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Cognitive modeling and dynamic probabilistic simulation of operating crew response to complex system accidents. Part 2: IDAC performance influencing factors model

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Abstract

This is the second in a series of five papers describing the **i**nformation, **d**ecision, and **a**ction in **c**rew context (IDAC) model for human reliability analysis. An example application of this modeling technique is also discussed in this series. The model is developed to probabilistically predict the responses of the nuclear power plant control room operating crew in accident conditions. The operator response spectrum includes cognitive, psychological, and physical activities during the course of an accident. This paper identifies the IDAC set of performance influencing factors (PIFs), providing their definitions and causal organization in the form of a modular influence diagram. Fifty PIFs are identified to support the IDAC model to be implemented in a computer simulation environment. They are classified into eleven hierarchically structured groups. The PIFs within each group are independent to each other; however, dependencies may exist between PIFs within different groups. The supporting evidence for the selection and organization of the influence paths based on psychological literature, observations, and various human reliability analysis methodologies is also indicated.

Keywords: Human reliability analysis; Performance influencing factors; Performance shaping factors; Cognitive; Dynamic probabilistic risk assessment

1. Introduction

This is the second in a series of five papers [1–4] discussing the **i**nformation, **d**ecision, and **a**ction in **c**rew context (IDAC) model for human reliability analysis (HRA) implementation. The model is developed primarily for use in a computer simulation platform to probabilistically predict the responses of a nuclear power plant (NPP) control room crew in dealing with system anomalies. The response spectrum includes cognitive, emotional, and physical activities in the process of solving a problem (e.g., bringing the system to a safe and stable state). IDAC aims at predicting an operator's response quantitatively for use in probabilistic risk assessment (PRA).

An overview of the IDAC model and its core elements has been provided in Paper 1 [1]. Among the core elements are the set of Performance Influencing Factors (PIFs) and their interdependencies. PIFs are used as a subset of causal factors and mechanisms through which a causal model of operator behavior is constructed. This paper introduces the IDAC PIFs and their interdependencies. The influences of PIFs on an individual's performance are discussed in Paper 4 [2].

Various PIFs are defined and discussed in Sections 2 and 3 together with supporting evidence for the selection and organization of the IDAC PIFs based on psychological literature, actual operating evidence, and various HRA methodologies. IDAC PIFs cover a broader set of causal types and mechanisms compared with other similar sets of performance shaping factors [5] or performance adjustment factors [6]. The interdependencies among PIFs are discussed in Sections 4 and 5. In addition, this part covers

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ways by which the value or state of a given PIF can be assessed directly, or as a function of other PIFs. Supporting evidence from psychological literature, experiments, actual events, and various HRA methodologies is provided.

An influence diagram, discussed in this paper is used to represent a set of causal relations among the PIFs. This influence diagram is supplemented by a number of mathematical relations for a more explicit representation of such relationships. These sometimes take the form of correlation or stochastic relations rather than deterministic links.

2. IDAC performance influencing factors

When an individual encounters an abnormal event, the natural reaction often includes physical, cognitive, and emotional responses [7]. These three types of response also influence each other. There is ample evidence suggesting that they also affect an individual's problem-solving behavior (discussed in details in Paper 4 [2]). In addition to these *internal* PIFs, there are *external* PIFs (e.g., organizational factors) that also affect an individual's behavior directly and indirectly.

The PIFs discussed in this paper are those that could play a tangible role in altering the course of an event through their effects on the operators' responses. The scenarios of interest are relatively dynamic and have a time window of up to a few hours. Thus, the PIFs requiring a relatively long time to have effects are not considered (e.g., learning related factors). The PIFs identified in this paper are mostly "frontline" factors. Those factors that have an indirect influence on operators' response are implicitly modeled by their influences on these frontline factors. For example, continuously long work hours or hard-to-adjust shift schedule could cause fatigue. In the current discussion, fatigue is a PIF affecting the operator's performance. The inappropriate shift schedule and long shifts are not included. Operator training is another example. Training affects the operator's proficiency in handling system anomalies; thus the proficiency (i.e., knowledge and skills) but not the training is a IDAC PIF. Of course such factors can also be added to the list explicitly in another deeper layer of the causal model.

A key requirement in identifying factors for use in a causal model for human errors is to have a precise definition for each factor, and to ensure that they do not overlap in definition and role in the overall model. This is important since IDAC is primarily developed to be applied in computer simulation. Accordingly all the rules and factors that guide and affect an operator's behaviors must be explicitly represented as computer instructions. As a result, there are fifty PIFs (divided into eleven groups) in the IDAC model compared with ten or even fewer PIFs used in typical HRA methods designed to be used manually (e.g., [8,9]). The IDAC PIFs allow a more precise definition in state assessment and causal mechanisms, and enable computer rules to interpret small differences in context which could result in visible different behaviors. In simpler models where expert judgment is often used to relate context to behavior, it is not practical to consider more than a handful of PIFs. It is relatively easy to see that the larger set of IDAC PIFs can be reduced through grouping and/or scope reduction.

Developing precise and non-overlapping definitions for all PIFs is extremely difficult given the current state of the art, the quality, form, and availability of relevant information, and complexities of communication across diverse disciplines in which subjects are studied often for entirely different reasons and end objectives. IDAC has made an attempt to meet these requirements. The fifty IDAC PIFs are classified into eleven hierarchically structured groups. The PIFs within each group are independent; however, dependencies may exist between PIFs within different groups. Fig. 1 shows the dependencies of the IDAC PIF groups.

As stated earlier, PIFs are grouped into internal PIFs and external PIFs. The internal PIFs are further divided into three groups: *Mental State, Memorized Information*, and *Physical Factors*. Mental State covers the operator's cognitive and emotional states. It consists of five PIF sub-groups representing different facets of an operator's state of mind. These five PIF sub-groups are hierarchically structured to represent a process of cognitive and emotional responses to stimuli, from top to bottom, including *Cognitive Modes and Tendencies, Emotional Arousal, Strains and Feelings, Perception and Appraisal*, and *Intrinsic Characteristics*. Memorized Information refers to the system-related information that is either

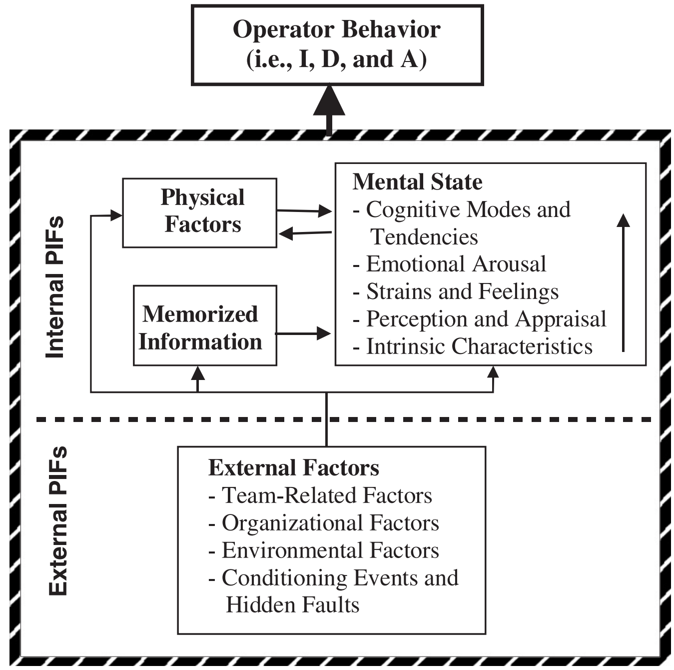

Fig. 1. Organization of PIF groups and high-level interdependencies.

perceived or recalled during an event. Physical Factors refer to ergonomic and physical abilities.

The External PIFs are classified into four groups: *Team-Related Factors, Organizational Factors, Environmental Factors*, and *Conditioning Events*. Team-Related Factors pertain to coordination requirements among crew, such as backup, mutual performance monitoring, mutual error correction, and information communicating [10]. Organizational Factors cover the influence of organization and management decisions on performance. Environmental Factors refer to the change of inhabitation that affects an operator's behavior (e.g., high temperatures caused by a fire). These influences are typically beyond the nominal organizational domain of control. Conditioning-Events covers the unanticipated changes of system state (e.g., latent failures).

