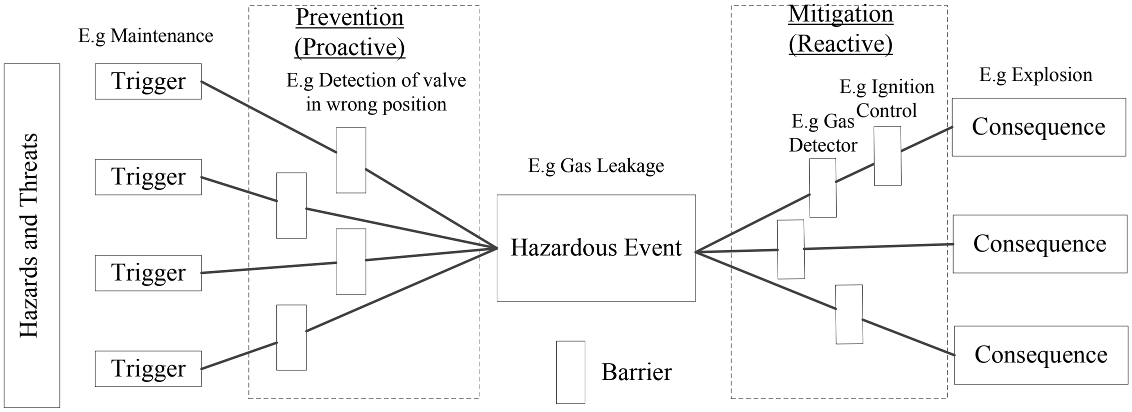

Figure 5 Bow-tie as a mental model to identify possible combinations to increase period risk

The same principle can be applied to estimating *period risk* when comparing alternative decision options. After identification of the consequence of the action on elements in the bow-tie diagram, activities that are planned during this period and corresponding hazards, possible deviations of operation environment should be identified to see how these deviations will influence the elements in the bow-tie.

4.3 Risk input to instantaneous decisions

4.3.1 Instantaneous decisions and time-dependent action risk

The key characteristic of *instantaneous decisions* is that they are execution decisions made by persons who monitor or control the on-going operation. In other words, they are the decisions that are made in the "coal face" and based on field observation. This includes detection and reaction to deviations or abnormal situations, and decisions to follow or violate rules. These sharp-end personnel are commonly regarded as the last barrier to prevent accidents from happening. How they treat risk as an input is different from blunt-end decision makers that make *strategic decisions* and operational managers or planners that make *operational decisions*. Risk needs to be expressed in a way to better recognize the situation. "*When people work offshore, they always ask the simple question, what do you want me to* *look for? During operation, the point is to know what to control, what to monitor*” (MIRMAP, 2014). Operation is a dynamic process, consequently, risk that is needed for instantaneous decision-making cannot be an average value over a period of time. To capture this dynamic attribute of risk, we propose another type of risk expression: *time-dependent action risk* to express what the risk is right now to assist in assessing an ongoing activity or operation.

For *instantaneous decisions*, although we may concerned about their immediate, short term and long term effects, we benefit more from controlling deviations or monitoring some "early warning indicators" to detect deviations and prevent them from developing into a hazardous situation.

Time-dependent action risk is a measure of risk subject to safety critical operating parameters against operating limits while doing one activity or activities. For example, when you drive a car on the road, *time-dependent action risk* changes along with changes in operating parameters, such as driving speed, road conditions, traffic flow, distance to the front car, aggressive drivers on the road, and so forth. Another example can be a pilot that looks out the window and judges the speed and descent rate required to reach the runway, or use the shape, shade, and size of clouds to determine whether they should fly through (Schraagen et al., 2008). These operating parameters will all be averaged out (and usually not explicitly included) in the modelling of *site-specific average risk* over a long period of time.

The tempo of changes in the risk level depends on how fast operating parameters change. Some examples of such physical operating parameters can be pressure, temperature, allowable separation distance, concentration of a contaminant, and so on. Environmental parameter can be maximum or minimum weather condition (e.g. wind speed).

4.3.2 Estimation of time-dependent action risk

From a risk analyst perspective, we cannot help drivers to control the car, but we can tell them what to look for when driving, and what the limits are. In Hayes (2012) study of safety barriers in operational decision-making, she found that “*the idea of defining an operating envelope or a set of pre-determined and formally recorded operating limits has wide acceptance in both industry standards and safety regulation for complex process plant (i.e. pressure, composition, or number of operators.)”*. The operating limits are typically based on engineering design consideration and risk analysis with reference from previous operating experience, such as pore pressure and fracture pressure in drilling activity. The closer the operating parameters approach the limits, the higher the *time-dependent action risk* is. Therefore, the *time-dependent action risk* can be estimated or predicted based on the margin between performance of parameters in the current situation and the operating limits.

It is worth noting that safety barrier performance can be one of the operating parameters used to estimate and control *time-dependent action risk*. Examples are minimum requirements for availability of safety systems (e.g. level of redundancy) or degradation condition of the safety barriers. Furthermore, t*ime-dependent action risk* is preferably expressed in terms of observable indicators for sharp-end personnel’s sake. For *instantaneous decisions*, we benefit more from preventing deviations or monitoring some "early warning indicators" to detect increase in risk and prevent them from developing into hazardous situation. This is supported by operators stating that “*Some small groups, contractors don’t need emphasis too much about risk. They need concrete indicators to look into”* (MIRMAP, 2014).