A more detailed discussion of these PIF groups and the specific PIFs included in them is provided in Section 3. Fig. 1 provides a high-level picture of the interdependencies of these PIF groups. Detailed discussions on such interdependencies between PIF groups and between individual PIFs are provided in Sections 4 and 5, respectively.

A significant number of studies were reviewed to identify and ensure the completeness of the IDAC PIFs. The corresponding findings and supporting evidence are presented in the discussion of individual factors later in this paper. Some factors mentioned in literature were not included in the IDAC model for various reasons. Examples are age [11], hunger or thirst, and gender [5]. Some other factors are modeled through IDAC behavior rules (e.g., "forgetting" [12]) or by a few of factors (e.g., social pressure [8] is covered by Team-Related Factors and Organizational Factors) rather than as a specific PIF. Some were found to be overly broad (e.g., organizational design [8] and management factors [13]) and as such had to be modeled through other more narrowly defined sets of PIFs.

It is acknowledged that specific implementations and applications of the IDAC model might require more detailed specifications or additional PIFs. For example, in IDAC, the PIF Human–System-Interface represents an overall quality assessment of the system controls and information display. To know the specific impact of such an influence on the operator's behavior requires distinguishing Human–System-Interface for each individual control and display.

3. Definitions of IDAC PIFs

This section is devoted to defining various PIFs and providing supporting evidence for them based on psychological literature, observations, and various HRA methodologies.

3.1. Definitions of the mental state factors

Hansen [14] articulates that the state of an individual's mind is a combination of cognition and emotion that are two continuous and parallel but inter-influencing processes. Hansen labels the emotional process as "stream of feelings" and adopts "stream of consciousness" [15] as a label for the cognitive process. The combination of these two parallel processes is denoted as "stream of mentation". The stream of mentation is represented by four IDAC PIF groups of Mental State: *Perception and Appraisal*, *Strains and Feelings*, *Emotional Arousal*, and *Cognitive Modes and Tendencies*. These four PIF groups represent four phases of mental activities. Another group denoted as *Intrinsic Characteristics* is included in Mental State to capture the effect due to individual differences. Mental State consists of the above five PIF groups to represent the state of an operator's mind.

An example of the influence path of the five Mental State groups can be reasoned as follows. Incoming information stimulates the operator's automatic response on information perception and situation appraisal, represented by "Perception and Appraisal", resulting in a series of emotional and cognitive responses. The emotional responses propagate from inner feelings to outward cognitive patterns or from being less observable to being more visible. The operator might not be conscious of his/her inner feelings not to mention other operators. The inner feelings are represented by "Strains and Feelings". The inner feelings propagate and turn to emotional expression (e.g., being stressful) which is represented by "Emotional Arousal." Consequently, cognitive activities could be impelled to certain patterns or modes (e.g., being biased). The operator is likely unaware of being trapped in such cognitive propensities; however, the revealed behavior patterns could be identified by other operators. Such patterns are represented by "Cognitive Modes and Tendencies".

The following subsections discuss the definition of individual PIF and the relevant factors identified in other HRA methods or psychology literature.

3.1.1. Cognitive modes and tendencies

Attention: refers to whether sufficient cognitive and physical resources are put at the "right" places. Human beings have limited attention resources, thus, inappropriate attention distribution could result in missing important information or causing unintended change in system state. Two types of attention are identified: *Attention to Current Task and Attention to Surrounding Environment*. The first kind of attention interacts with the Human–System-Interface to monitor and control the system. The second kind of attention interacts with the surrounding environment to prevent against changing system state unintentionally.

Example factors in other HRA methods and in literature, similar or related to attention, include "sensory deprivation" [5], "monotony" [16], "high attention demand" [17,18], and "attention and motivation" [19].

Alertness: is a measure of the total amount of attention resource available to detect the state of the external world. It differs from Attention in the sense that reduced alertness is an overall degradation in utilizing one's cognitive and physical recourses, whereas reduced attention is an inappropriate distribution of such resources. Decreased alertness could, for example, result in decreased vigilance/watchfulness, longer time for various types of activities.

Examples of similar or contributing factors seen in other HRA methods and in literature include ''long, uneventful vigilance periods'' [5], ''monotony'' [16], ''vigilance failure'' [20], ''disruption of circadian rhythm'' [5], ''lack of physical exercise'' [5], and ''sleepiness at different work shifts'' [17,18].

Bias: is characterized as a cognitive preoccupation or obsession that causes strong confidence in reaching preset goals despite the presence of contradictory evidence. In other words, it is a purposeful behavior to concentrate resources on the subjects of interest to reach preset goals. Extreme bias becomes fixation. Such behavior could induce systematic errors. Biases can be classified as ''internally-caused'' or ''externally-caused''. Internally-caused biases are the preferences or inclinations in judgment due to pre-existing strong beliefs based on the operator's experience and knowledge. Externally-caused biases are the preferences or inclinations in judgment encouraged or imposed by external sources (e.g., manager, organization culture, or a recognized authority). Several kinds of bias have been identified in literature. Examples are:

- Belief bias [21]: is manifestation of personal beliefs overriding logical conclusions. Consequently, for example, a logically invalid statement would be thought of as valid.
- Confirmation bias [21]: results from a person's tendency to selectively use information; accepting information that confirms one's hypotheses and rejecting inconsistent information.
- Other types of cited biases including matching bias, conclusion bias [21], biases caused by heuristics [22], subadditivity bias, hindsight bias, and averaging bias [23].

Examples of factors in other HRA methods and in literature related to or contributing to bias include ''expectation bias'' [20], ''infrequency bias'' [20], ''failure to recognize or refusing to believe accumulating evidence'' [24], ''unfamiliarity with a situation which is potentially important but which only occurs infrequently or which is novel'' [25], and ''a mismatch between perceived and real risk'' [25].

3.1.2. Emotional arousal

Stress: Gaillards [26] defines stress as ''a state in which the operator feels threatened and is afraid of losing control over the situation''. Swain and Guttmann [5] define stress as ''bodily or mental tension'' which is caused by physical or psychological stressors, or both. They further classify psychological stress into disruptive stress and facilitative stress. Disruptive stress is an acute stressor that ''threatens us, frightens us, worries us, angers us, or makes us uncertain'' [5]. Facilitative stress, also called arousal, is ''the result of any stressor that alerts us, prods us to action, thrills us, or makes us eager (to respond).'' When facilitative stress is strong, it could have a disruptive effect.

Four types of Stress have been identified: *pressure, conflict, frustration* [7,27], and *uncertainty*. Pressure stress results from immediate attention demanded by urgent matters. Conflict stress is the incompatible inner needs caused by intending to achieve multiple goals simultaneously. Frustration stress is caused by the perception of a goal being blocked. Uncertainty stress results from an inability to understand the situation and lack of a plan to respond to ensuing events or conditions.

Different types of stress have different influences on an operator's behavior. For example, pressure stress, arising from a large demand, could result in an operator mobilizing more of his available resources to meet the demand. Conflict stress, arising from conflicting needs for resource distribution among multiple goals, could compel the operator to reduce demand (e.g., by giving up or postponing the pursuit of some goals) or gain more resources (e.g., by asking for help). Frustration stress, which arises when efforts to achieve a goal are being blocked, would motivate the operator to seek an alternative method to achieve the goal or to give up the goal. Uncertainty stress, arising from the lack of a clear picture of the situation, would promote behaviors that help to gain more confidence. Obtaining more information in order to have a better understanding of the current situation is the likely response.

Example factors in other HRA methods and in literature relating to Stress include ''stress'' [28], ''arousal level'' [29], and ''psychological stress'' [12].

3.1.3. Strains and feelings

Time-Constraint Load: is a strain resulting from the feeling of not having sufficient time to solve the problem. The terms ''time stress'' and ''time pressure'' [30] have similar meanings. Time pressure and time stress however normally represent combined task properties of time sufficiency, urgency, task complexity, and task quantity. The IDAC Time-Constraint-Load relates only to the time dimension. Other task-related properties are covered by other IDAC PIFs.

Fig. 2 shows a graphical expression of the Time-Constraint-Load concept. Time-Constraint-Load is determined by the relative lengths in time of ''perceived time available'' (i.e., the available time to act on the system

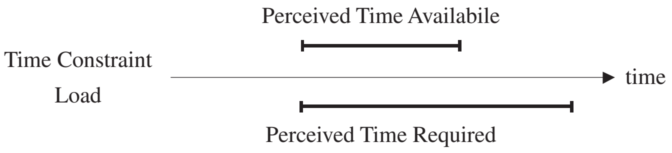

Fig. 2. A graphical representation of time-constraint load.

before things go bad) and "perceived time required" (i.e., the time required for the operator to complete the control process) for a task. The lower the ratio of perceived time available to perceived time required, the higher the score of Time-Constraint-Load. Each task has its Time-Constraint-Load. There is also a Time-Constraint-Load to represent the overall time constraint aggregated from all tasks.

Other definitions seen in literature include:

- "the difference between the amount of available time and the amount of time required to resolve a task" [31].
- "the rate at which the situation moves towards the moment at which the negative consequences materialize" [32].

Obviously there is both the real duration of time and its perception. Time-Constraint-Load is more dependent on the person's sense of time sufficiency rather than on the actual available time [30,33,34]. IDAC's Time-Constraint-Load is based on time perception, and consequently a definition such as the first one above is viewed as inadequate.

Example factors in other HRA methods and in literature related to Time-Constraint-Load include "time pressure" [13,16–18,35], "time stress" [36], "task time/resource demand" [8], "time" [17,18], "a shortage of time available for error detection and correction" [25], and "time constraints" [12].

Task-Related Load: is the load induced by aggregated demands on task related properties including task quantity, complexity, importance, and accuracy requirement (i.e., fault tolerance) per unit of time. The perceived level of these attributes is of course dependent on the individual operator's proficiency, and familiarity with the tasks. The IDAC definition of Task-Related-Load is normalized to time units to make this load a separate and independent dimension from Time-Constraint-Load. Fig. 3 shows a graphical representation of the relative Task-Related-Loads for two different situations. The number of lines parallel to the time axis represents the number of tasks that need to be performed "simultaneously". The thickness of a line represents combined demands on the complexity and accuracy requirements of a task. Thus, a Task-Related-Load is associated with a task. A global Task-Related-Load reflects the aggregated result from the individual Task-Related-Loads.

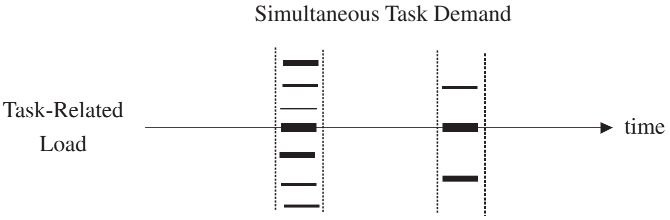

Fig. 3. A graphical representation of task-related load.

Similar to the case of "time stress" versus Time-Related-Load, the term "workload" seen in literature normally has a broader meaning than Task-Related-Load. For example, a study on human factors affecting tank crew performance [37] has concluded that workload has four attributes: imposed actual task demand (in terms of difficulty, number, rate, and complexity), the operator's level of performance, the exerted cognitive and physical efforts to achieve certain performances, and the operator's feelings about how effortful the work is. Of the above four attributes only the first and fourth attributes are covered by Task-Related-Load. The other attributes are the result of reacting to the overall demands.

Example factors similar or related to Task-Related-Load seen in other HRA methods and in broader literature include "task speed" [5], "task load" [5], "task precision" [16], "high workload" [35,36], "high demand on mental capacity" [17,18], "workload" [13], "excessive workloads" [12], "task time/resource demand" [8], and "work demanding great psychological effort" [17,18].

Non-Task-Related Load: is the load induced by extra work that needs to be performed in addition to the tasks for solving the problem at hand. For example, making or answering phone calls to or from management to report current system status while attending all other necessary tasks could be stressful.

Examples of similar concepts in other HRA methods and in literature include "disturbance when performing an activity" [17,18], "distraction" [12], "many people and disturbances in the control room" [17,18], "distraction/preoccupation" [20], and "interfering activities" [12].

Passive Information Load: is created by perception of the information revealed by the external world. In the Three-Mile Island NPP accident for example, the operators were overwhelmed by the huge number of alarms activated within a few minutes following the initiating event, as described by one of the operators to the investigating committee: "When the first alarm sounded followed by a cascade of alarms that numbered 100 within minutes…The control room operator Faust recalled for the commission his reaction to the incessant alarms: I would have liked to have thrown away the alarm panel. It was not giving us any useful information" [38].

Examples of similar concepts in other HRA methods and in literature are "complexity/information load" [5], "stimulus overload" [20], and "demands on high information capacity simultaneously" [17,18].

Confidence in Performance: is the feeling of assurance whether the situation is on track. During an incident, an operator constantly generates hypotheses for the situation and generates goals to address the problem. The operator observes system response to confirm correctness and achievability of the goals. Confidence-in-Performance results from such confirmations and is an attribute attached to each task. Thus, in the situations where the operator is performing multiple tasks simultaneously the operator has different levels of Confidence-in-Performance for each task. A global Confidence-in-Performance reflects the aggregated result from the individual Confidence-in-Performances.

Examples of similar or related concepts in other HRA methods and in literature include "situation awareness" [37], "confusion" [12] and "confidence" [29].

3.1.4. Perception and appraisal

Perceived Severity of Consequences Associated with Current Diagnosis/Decision: is the immediate perception of the potential adverse consequences which could result from the situation. An operator's priority of a particular task among many others, in general, is dependent on two attributes: importance and urgency. Perceived-Severity-of-Consequences-Associated-with-Current-Diagnosis indicates the importance of a task. The urgency is represented by Time-Constraint-Load.

Example factors similar or related to Perceived-Severity-of-Consequences-Associated-with-Current-Diagnosis seen in other HRA methods and in broader literature include "task criticality" [5] and "high jeopardy risk" [5].

Perceived Criticality of System Condition: is the appraisal of the system safety margin which usually is indicated by the absolute values, rate of change, and changing direction of a few key parameters. Each key parameter has a normal operation range. Exceeding such a range means that system safety is threaten. Perceived-Criticality-of-System-Condition is different from Perceived-Severity-of-Consequences-Associated-with-Current-Diagnosis, as the latter indicates the potential consequence of failure or loss of integrity of the system whereas the former indicates how close the system is to the state of failure.

An example of a similar concept in other HRA methods and in literature is the "rate at which the situation moves towards the moment at which negative consequences materialize" [32].

Perceived Familiarity with Situation: is the similarities perceived by the operator between the current situation and what the operator has experienced or been trained on (e.g., simulator training). Perceived-Familiarity-with-Situation can explain why the same task is assessed differently in terms of its complexity by different operators. Based on the demand-and-resource concept, the same task implies the same task demands; however, familiarity with the task would provide the operator with an additional resource to meet the demand.

Examples of similar concepts in other HRA methods and in literature related to Perceived-Familiarity-with-Situation include "interpretation (requirements)" [5] and "previous experience with similar symptoms" [36].

Perceived System Confirmatory/Contradictory Responses: is an aggregated indication of the observed positive and negative system responses corresponding to what is expected by the operator.

Example factors in other HRA methods and in literature related to Perceived-System-Confirmatory/Contradictory-Responses include "feedback" [5], "expectancy or set" [12], and "inconsistent cuing" [5].

Perception of Alarms' quantity, intensity, and importance: In operating NPPs, alarms are key elements for assessing system state. Typically there are about one thousand alarm tiles on the control panel of a NPP control room. The system anomalies usually are indicated by these alarms with great detail. Perception-of-Alarms-Quantity reflects the total number of activated alarms perceived by the operator. Perception-of-Alarms-Intensity reflects the highest alarm occurrence rate perceived in a short time interval. In some NPP control rooms, each alarm tile is colored with green, yellow, orange, or red to indicate its importance. Perception-of-Alarms-Importance represents the aggregated effect of these colors on the operator.