4.4 Risk input to emergency decisions

When an operation is identified to move into an emergency situation, the decisions made aim at controlling the situation, to recover to a normal situation or to mitigate the consequences. Normally, the time available to make *emergency decisions* is shorter than for *instantaneous decisions*. One example of *emergency decision* is whether to close Emergency Shutdown Valves (ESD) upon a process leak. There are many factors that influence the risk level in such a situation and normally they can change fast. People will typically judge the risk level based on leak size, escalation speed, classified area (i.e. hazardous, non-hazardous), whether leak is ignited, and so forth. Principally, *emergency decisions* are made based on a similar input as *instantaneous decisions*, since the decision is based on a set of operating parameters and a safe envelope boundary.

Basing the intervention in emergency situations on observation and control of a set of well-known operating parameters is "common practice", without the sharp-end operators' necessarily keeping the concept of risk in mind. The challenge lies in how to interpret multiple changing parameters so that a reasonable impression of the risk level can be generated. The investigation into the Macondo oil spill disaster highlighted failure of situation awareness (OSC, 2011). Frequently recurring alarms and flashing lights makes it difficult for personnel on board to acknowledge what is going on (CCR, 2011). In practice, *comprehension* of *the current situation* and *projection of future status* has been an arena that relies heavily on the expertise and experience of "coal-face" operators. This is part of the reasons why "deference to expertise" for decision-making in high pressure situations has been proposed (Weick and Sutcliffe, 2007). However, study of information processing in the minds of "experts" to see how they derive the general risk picture to structure an analytical framework is beneficial, especially for less experienced workers on the field.

4.5 Summary of risk types and applicable decision types

Table 1 summarizes the discussion in Section 4. The risk expression and corresponding risk assessment methods must be customized to the decision context to assist in the search for concrete risk reduction measures and effective risk control. The classification system does not contain novel aspects in the sense that it has identified new aspects of risk. However, it provides a structure that is novel and that should help in understanding how we need different aspects of risk and different ways of expressing risk in different situations. Another merit of the classification system is that it can facilitate communication among decision-makers by clarifying that we may be addressing different aspects when we use the term "risk".

To illustrate this further, we may look at how classified risk types can improve Management of Change (MoC) during operation. Missing or failed change management has been identified as a contributor to several major accidents that has happened in the last decades. ISO/TS 16530-2 (ISO, 2013) lists the requirement of "*identifying the change in risk level(s) via use of a risk assessment matrix or other means*". This is a requirement for managing *activity consequence risk* without specifying how to do it. In addition, risk involved in executing the change – *activity performance risk* - is overlooked and not well managed. Another aspect that needs to be managed is the *time-dependent action risk.* This is to make sure executing the change will not put the system into a dangerous zone by monitoring related operating parameters against safety boundaries.

Table 1 Summary of risk types

Risk Type		**Description**	**Expression**	**Estimation**	**Applicable Decision types**
Average risk		Risk for an industry, a nation or an even wider scope averaging over a large group of plants, activities, areas and personnel	Frequency	Retrospective statistical data	Strategic decision (at national or industry level)
Site-specific average risk		Risk for a specific plant, averaged over a year and taking into account specific characteristics of the particular plant	Expected loss calculated from probability of scenarios and corresponding consequences	QRA/TRA	Strategic decision (at plant level)
Activity risk	Activity consequence risk	An expression of the effect that completing an activity will have on the risk level after the activity has been	Barriers integrity under defence-in-depth principle	Evaluation of impact on safety barriers (failure or degrading,	Operational decision with long term effects

		completed (risk after the activity)	Site-specific average risk if impact is quantifiable and can be reflected in QRA model	improving and how long) QRA/TRA	
	Activity performance risk	An expression of risk level associated with performing a specific activity (risk during the activity)	Critical safety parameters (e.g. activity specific hazards, activity designed technical and operational barriers, competence of operator)	Process activity statistics Risk influencing diagram	Operational decision with effect over an activity
Period risk		An expression of risk for a plant or facility over a (normally short) period of time	Possible interactive couplings between activities in concerned period	Evaluation of hazards involved in the period to elements in bow-tie diagram	Operational decision with effect over a period of several activities, or a particular period
Time-dependent action risk		An expression of short-term risk variation while performing one or several activities	Indicators derived from operating parameters against operating limits. In some cases, a general indicator is preferred.	Safety margins of operating parameters that are left before the system drift into a danger zone	Instantaneous and emergent decisions

Figure 6 is prepared to illustrate the differences between the proposed risk expressions. For instance, safety critical equipment 1 is tested and it fails to function. This indicates that the plant risk level has changed and triggers a need to update. The risk may be reflected by updating *site-specific average risk* under the assumption that the plant stays in that condition for a year. If maintenance of equipment 1 is decided, extra risk is introduced due to all effects of the maintenance activity on the plant while the work is ongoing. This is *activity performance risk.* Correspondingly, *time-dependent action risk* shows variation of risk at activity level with concrete values of parameters (e.g. temperature -15°, pressure 14.5 bar) against operating limits as input. *Activity consequence risk* is an updated *site-specific average risk* level after equipment is returned to service. *Period risk* is based on *activity performance risk* of simultaneous activities, with interactions being considered as an additional factor.

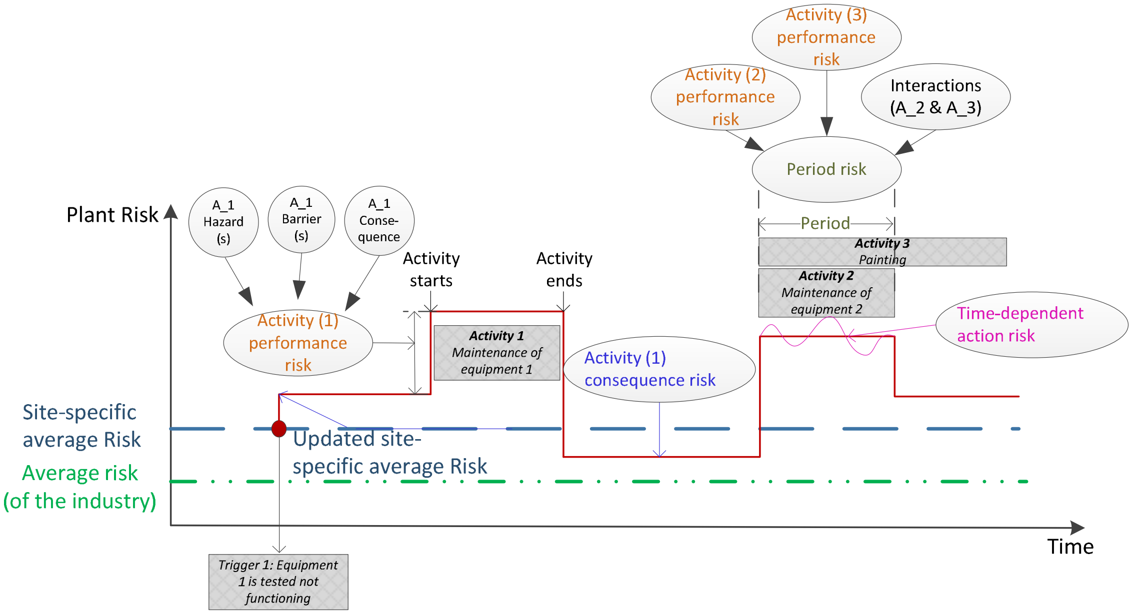

Figure 6 Illustration of principle difference of classified risk expressions

There are two things worth mentioning in relation to this. The *Site-specific average risk* sums up risks due to all possible major accident scenarios caused by hazardous events and uses average input values (e.g. frequency of hazardous events, probability of failure of barriers, average performance of risk factors, exposure of personnel). *Site-specific average risk* can be updated when the status of these inputs are updated. This is the same concept as "point-in-time risk" ("instantaneous risk", "configuration specific risk") that is used in the nuclear industry. This reflects "*the current plant configuration in terms of the known status of the various system and/or components, for example, whether there are any components out of service for maintenance or tests*" (IAEA, 1999). Another reference can be the "Risk Barometer". The "Risk Barometer" technique aims to continuously "*monitor risk picture changes and support decision makers in daily operations*" (Paltrinieri et al., 2014). The risk picture is based on the existing QRA and a set of risk indicators are introduced to measure the status of the various parameters influencing accident scenarios, including the ones defining the status of the safety barriers in the process area. We interpret the updated risk picture as a *site-specific average risk*, since what has been predicted is the average risk level over the rest of the lifetime of the system, even though the updating is done on a daily basis.

Activity performance risk and *period risk* consider much more specific and detailed factors (i.e. operational barriers) than *site-specific average risk*. We illustrate it using a theoretical calculation[1] of major accident risk that takes into account the following factors: The frequency of a hazardous event (F_{HE}), the probability of failure of barriers ($\Pr(f_{B1}) \dots \Pr(f_{Bm})$), and the consequence (C).

$$\text{Site} - \text{specific average risk} = \sum_{i=1}^{n} F_{HE\_i} \times \Pr(f_{Bi\_1}) \times \Pr(f_{Bi\_2}) \dots \Pr(f_{Bi\_j}) \times C_i$$

Suppose barrier 1 for hazardous event 1 is out of function, the updated *site-specific average risk* is:

$$F_{HE_1} \times 1 \times \Pr(f_{B1\_2}) \dots \Pr(f_{B1\_j}) \times C_1 + \sum_{i=2}^{n} F_{HE\_i} \times \Pr(f_{Bi\_1}) \times \Pr(f_{Bi\_2}) \dots \Pr(f_{Bi\_j}) \times C_i$$

While executing a maintenance activity on barrier 1, barrier 2 may be disconnected. To compensate for this, a temporary barrier 2 will be introduced with probability of failure $\Pr(f_{TB1\_2})$. The maintenance activity may also expose twice as many personnel on the site. As a result, the *activity performance risk* of this maintenance work is:

$$F_{HE_1} \times 1 \times 1 \times \Pr(f_{TB1\_2}) \dots \Pr(f_{B1\_j}) \times 2C_1$$

This *activity performance risk* "disappears" after the maintenance finished. If we assume the plant stays in the same condition during the maintenance period, the updated *site-specific average risk* during execution of maintenance is

$$F_{HE_1} \times 1 \times 1 \times \Pr(f_{TB1\_2}) \dots \Pr\left(f_{B1_j}\right) \times 2C_1 + \sum_{i=2}^{n} F_{HE\_i} \times \Pr(f_{Bi\_1}) \times \Pr(f_{Bi\_2}) \dots \Pr(f_{Bi\_j}) \times C_i$$

If our focus is only on avoiding major accident while doing the work, or during a particular period, it is not always necessary to update the risk level for the whole plant. The same principle applies to *period risk*.

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[1] The formulas are only for illustrative purpose from a theoretical point of view to see differences between site-specific average risk and activity performance risk.

5. EXAMPLE

In this section, proposed risk types are applied to decision situations regarding ESD (Emergency Shutdown) Valves to illustrate how they can be used in practice and how different aspects of risk can be revealed to assist more concrete decision contexts.

The ESD Valves on an offshore installation have been causing problems. Tests have shown that the probability of closing on demand not has been as required and there have also been observed internal leaks on several occasions. This is a concern for the platform management and a number of actions are being considered and/or are being implemented. The decisions involved and risk information are listed in Table 2.