Perceived Decision Responsibility: is the awareness of responsibility and accountability toward the operator's decisions or actions. When potentially major negative consequences are involved, some people tend to delegate or transfer decisions to others. They do not want to be responsible for major losses [32]. Perceived-Decision-Responsibility is assessed based on where the decision is originated and whether there are sufficient reasons for implementing a decision (or action). For example, a decision resulting directly from a procedure would have a different Perceived-Decision-Responsibility compared with the same decision based on the operator's own knowledge. The responsibility of failure in the former case would be attributed to the procedure writers, whereas in the latter case the responsibility would be attributed to the operator.

An example of a similar concept in other HRA methods and in literature related to Perceived-Decision-Responsibility is "threat of failure and loss of job" [5].

Perceived Complexity of (Problem Solving) Strategy: IDAC identifies nine general problem solving strategies (see Paper 1 [1]) for problem solving. These nine strategies have inherently different complexities depending on their demands on mental effort. Perceived-Complexity-of-Strategy is the operator's perception of such complexities. Complexity perception can affect the likelihood of selecting or giving up a particular strategy.

An example factor in other HRA methods and in literature related to Perceived-Complexity-of-Strategy is "cognitive complexity" [28].

Perceived Task Complexity: The task complexity refers to the level of cognitive and physical effort required to complete the task for an average operator. For example precision requirements and computational demands are factors in determining complexities of a task. Such complexity factors can in principle be measured objectively. For example, the "step complexity measure" [39] calculates the complexity of performing an emergency operating procedure step. The perception of these inherent complexities is Perceived-Task-Complexity, which when combined with Perceived-Familiarity-with-Situation results in the individual's perception of task difficulty.

Examples of similar concepts in other HRA methods and in literature related to Perceived-Task-Complexity include "calculation requirements" [5], "task complexity" [16–18], "simplicity, complexity, and precision of task" [16], "task interdependence" [10], "dynamic versus step by step activities" [5], "high demand on performance" [17,18], "cognitive complexity" [28], and "levels of automation" [13].

Perception of Problem-Solving Resources: is the operator's high-level assessment of the internal and external resources available for him/her to solve the problem. An example of an internal resources is the number of methods that the operator knows for solving the problem. Examples of external resources are teammates, procedures, decision-aid systems, and remote technical support centers.

Examples of similar concepts in other HRA methods and in literature related to Perception-of-Problem-Solving-Resources include "technological systems" [10], "automation quality" [13], "mobilization of extra resources" [17,18], "reinforcement absent or negative" [5], and "resource availability" [10].

Awareness of Role/Responsibility: Awareness-of-Role/Responsibility includes the awareness of the operator's primary responsibilities (i.e., officially assigned) and subsidiary responsibilities (i.e., unofficially assigned responsibilities such as assisting teammates whenever needed). The first type of awareness drives the operator to comply with his/her responsibilities. The second type of awareness enhances teamwork.

Example factors in other HRA methods and in literature related to Awareness-of-Role/Responsibility include "group norm" [40], "inadequate job specification" [36], "performance norms" [10], "team support (job description)" [8], "unclear allocation of function and responsibility" [25], "no one understanding the rule" [35], and "role of operation" [41].

3.1.5. *Intrinsic characteristics*

Intrinsic Characteristics refers to the factors and dimensions collectively named by some as "personality" [42] or "intrinsic human variability" [43]. Intrinsic Characteristics is subdivided into two groups: "Temperament" and "Cognitive Faculties".

"Modern psychologists use the word *temperament* to refer to a person's predisposition to respond to specific events in a specific way; thus, temperament refers to the style rather than to the content of behavior" [44]. A dictionary definition of temperament is "the manner of thinking, behaving, or reacting characteristic of a specific person" [45]. An individual's response tendencies, personality traits, have been classified and characterized in a number of ways. Examples are the four "basic humors" by ancient Greek physician Hippocrates, five personality factors by Tupes and Christal [46], and five types of problem solver by Woods et al. [47]. Of these IDAC explicitly considers three main PIFs: Self Confidence, Problem Solving Style, and Morale-Motivation-Attitude, to be included in the type of Temperament—leaving out certain emotional dimensions (e.g., hot-headed, calm, hopeful).

The Cognitive Faculties cover the individual differences in mental capabilities (e.g., memory capacity, and sharpness). Such intrinsic differences are not currently modeled in the form of a specific set of PIFs.

Self Confidence: refers to the operator's self-estimation of his/her overall problem-solving knowledge and skills. Such an image could result in different problem-solving tendencies and preferences. Self-Confidence also is an indicator of an individual's intrinsic adaptability to the demands of the external world. For instance, different people have different levels of adaptability to time pressure [31,48]; experienced operators are more confident than inexperienced operators in facing the same scenarios [49]. Such difference in operation is not only dependent on the operator's knowledge or skill level but also affected by Self-Confidence. Overconfidence might result in premature decisions, bias and fixation, and neglect of industrial (safe) practices.

Problem Solving Style: is an individual's inherent cognitive tendency. Such tendencies would affect selection of problem-solving strategies (see Paper 1 [1]). For example, Woods et al. [47] identified five types of problem solver: *vagabond* (the person jumps from issue to issue without satisfactory resolution of any), *hamlet* (the person looks at each situation from multiple viewpoints and considers many possible explanations of observed findings), *garden path* (or fixation prone; the person persists on a certain issue or activity), *inspector plodder* (the person exhibits very thorough consideration of evidence and possible explanations via explicit chains of reasoning and then narrows in on possibilities), and *expert focuser* (the person is adept at seeing and focusing in on the critical data from the current context so that he/she is always working on the most relevant part of the situation).

Morale-Motivation-Attitude: is a combined indication of an individual's willingness and commitment to perform his/her job in a thoughtful and thorough manner. Morale and Motivation are the elements energizing, directing or channeling, and maintaining or sustaining an individual's behavior [50]. Attitude is a positive or negative state of mind or feeling towards the work, manifesting itself through such things as willingness to voluntarily help out a coworker and to take on other duties beyond regularly assigned ones. Other definitions of attitude cited in Brief [51] are "a psychological tendency that is expressed by evaluating a particular entity with some degree of favor or disfavor" [52] and "a state of a person that predisposes a favorable or unfavorable response to an object, person, or idea" [53].

Similar or related factors in other HRA methods and in literature related to Morale-Motivation-Attitude include "morale/motivation" [41], "motivation and attitudes" [5], "rewards, recognition, and benefits" [5], "monotonous, degrading, or meaningless work" [5], "personality and attitudes" [5], "attitudes based on influence of family and other outside persons or agencies" [5], "laziness" [35], "satisfaction with work performance quality" [17,18], "attention and motivation" [19], "incentive or reward systems" [10], "status relations and reward allocation" [40], "conflicts of motives about job performance" [5], "more exciting way of working" [35], "attitude to work" [17,18], "motivation" [12], "vocational interests, job satisfaction" [54], "personality traits" [10], and "low morale" [25].

3.2. Memorized information

Knowledge and Experience: Knowledge is the totality of an operator's fundamental and engineering understanding of the system design, purposes, elements, functions, and operations, in relation to the operator's responsibilities, position, and the specific activities or tasks being undertaken. Also new knowledge might be gained through practices. However, within the time window of interest (i.e., duration of an accident) such a learning effect is neglected. Experience is the accumulation of information and knowledge gained through direct or indirect interactions with the system. It includes ways of coping with situations, solving problems, and making decisions to which the operator has been exposed. Experience is gained in part by putting knowledge into practice. However, experience does not cover the self confidence accumulated through such practice.

In IDAC, Knowledge and Experience represent the operator's domain-specific knowledge which is stored in the operator's knowledge base. An operator's overall proficiency in handling unexpected situations is surrogated by the amount of information stored in the knowledge base.