Table 2 Decisions and risk information

Decision	**Risk information**
A long-term solution to the problem would be to replace all the valves with new valves with an improved specification. This is however a costly and time-consuming operation, involving considerable risk. A short-term solution (that may also be acceptable in the longer term), is therefore to perform more maintenance on the valves and to test them more often. This can contribute to improve the reliability to an acceptable level.	This is an operational decision that influences the long-term performance of the system. To support this specific decision-making context with two alternatives, the *activity consequence risk* describes the resulting risk from the decision, and this can be accumulated into the *site-specific average risk* to get an update of the risk for the plant. Meanwhile, the two alternatives may involve considerable risk during the performance of the work. *Activity performance risk*, expressed by activity specific hazards and status of safety critical factors relevant for the work, indicates the risk during the work. For replacement of valves, a series of activities such as shipment of new valves, lifting valves to platform, retrieval of old valves, establishing bypass etc. introduces additional hazards that may increase *activity performance risk* level.
As part of the short-term solution, plans are being prepared for performing maintenance on all the valves and to test them. As part of the preparations, risk is being considered and risk reducing measures are introduced to ensure that the work can be performed safely.	Two aspects of risk are relevant. First, scheduling maintenance or test work so that *period risk* can be acceptable. Which valve is out of service needs to be reflected in order to maintain the whole plant *site-specific average risk* acceptable. Second, the *activity performance risk* associated with maintenance or test activity itself is under control. Maintenance of ESD valves involves high probability of hydrocarbon leak due to manual intervention. The maintenance specific hazards include but not limit to human errors (i.e. no gas freeing, inadequate blinding, equipment not disconnected, flange not assembled, etc.), ignition source introduced by hot work, more exposed personnel, and so on. Other safety critical parameters such as weather condition, wind speed also need consideration. Correspondingly, whether risk reduction measures (i.e. technical barriers, operational barriers) towards these hazards are in place and their average performance are critical to predict *activity performance risk*. If necessary, more reduction measures should be planned to keep *activity performance risk* at an acceptable level.
Planning has been completed for some of the valves, and one of them is due for maintenance tomorrow. The platform management has to decide if it is safe to start the work the next day or not.	For this decision, two types of risk information are relevant. First, using updated *activity performance risk* to verify that it is not changed, due to changes in hazards, weather, actual performance of risk reduction measures (e.g. supervisor and documentation available), or actual number of personnel present during execution of the maintenance work. Second, using *period risk* to control risk level over next 24 hours by checking whether simultaneous activities are scheduled, and possible interactions (e.g. if extra people will be present because of other work).
During performance of the work, it is identified that one defect valve must be replaced immediately. The new valve is transported by supply vessel. Crane operator starts to plan when to start lifting from deck to platform.	Before lifting, status of operating parameters is used to construct a *time-dependent action risk* picture. Ship movement, wind direction, wave height and crane movement are some of the relevant parameters.

Decision	Risk information
Work on another of the valves is underway. During performance of the work, a leak of hydrocarbons suddenly occurs because of failure of one of the valves that isolate the ESD-valve from the rest of the plant. The situation has to be handled correctly to ensure the safety of personnel and the right course of action must be chosen.	In practice, this decision is made based on experience and observation of the situation (a set of critical parameters, such as leak size, gas flow rate, ignition possibility etc.), without a formal risk analysis to support the decision. Formally, it is the *Time-dependent action risk* that is relevant.

6. DISCUSSION AND CONCLUSION

6.1 Summary of the work

In this paper, we have classified decisions in a process plant from a risk assessment perspective into four main types. These decision types form the background for exploration of what risk information we actually need to express to support decision-making. A classification scheme of risk information into *average risk, site-specific average risk, activity risk (activity performance risk* and *activity consequence risk), period risk* and *time-dependent action risk* is proposed, together with descriptions of how they can be estimated as input to various decision types. *Activity risk* is further divided into *activity performance risk* and *activity consequence risk.*

6.2 Implications of the classification scheme

The classification scheme provides a formalization of the types of information required in different contexts and illustrates that risk expression and corresponding risk assessment methods must be customized to the decision context. This is not new, but formalization can be a help in selecting the best approach in different situations, thereby also assisting the search for concrete risk reduction measures and effective risk control. With the widening scope of application of risk assessment from design phase to operational settings in oil and gas industry, this becomes increasingly important.

The new classification has novel aspects in the way of providing more specific risk information to support various decisions in different contexts. This is shown in section 5 and as a result, a specific risk picture can be constructed as an input to risk-informed decision making (RIDM) for each decision context. As indicated, expressing risk explicitly in terms of expected loss is not necessarily the best approach in all situations.

An important benefit of the classification system is that it can improve communication among decision-makers. The risk considered in different situations varies and these differences are not necessarily clearly acknowledged and described. When an operational manager asks “what is the risk with this job?”, this can be understood in many ways:

- What can go wrong during execution of the work? – *activity performance risk*
- What are the undesired consequences to the system if the work is done (or not done)? – *activity consequence risk*
- Can the work interact with hazards involved in other planned (simultaneous) activities? – *period risk*

Without accurately specifying what is meant, there is significant scope for misunderstandings.

6.3 Risk types and quantification

The starting point for this paper was the use of quantitative risk assessment and the attempts at extending the use of the results to operational decisions. However, as illustrated in the discussion above, the risk does not necessarily need to be quantified in all circumstances. As pointed out, there may also be modelling issues (e.g. in QRA) which means that quantitative models are not possible to use at all or may give misleading results. This issues needs to be kept in mind in practical applications (UKOOA, 1999). Presenting qualitative information in a structured manner may be an option in such cases, although this has not been explored further in this paper. One advantage of quantification is however that comparison between options and comparisons with decision criteria usually becomes easier.