Examples of similar or related concepts in other HRA methods and in literature include "long and short-term memory" [5], "knowledge of required performance standards" [5], "inadequate knowledge training" [12,55], "inadequate technical knowledge" [55], "inadequate knowledge of systems and plant operations" [55], "knowledge and skill" [19], "knowledge and experience sufficient to manage work tasks during shift" [17,18], "experience" [28], "inexperience" [25,35], "experience inside and outside a control room" [11], "previous experience with similar symptoms" [36], "training, expertise, experience, and competence" [17,18,28], "previous training/experience" [5], "errors of misinterpretation" [17,18], "position/ability" [16], "formal versus informal training" [13], "education" [11], "sufficient education to perform work safely in outage" [17,18], "insufficient training or experience" [36], "inadequate reasoning and problem-solving capability" [12], "training/education systems" [10], "presence of a training department" [13], "a mismatch of the world between an operator's model and the one imaged by the designers" [25], "a mismatch between the educational achievement level of an individual and requirements of the task" [25], and "a need for absolute judgment which are beyond the capabilities or experience of an operator" [25].

Skills: is the ability to understand a situation and perform needed actions without much cognitive effort. Insufficiency of skills can manifest itself in reduced work quality and time delay.

Cannon-Bowers and Salas [56] list four kinds of knowledge for a team to work properly: task-specific knowledge, task-related knowledge, teammates-related knowledge, and shared attitudes/beliefs. Task-specific knowledge allows crew to take actions in a coordinated manner and to have compatible expectations for performances. Task-related knowledge refers to common knowledge, such as the task performing process and the task importance. Teammate-related knowledge refers to the mutual understanding of each other's preferences, strengths, weaknesses, and behavioral tendencies. Shared attitudes/beliefs refers to compatible perception about goals, resources, challenges, etc. The first two types of knowledge are modeled by Knowledge and Experience, and Skills in IDAC. The third type of team-sharing knowledge is covered by PIF Awareness-of-Role/Responsibility. The last type of knowledge is represented by IDAC PIFs Morale-Motivation-Attitude and Work-Process-Design-Tasking-and-Directions in the Organizational Factors.

Examples of similar concepts in other HRA methods and in literature include "inadequate skill level" [12], "state of current practice or skill" [5], "inadequate skill training" [12], "training/education systems" [10], "training" [28], "presence of a training department" [13], "insufficient training or experience" [36], "knowledge and skill" [19], and "skills and competencies required to perform tasks" [13].

Memory of Recent Diagnoses, Actions, and Results: is the memory of event history including diagnoses, performed actions and their results, the states of ongoing tasks, and the planned tasks. A study [37] has shown that an airplane pilot's awareness of errors committed can affect his/her performance due to increased burden resulting from expecting additional tasks to fix the errors.

Memory of Incoming Information: is the set of system information, operators' communication, and other events during the course of an incident, registered in the operator's memory.

3.3. Physical PIFs

Fatigue: is the state of physical weariness that could affect the operator's performance such as causing for example more errors on skill-based actions, or delayed cognitive responses. Fatigue could also cause mental weariness, an effect covered by Alertness. Fatigue has been identified as an important PIF in the transportation industry [57–59].

Examples of similar concepts related or contributing to Fatigue in other HRA methods and in literature are: "fatigue" [5,12], "work hours and work breaks" [5], "fitness for duty" [19], "shift rotation and night work" [5], "disruption of circadian rhythm" [5], and "shift patterns" [13].

Physical Abilities: measures the ergonomic compatibility between an operator and the system. Examples are being too short to reach, too big to fit, too weak to lift, etc. Wickens et al. [60] identify six types of factors affecting performance: visibility, sensation, perception, cognition and communication, motor control, and muscular strength. Of these motor control and muscular strength are covered by Physical-Abilities. Inadequate physical ability refers to the situation where the operator's physical ability falls outside of the normal range anticipated in the Human–System Interface design.

3.4. External PIFs

3.4.1. Team-related factors

Team Cohesiveness: sometimes called "group morale" or "group emotion" is an indication of team integrity. Group solidarity, group harmony, and the manner in which team members get along with each other are all aspects of the integrative dimension. Mullen and Copper [61,62] distinguish three facets of cohesiveness: interpersonal attraction of team members, commitment to the team task, and group pride and team spirit.

Examples of similar concepts in other HRA methods and in literature include "cohesion" [62], "team spirit" [10], "group identifications" [5], "group cohesiveness" [40], "team support (cohesiveness)" [8], "mutual support" [62], "cooperation problem with planner" [17,18], "team interactions" [10], "cooperation and competition" [40], "team compatibility" [10], and "interpersonal attraction" [40].

Team Coordination: refers to the effectiveness of a team organized as a unit to perform a task both in time and space dimensions as well as in terms of division of responsibilities and command and control. It also refers to the degree of harmonization and synchronization of each individual operator's contribution to the team task [62]. In some studies this is referred to as "group norm":

- "an idea in the mind of the members of a group, an idea that can be put in the form of a statement specifying what the members or other people should do, ought to do, are expected to do, under the given circumstance" [63].
- "a shared expectation of an acceptable range of behavior in relation to some value" [64].
- "the shared group expectations that are standardized generalizations applied to classes of objects, having a moral or evaluative basis, and that prescribe a range of acceptable behavior or proscribe a range of unacceptable behavior, under given circumstances" [40].

Training the operating crew as a team is an important factor affecting the group norm. Examples of similar concepts in other HRA methods and in literature include "inter-group and intra-group coordination" [19], "coordination" [62], and "team work" [13].

3.4.1.1. Team communication availability and quality.

Communication Availability refers to the availability of the tools, means, and mechanisms for team members to exchange information. In particular when crew members are dispersed at different physical locations, task coordination usually relies heavily on the communication means. Communication allows crew members to have knowledge of a shared situation [65].

Communication Quality refers to the degree to which the information received by the receiver corresponds to the information transmitted by the sender. Malfunctioning communication equipment and signal disturbance are some of the causes of poor communication quality.

Examples of similar concepts in other HRA methods and in literature include "inadequate communication protocol & means" [36], "communication" [8,10,13,28,40,55,62], "communication training" [8], "oral instructions" [5], and "poor communication" [12].

Team Composition relates to the size and homogeneity/heterogeneity of crew that provides complementariness and redundancy of the required knowledge and skills to complete a task [10]. The team size usually is determined by the nature of the team mission. Too small a size creates excessive workload for team members. Too large a size not only wastes resources, but also could reduce performance. Task force in general includes executive, supervision, and backup. Homogeneity and heterogeneity ensure that a team has a sufficient repertoire and is capable of handling tasks properly.

Examples of similar concepts in other HRA methods and in literature include "manning parameters"[5], "crew team structure" [28], "appropriate number of staff to accomplish the work" [19], "team size/composition" [10,40], "team structure" [5], "potency/team self-efficacy" [10], "hiring and placement" [13], "personnel not available for help" [17,18], "inadequate supervision" [55], "supervision" [13,19], "balance of member contribution" [62], "group identifications" [5], "staffing" [66], and "sufficient staff" [13].

Leadership: Paglis and Green [67] define leadership as "the process of diagnosing where the work group is now and where it needs to be in the future, and formulating a strategy for getting there. Leadership also involves implementing change through developing a base of influence with followers, motivating them to commit to and to work hard in pursuit of change goals, and working with them to overcome obstacles to change." Based on this definition, leadership efficacy can be measured by whether the leader(s) can "set a direction for the workgroup, building relations with followers in order to gain their commitment to change goals, and working with them to overcome obstacles to change" [67].

Examples of similar factors or concepts in other HRA methods and in literature include "leadership" [10,13,40], "leadership and administration" [13], and "commander's confidence, rank, experience, reliability (of the leader), persuasion and ascendancy" [29].

3.4.2. Organizational factors

Work Process Design, Tasking, and Directions: refers to task planning (e.g., sequencing and coordination of tasks) and clarity of task assignment. It affects the resource accessibility and, possibly, causes task interference or conflict among the crew. For example, poor task scheduling could cause interferences between inter-dependent tasks performed by different work units (or operators).

Examples of similar concepts or factors in other HRA methods and in literature include "work design" [10], "insufficient information in operational order concerning the performance of tasks" [17,18], "task organization" [17,18], "bad planning of work permits" [17,18], "work permit was not handed in on time (and therefore delayed other activities)" [17,18], "task preparation" [16], "work package development, quality assurance, and use" [55], "boundary management (task selection)" [10], "task rule, planning, procedures" [8], "maintenance management" [13], "design of the sidings make the violation necessary" [35], "the purpose and object of the work permit was not specified" [68], "indistinct information concerning the prioritization of different work activities" [17,18], "confusing directives" [12], "command and control including resource allocation" [55], "erroneous instructions or directives" [12], "planning and scheduling of work activities" [19], "job planning" [13], and "no obvious way to keep track of progress during an activity" [25].

Human–System Interface: refers to designs and layout qualities of the control panel that consider both ergonomics and human information processing. It includes not only the quality of displays, labeling, and means of controls but also the quality of the software behind the scene controlling those displays. Poor Human–System-Interface quality could, for example, result in performing action on an undesired target (e.g., pushing the wrong button), delayed response (e.g., due to prolonged diagnosis resulting from too much non-situation related information displayed in the control panel).

Examples of similar factors and concepts in other HRA methods and in literature include "man-machine interface" [5,13,28], "design of Human–System Interfaces" [19], "instrument (e.g., alarm or annunciator for cues, or safety parameter display system)" [28], "information availability" [12], "arrangement of equipment" [16], "technical layout of the system" [16], "ineffective abnormal indications" [55], "inadequate engineering evaluation and review" [55], "perceptual requirements" [5], "control–display relationships" [5], "quality of information and interface" [17,18], "control and display location, identification and coding, and operation and response" [12], "availability of feedback information" [12], "display range, labeling, marking, accuracy, and reliability" [16], "perceptual discrimination failure [20], usability of control" [16], "a low signal-to-noise ratio" [25], and "control room information in annual outage" [68].

Safety and Quality Culture: is the result of organizational attitude and effort to maintain personnel safety and work quality at high priority even when it might impact productivity. Organizational culture is comprised of common values, attitudes, and beliefs of the individuals working within that organization [69]. The International Atomic Energy Agency (IAEA) defines safety culture for nuclear power operation as "assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance" and adds that "safety culture is attitudinal as well as structural, relates both to organizations and individuals…" [70,71].

Examples of similar concepts in other HRA methods and in literature include "an established safety culture" [19], "culture" [10], "safety policy" [13], "safety perception" [13], "safety climate" [72,73], "quality assurance" [16], "satisfaction with work performance quality" [17,18], "quick way of working" [35], "bad shift hand over" [17,18], "failure to respond to industry and internal notices" [55], "incompatibility between protection and production" [13], "management turns a blind eye" [35], "it's a macho way to work" [35], "inadequate post-maintenance testing" [55], "failure to follow industrial practices" [55], "failure to correct known deficiencies" [55], "rules of operation, managing, or decision-making" [10], "reporting of accident/incident" [13], "ambiguity in the required performance standard" [25], and "quality (equipment, function) control" [8].

Work Environment (Physical): refers to the physical characteristics of the work environment that might affect the operator's performance. For example, poor illumination and constant noise could reduce information perception. A narrow work space or walking path would increase the likelihood of an operator interposing unintended actions on the system. Work-Environment covers the design of the entire control room whereas Human-System-Interface focuses on the control panel design.

Examples of concepts in other HRA methods and in literature include "work place design" [13], "physical environment" [10], "appropriate control and environmental factors (e.g., noise, vibration, temperature etc.)" [19], "workplace layout" [8], "movement constriction" [5], "quality of the working environment" [5], "distractions (i.e., noise, glare, movement, flicker, color)" [5], "vibration" [5], "environmental stress (noise level, lighting levels, temperature, etc.)" [8,12], "I had to make many unnecessary moves when I worked locally" [17,18], "configuration management of work place" [55], and "control room architectural feature" [5].

3.4.2.1. Tool availability, adequacy and quality. *Tool Availability* refers to the accessibility of required tools especially those specifically designed tools for certain tasks.

Unavailability of tools could lead to suspension of the task or promote the use of inappropriate surrogate tools.

Tool Adequacy and Quality refers to the task-fitness, handiness, and readiness of the available tools. Some tasks require specially designed tools. General tools might be able to achieve the same goal; however, using general tools while specially designed tools are required is likely to jeopardize the task. Some tools require periodical calibration. Failure to do so would result in incorrect measurement. Tools in IDAC not only include hardware but also software. For example, in situations where system upgrades require software, the software package provided by the vendor is part of the tool package for the task. A defective software package or inappropriate software version delivered is likely to cause system failure.

Examples of similar concepts in other HRA methods and in literature include "availability/adequacy of special equipment/tools and supplies" [5], "appropriate/sufficient tools and equipment" [13,19], "arrangement of equipment" [16], "equivocation of equipment" [16], "equipment was not in the right place when I needed it" [17,18], "instrument inadequate" [36], "handling/usability of equipment" [16], and "personal protective equipment" [13].

3.4.2.2. Procedure availability, adequacy and quality.

Procedure Availability is the accessibility of the required procedures. Unavailability of the required procedures would force the task to change from rule-based (following written instruction) to knowledge-based or remaining as rule-based but by following memorized rules instead of written procedures. Knowledge-based tasks are more error-prone [74]. Thus, procedure unavailability when procedure is needed is likely to increase failure probability.

Procedure Adequacy and Quality refers to the completeness of content and ease of following procedures. Examples of poor procedures are those that are hard to understand, poorly formatted, too long to finish, not specific on the applicable conditions and restrictions, contain incorrect information, require mental calculations, and similar procedural titles which can not be easily distinguished from another immediately.

Examples of similar concepts in other HRA methods and in literature include "procedures quality" [13], "operating procedures" [5,17,18], "rule impossible to work to" [35], "many extra documents in addition to orders and instructions" [17,18], "many extra instructions" [17,18], "context of emergency operating procedure" [28], "incomplete or inconsistent instructions" [12], "inadequate procedures and procedures development" [55], "complete, technically accurate and usable procedures" [19], "procedural requirements (standards, rules, and administrative controls)" [10,13], "rule is outdated" [35], "erroneous instructions or directives" [12], "clarity, precision, design, content, completeness, and presence of procedures" [16], "accurate and complete reference documentation" [19], "emergency resources and procedures" [13], and "meaningfulness of procedure" [41].

3.4.3. Environmental factors

Environmental Factors are the gradual or rapid environmental changes affecting human performance. For example, in some NPP control rooms, there is a large number of alarms color coded to indicate their importance. The state of an alarm could be steady light-on, steady light-off, or blinking. Accompanying the alarm activation is the annunciator warning sound. The visual and audio effects of such surrounding changes could affect the operator's performance [38]. Examples of severe environmental changes are uninhabitable control room (e.g., caused by fire) and blocked physical access.

Examples of similar factors in other HRA methods, event reports, and in literature include "temperature extremes" [5], "radiation" [5], "atmospheric insufficiency" [5], "G-force extremes" [5], "environment" [75], "spatial disorientation" [76], and security denial of access.

3.4.4. Conditioning events

Conditioning-Events is the pre-existing problems that reveal themselves under certain conditions and opportunities. Conditioning-Events could confuse the assessment of system state due to conflicts between the observed plant symptoms and the expected symptoms (generated by the operator's mental model). Such confusions would require more cognitive effort on the part of operator to integrate information to make a diagnosis [77]. For example, the mode confusion caused by inconsistent synchronization between cockpit pilots and the automated cockpit system is believed to be the dominant cause of some aviation incidents [78]. The cause is that the system is designed to provide required functional outputs automatically and as such typically less attention is paid to software transparency for the pilot, and pilot's comprehension of the behavior of the control system.

Examples of similar concepts in other HRA methods and in literature related to or causing Conditioning-Events include "external event" [16], "latent error" [13], "poor, ambiguous or ill-matched system feedback" [25], "maintenance" [8], "technology-centered automation" [79], and "inadequate maintenance and maintenance practice" [55].