In principle, there will be a relationship between the complexity of the decision situation and the need for formal analysis and quantification of risk [2](Figure 7). If the situation involves several hazards and many activities, quantification (e.g. expected loss) is useful because different alternatives may be too difficult to compare without expressing this with one (or a few) parameters/numbers. On the contrary, for decisions involving only one activity, with only one hazard, safety critical factors will be relatively few. In such cases, quantification of expected loss is not necessary. This is supported by the Health and Safety Executive in UK and Health and Safety Representatives Sweden (Arbetsmiljöfonden, 1988) (Pickering and Cowley, 2010) stating that when control measure is “immediately apparent” or an exploratory investigation sufficed, the risk assessment stage can be bypassed by identifying hazards and then simply deciding what to do with them.

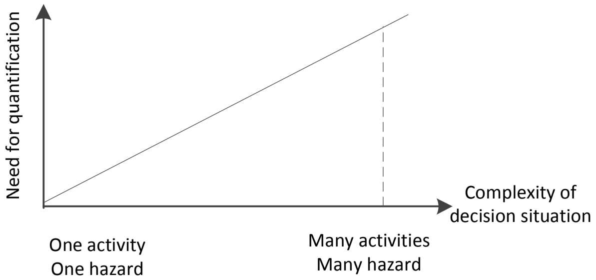

Figure 7 Relationship between complexity of decision situation and need for quantification

6.4 Challenges of using different risk expressions

Operational decisions have been treated differently compared to *strategic decisions* from a risk assessment point of view. This is pointed out by Andersen and Mostue (2012), stating that lack of formal risk analysis methods in daily operation in oil and gas industry raises questions about the ability to ensure safe operation. Even though the planning horizon is short for *operational decisions*, rational choice is still expected to be a suitable theory for describing these types of decisions under current knowledge of the situation, with proper risk information as input. Current practices do not help much with estimating *activity performance risk*, *period risk* and *time-dependent action risk*. The challenge in using *activity consequence risk* actually lies in the level of details while modelling *site-specific average risk*. Current QRA and area risk chart etc. are static and lack sufficient detail so that important changes in safety functions or technical conditions not can be included on a continuous basis. For a*ctivity performance risk*, the key is to identify critical safety parameters, especially technical and operational barriers and influences from surroundings. Best practices, incident/accident reports and experience from operational experts are the best sources, despite the fact that identifying a complete set of parameters is challenging and time-consuming. Analysis of interactions is pivotal for *period risk*. However, there are presently no guidelines or methods to illustrate how to identify these interactions.

It might be questioned whether *time-dependent action risk* is a useful concept or tool for *instantaneous decisions* and *emergency decisions*. As illustrated in section 3, NDM provides a description of the mechanisms behind these two types of decisions. These decisions rely heavily on experience-based judgement – the mental model in the decision-makers mind – to interpret abnormal situations, simulate

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[2] Figure 7 is only to illustrate that along with increase of complexity of decision situation, the need for quantification is increased. The relation doesn’t have to be linear.

and imagine what might happen and look for the first workable option to avoid accidents. Therefore, systematic processing of such risk information will benefit sharp-end operators towards a decision process more characterized by rational decision making theory.

There are two merits of using the *time-dependent action risk* concept. Firstly, analytical and systematic work can help identify a complete picture of what the sharp-end operators need to monitor, especially for operators who are less experienced. Secondly, a prediction of risk level (i.e. in terms of probability of accident happening) based on multiple deviations or warning indicators can help construct a clearer risk picture. At the same time, it is also a challenge to generate the models necessary to quantify risk. Another challenge in relation to using the risk types will be to maintain consistency between proposed risk types, in the sense that if we look at integrated *activity performance risk* and *period risk* over a year; we should arrive at *site-specific average risk*. This need not necessarily be the case, since different models and different factors are used for estimation. With the same reasoning, integration of *time-dependent action risk* over time is not necessarily equal to *activity performance risk*. However, since these risk types are used for different purposes and different situations, this need not necessarily be a problem. The main thing is that they provide adequate decision support for the situations they are intended to support, and that suitable decision criteria are established to fit those situations.

6.5 Future work

Based on the classified risk expressions, further work is ongoing to develop practical guidance to provide sufficient risk information to support operational decision-making, based on the classifications in this paper. The next step will focus on expression of risk types, to review and find suitable and concrete risk measures to express each risk type, especially the ones that current risk measures in terms of expected loss are not suitable for. This means current practices for operational risk analysis will be reviewed and their suitability, advantages and disadvantages will be evaluated. A further step will be modelling some of the risk types, with special interests in modelling *activity performance risk*, *activity consequence risk* and *period risk*. This will also be an attempt to facilitate the process of developing formal risk analysis methods in daily operation by identifying, assessing and handling risks more explicitly and traceable.