4. Overview of PIFs dependencies

This section and Section 5 explore the interdependencies between IDAC PIFs and the methods for assessing their states. An influence diagram is used to represent a set of causal relations and interdependencies among the PIFs. This influence diagram is supplemented by a set of mathematical relations for a more explicit set of relationships, which often take the form of an expression of tendency and/or stochastic relations rather than deterministic links. The assumed forms of these relations have inputs from available empirical and theoretical models, event analysis, simulator exercises, as well as the opinions of other researchers and practitioners found in literature.

4.1. PIF group interdependencies

IDAC is developed for implementation in a computer simulation environment [80–82] in which all activities (including the responses of operators and system) only could take place in finite discrete time steps. The time difference between two consecutive time steps is a constant Δt. IDAC models one-way bottom-up influences among Mental State PIFs based on the theory of stream of feelings [15]. The high-level Mental State PIFs (e.g., Bias), such as the A1 shown in Fig. 4, affecting the PIFs at lower levels (e.g., Perception and Appraisal PIFs), such as the C1 or C2 shown in Fig. 4, takes place between the consecutive time steps. Such influences can be explained as follows. Mental State at a time t affects the operator's response (such as an action changing the system state) that in turn affects the content of information from the system in the next time step (at $t+\Delta t$). As a result, Mental State at time "$t+\Delta t$" will be affected. In other words, Mental State at time t could affect Mental State at time $t+\Delta t$, and so on. Such chronological influences could be seen as downward arrows of the effects of high-level PIFs on low-level PIFs shown in Fig. 4. This approach to "feedback" i.e., having one-way influences (i.e., bottom-up influences) within the same time step and the influences in the opposite direction between two time steps is not only the most realistic model of how such influences work, but it also greatly reduces the problem complexity for implementing IDAC in computer simulation.

PIF group-to-group interdependencies are represented by a hierarchical structure as shown in Fig. 5 and explained in Table 1. In Table 1, the cells with an 'X' mark indicate PIF influences within a time step (i.e., the bottom-up influences). For example, the PIFs of "Emotional Arousal" category could affect the PIFs of "Cognitive Modes and Tendencies" at the same time step. The cells with number codes indicate influences between two consecutive time steps (i.e., the top-to-bottom influences). For example, "Cognitive Modes and Tendencies" at time t would affect the operator's information perception behavior, in turn affecting the "Memorized Information" at time "$t+\Delta t$". The X-marked influences are discussed in detail in Section 5. The influences in the numbered cells are either treated within the dynamic framework (discussed in [1,2,4]), or not modeled.

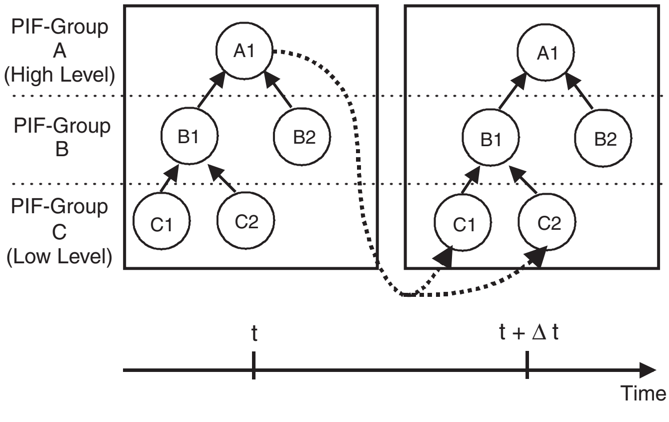

Fig. 4. A conceptual representation of modeling feedback among performance influencing factors.

The influences shown in Table 1 are better explained in a bottom-up order. Incoming Information is perceived that changes Memorized-Information and consequently changes the Perception-and-Appraisal. The impact of the Environmental-Factors and Conditioning-Events are first felt by the operator through the Incoming Information (number (8) in Table 1). This in turn could affect Memorized Information. The Team-Related Factors and Organizational Factors have three kinds of influences. First, they affect the operator's perception of work resources when the need arises. For example, Procedure-Availability (an Organizational Factor) and Communication-Availability (a Team-Related Factor) would affect the operator's behavior when such means and resources are needed. Second, they affect an operator's Mental State prior to the event (number (6) in Table 1). For example, organizational policy and Team-Cohesiveness could affect Morale-Motivation-Attitude (a Intrinsic-Characteristics PIF). Inappropriate work shift schedule would cause fatigue (one of the Physical Factors). Training could affect the operator's Knowledge, Experience, and Skills. Third, they affect the incoming information (number (7) in Table 1). For example, Human–System-Interface and Communication-Availability-and-Quality of the Organizational Factors would affect information accessibility.

Memorized-Information would directly affect Perception-and-Appraisal of Mental State. Physical-Factors (e.g., fatigue) and the Intrinsic-Characteristics would affect an operator's internal responses to the external stimuli. Intrinsic Characteristics reflect individual differences. Two operators receiving the same training could develop different levels of knowledge and skills (number (4) in Table 1). Some individual differences currently are not modeled, for example, learning and memorizing capabilities. Personal efforts causing changes in organization and team (number (5) in Table 1) are not in the current IDAC modeling scope.

Mental State has significant influence on the activities in the next time step. For example, being stressful and being biased, could affect the operator's information perception and comprehension (number (1) in Table 1). Mental State motivates action to change the system state and in turn would affect the incoming information (number (2) in Table 1). Some psychological feelings could affect the physical state (e.g., being stressful affects fatigue); see number (3) in Table 1.

Fig. 5 is an expanded version of Fig. 1 with all PIFs explicitly listed. In this figure the lines of influence within the same time step (i.e., 'X' makes in Table 1) are shown for all PIF groups.