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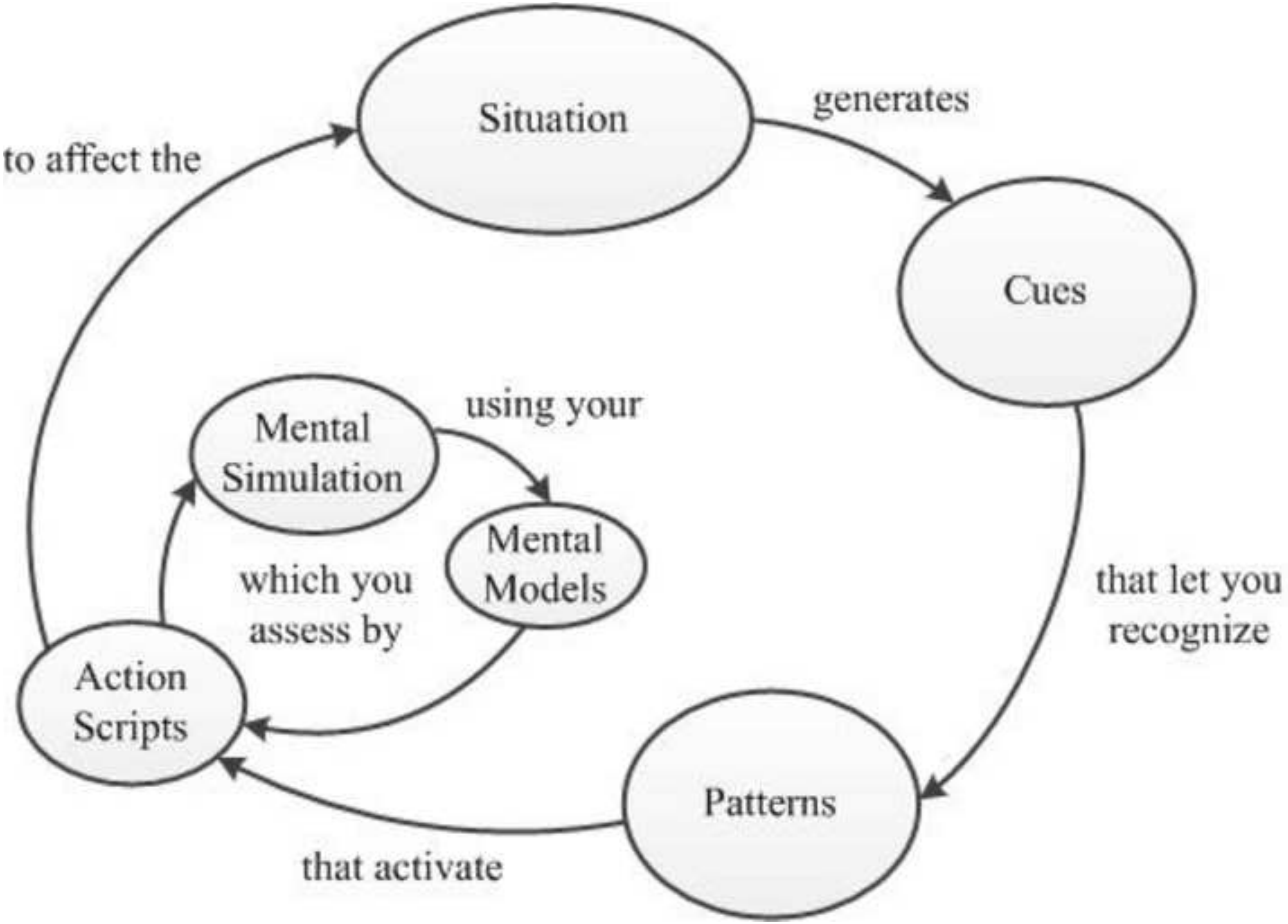

Situation
generates
Cues
that let you recognize
Patterns
that activate
Action Scripts
which you assess by
Mental Simulation
using your
Mental Models
to affect the

Figure

Strategic decisions

- Long planning horizon (years)
- Risk and benefits of decision alternatives are considered carefully
- Made by blunt-end decision-makers

Operational decisions

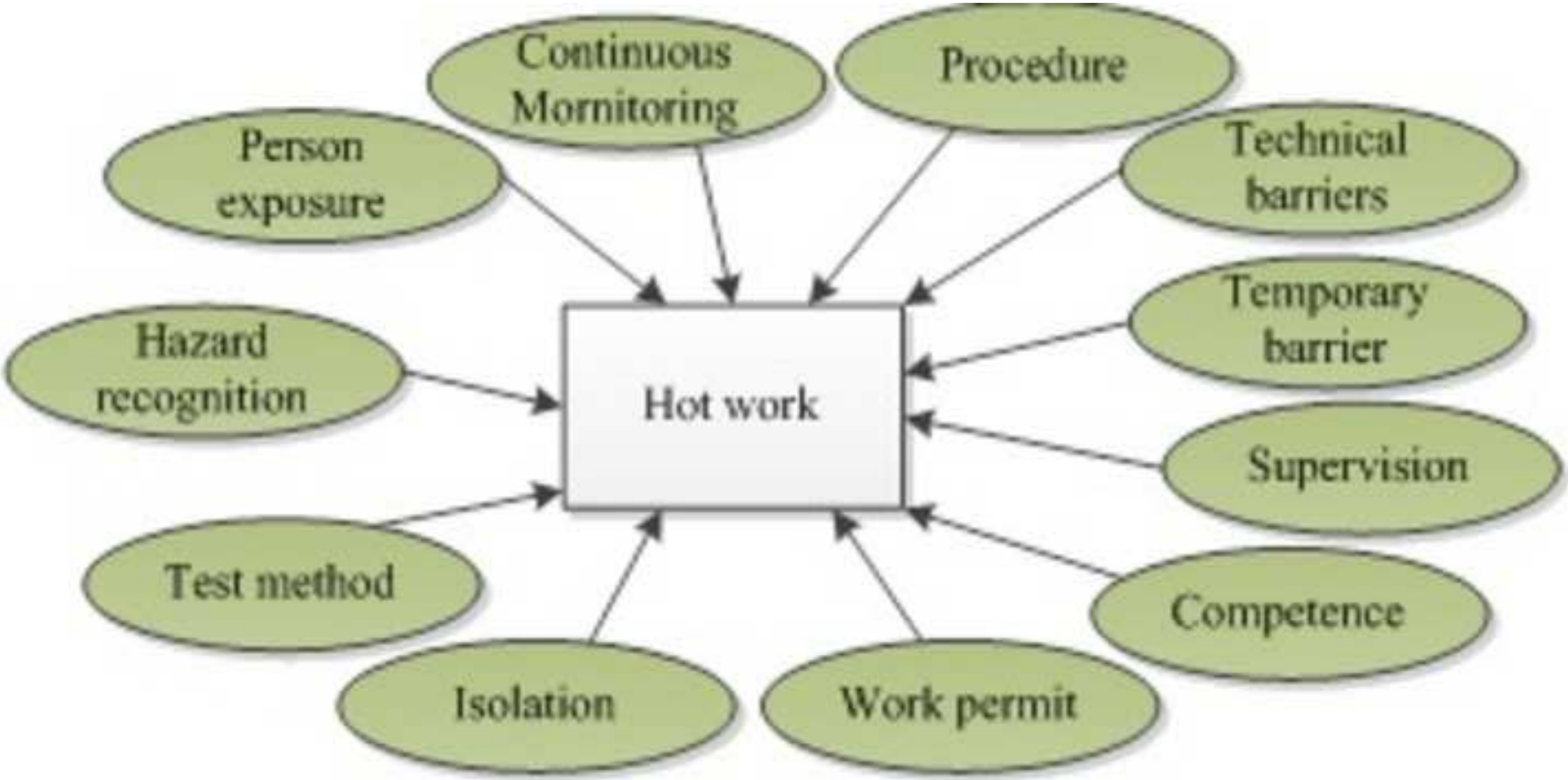
- Short planning horizon but long enough to carry out risk assessment
- Made by middle level decision makers (planners)

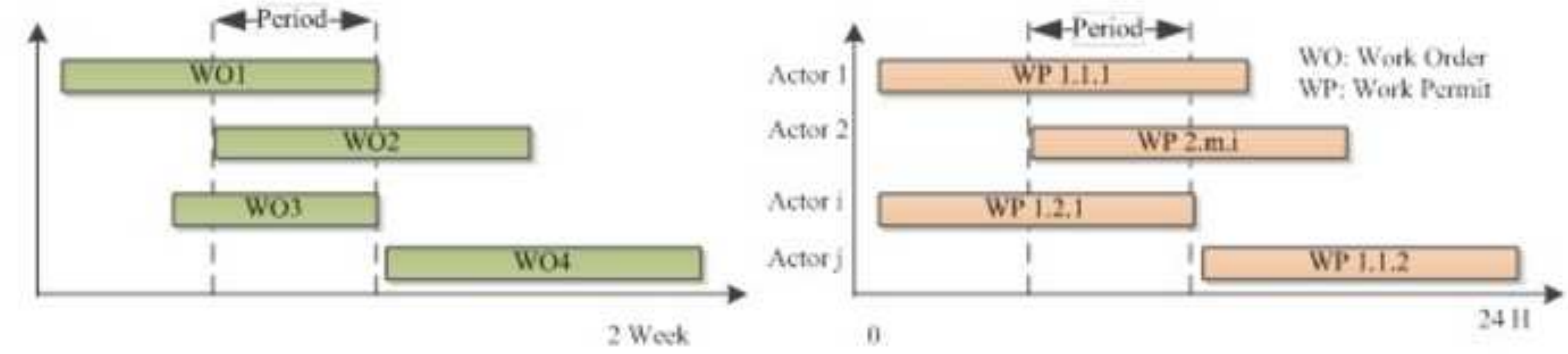
Instantaneous decisions

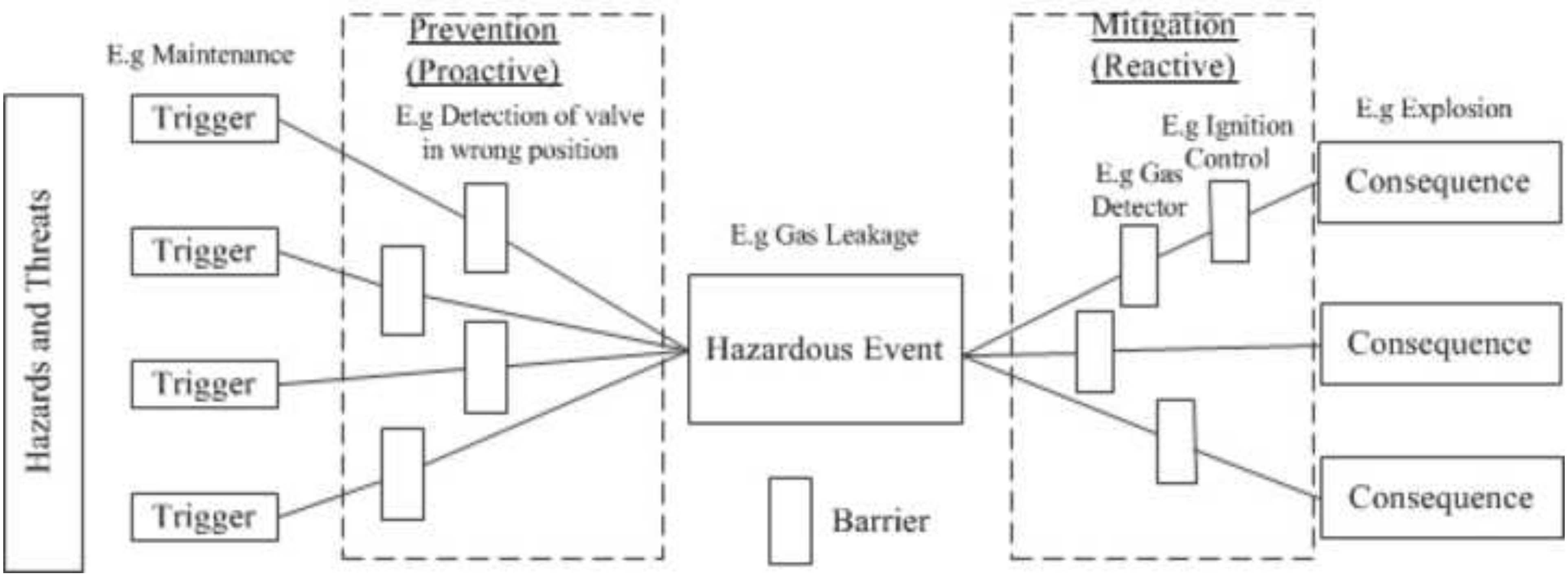
- Spontaneous decisions to follow or violate procedure or decisions triggered by external deviations
- Made by personnel who monitor or control on-going operation

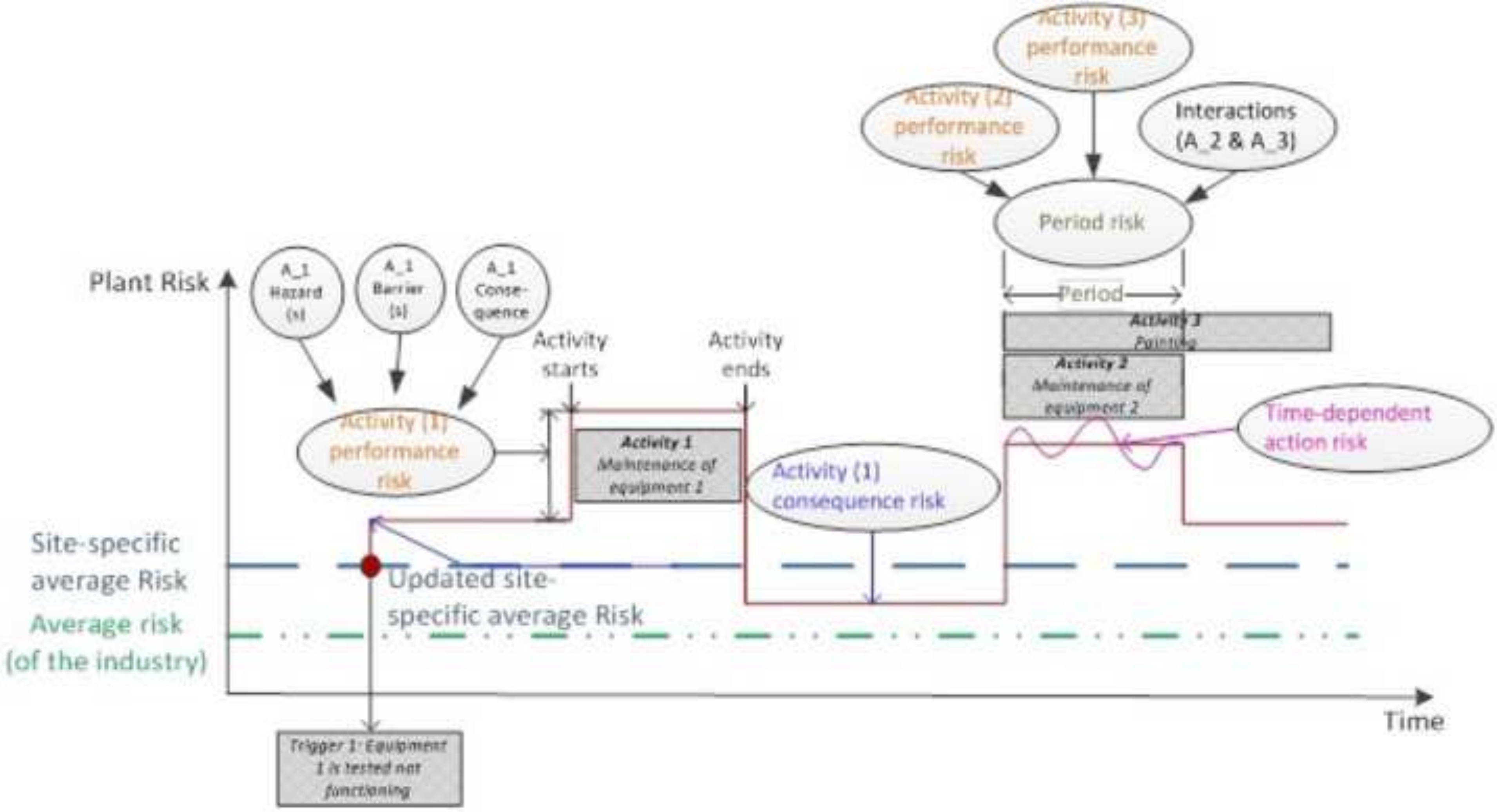
Emergency decisions

- Execution decision to avoid or adapt to hazardous situations
- Fundamentally impacted by experience and judgments
- Triggered by indicators out of comfortable zone
- Made by emergency response team


Continuous Mornitoring
Procedure
Person exposure
Technical barriers
Temporary barrier
Hazard recognition
Hot work
Supervision
Test method
Competence
Isolation
Work permit


Period
WO1
WO2
WO3
WO4
2 Week
Period
Actor 1
Actor 2
Actor i
Actor j
WP 1.1.1
WP 2.m.i
WP 1.2.1
WP 1.1.2
0
24 H
WO: Work Order
WP: Work Permit


Hazards and Threats
E.g Maintenance
Trigger
Trigger
Trigger
Trigger
Prevention
(Proactive)
E.g Detection of valve
in wrong position
E.g Gas Leakage
Hazardous Event
Barrier
Mitigation
(Reactive)
E.g Ignition
Control
E.g Gas
Detector
E.g Explosion
Consequence
Consequence
Consequence


Activity (3) performance risk
Activity (2) performance risk
Interactions (A_2 & A_3)
Period risk
Period
Activity 3 Painting
Activity 2 Maintenance of equipment 2
Time-dependent action risk
Plant Risk
A_1 Hazard (s)
A_1 Barrier (s)
A_1 Conse-quence
Activity starts
Activity ends
Activity (1) performance risk
Activity 1 Maintenance of equipment 1
Activity (1) consequence risk
Site-specific average Risk
Updated site-specific average Risk
Average risk (of the industry)
Time
Trigger 1: Equipment 1 is tested not functioning

Figure

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