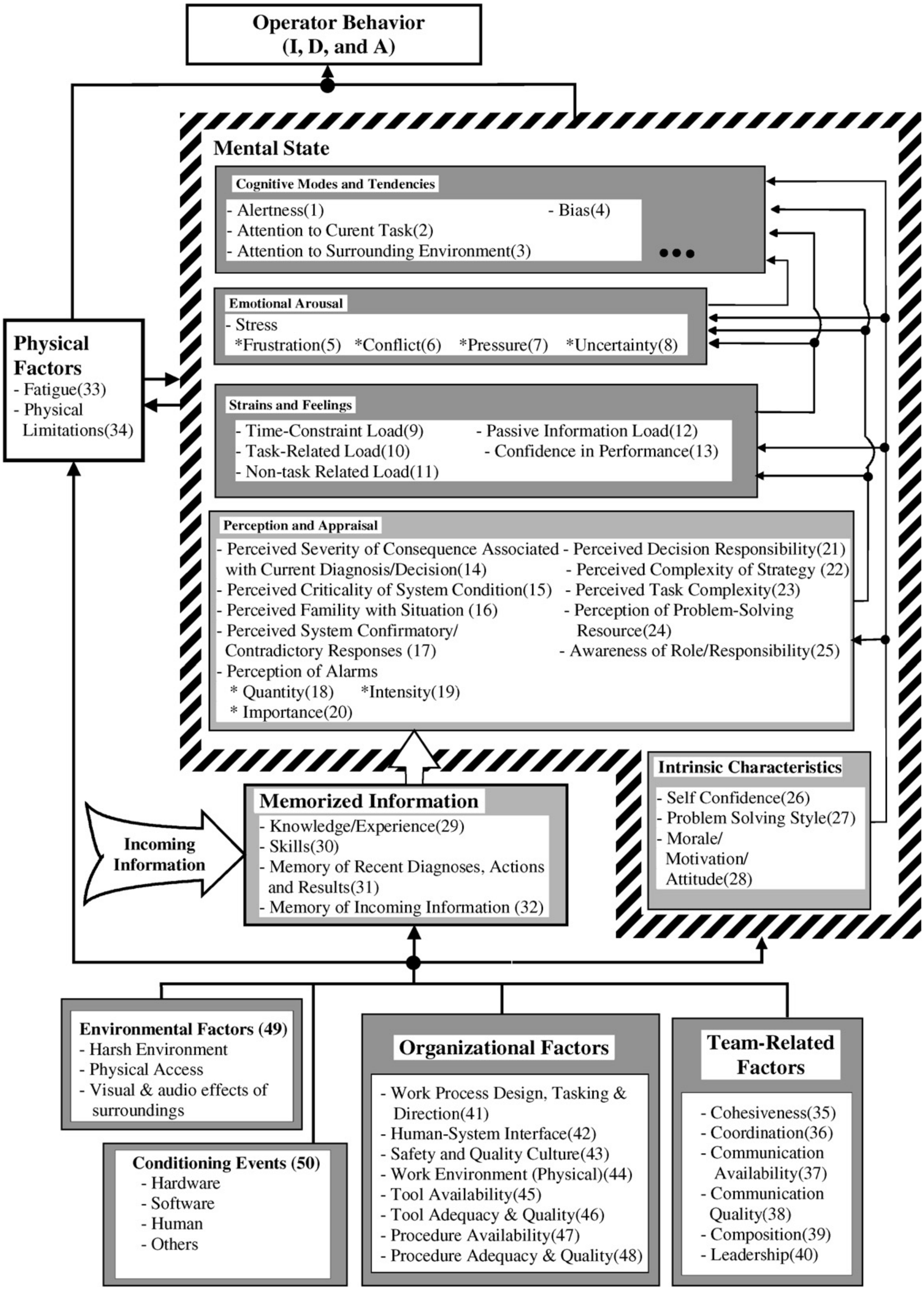

Fig. 5. The hierarchical structure and influence paths of the IDAC performance influencing factors.

4.2. Influence of dynamics

As stated earlier, Mental State affects the operator's behavior. In IDAC the operator's response is further divided into three phases: information perception and pre-processing (**I**), diagnosis and decision-making (**D**), and action execution (**A**) (see Paper [1] for summary and Paper 3 [4] for details). As discussed in Paper 1 [1], an operator's problem-solving process in the course of an event is a repeat process of I-D-A cycle. The I-D-A activities are

Table 1
The high-level dependencies of the performance influencing factors

Dependent PIF group		Mental state					Physical factors	Memorized information	External factors				Incoming information
Independent PIF group		Cognitive modes and tendencies	Emotional arousal	Strains and feelings	Perception and appraisal	Intrinsic characteristics			Team-related factors	Organizational factors	Environmental factors	Conditioning events	
Mental state	Cognitive modes and tendencies		—	—	—	—	—	(1)[a]	—	—	—	—	(2)a
	Emotional arousal	X		—	—	—	(3)[a]	(1)[a]	—	—	—	—	(2)*
	Strains and feelings	X	X		—	—	(3)[a]	—	—	—	—	—	(2)[a]
	Perception and appraisal	X	X	X		—	—	—	—	—	—	—	(2)[a]
	Intrinsic characteristics	X	X	X	X		—	(4)[a]	(5)[a]	(5)[a]	—	—	—
Physical factors		X	X	X	X	—		—	—	—	—	—	—
Memorized information		—	—	—	X	—	—		—	—	—	—	—
External performance influencing factors	Team-related factors	X	X	X	X	(6)	(6)	(6)		—	—	—	(7)[a]
	Organizational factors	X	X	X	X	(6)	(6)	(6)	—		—	—	(7)[a]
	Environmental factors	—	—	—	—	—	—	—	—	—		—	(8)[a]
	Conditioning events	—	—	—	—	—	—	—	—	—	—		(8)*
Incoming information		—	—	—	—	—	—	X	—	—	—	—	

(X) Factor in the row (left hand side) affects factor in the column (upper side).
(1) The high-level Mental State (e.g., bias and stress) could affect information perception and comprehension.
(2) Actions due to the Mental State PIFs could change the system state, and consequently change the incoming information.
(3) The operator's emotional state could affect his/her physical state.
(4) Example: Some people have better memory recall and storage capacity than others.
(5) Personal efforts cause changes in the organization and team.
(6) Only the ultimate downstream effects and not the paths of influence are modeled in the current version of IDAC. A more comprehensive list of organizational factors and team-related factors can include elements that would affect Intrinsic Characteristics PIFs.
(7) Continuous influence on the availability and quality of the incoming information.
(8) The impact on operator Mental State is through the incoming information, reflecting the state of the system.
[a] Top-down influences taking place at the next time step.

shown at the block on the top in Figs. 1 and 5. Whenever activities take place in the I, D, or A block, Mental State is updated to reflect those activities. On the other hand, Mental State would affect the activities inside the I, D, and A blocks.

5. Assessing the states of PIFs

This section provides guidelines for assessing the states of IDAC PIFs. The quantitative state assessment and representation of these PFIs are an ongoing project.

The state of a PIF can be either directly determined or calculated as a function of the states of other PIFs. Methods for assessing the PIFs which can be directly determined include expert judgment, field experience and experiment, and auditing systems (e.g., use of questionnaires, plant visits, procedures walkthrough, and interviewing operators.) These PIFs normally appear on the edges (input nodes) of the PIF influence diagram as shown in Fig. 5. Assessing the PIFs whose states are dependent on other PIFs' states (inner nodes of the PIF influence diagram of Fig. 5) can take many forms.

We have found the notion of "demand and resource" to be very useful as the basis for structuring such functions and in determining the dependent PIFs effects on demand or resource. Mental load theories and stress theories use three factors to indicate a person's mental load or stress: demand, resource, and attitude [26]. Demand refers to the operator's perception of the system needs such as the perception of the number of tasks to be performed in a given period of time. Resource refers to the operator's perception of the ability to meet the demand including the perception of help that the operator might have.

All the methods mentioned earlier for assessing directly determined PIFs plus the evidence from literature can be used to identify the PIFs contributing to demand or resource for a given dependent PIF. In some situations, the meaning of a PIF is too abstract to specify appropriate practical measures. This requires extending and extrapolating the meaning of the PIF so that it can be represented by other PIFs with more concrete meanings. This process could continue until the meanings of the surrogate PIFs are concrete enough for assessment and measurement. An example of surrogate measures can be found in assessing "time demand". "Time demand" could be surrogated by the perceived level of situation emergency. The more urgent the situation, the greater is the time demand. Greater time demand results in requiring shorter available time for response. The emergency situation can be further surrogated as the number, intensity, and importance of alarms activated. The alarms' states, which are among the dynamic PIFs, can be determined directly.

In the following, the above techniques are applied to explain how various IDAC PIFs might be assessed. The discussion is organized based on the influence diagram of Fig. 5. The detailed PIF-to-PIF interdependencies identified through the above process are summarized in Section 6.

5.1. Mental state

Most of Mental State PIFs can be assessed by the causal decomposition method except for the PIFs within Intrinsic Characteristics which are determined directly.

5.1.1. Cognitive modes and tendencies

Alertness: Fatigue [57,58] would result in low alertness level, as does low Morale-Motivation-Attitude. Studies, for example [65], also show that team members use communication to keep mutual situational awareness; thus availability and quality of communication means (i.e., Communication of Team-Related Factors) and high team cohesiveness (i.e., Team Cohesiveness of Team-Related Factors) have a positive influence on alertness.

Attention to Current Task: Memory-of-Recent-Diagnoses-Actions-and-Results is one of the influencing factors since Attention-to-Current-Task is related to a specific task and thus memory and information on the task is naturally an essential component affecting the degree of attention and awareness on the task. High stress, poor quality of Human–System-Interface, and environmental conditions could cause attention failure (i.e., missing key information due to altered attention) [24]. Stress is a driving force that motivates an individual to pay attention to events and activities.

Demand-and-resource model can be used to assess the Human–System-Interface effect on Attention-to-Current-Task. Human–System-Interface design could affect attention in at least three ways, all through its effect on information perception: (1) demand has been blocked. Poor Human–System-Interface could limit the availability of information, denying needed cues to the operator, and thus (2) requiring additional effort to apply the resource. Poor Human–System-Interface could impose an additional burden or barrier to getting information, a kind of "out of sight, out of mind" situation where getting information requires additional effort and workload. For example, if some indicators are located at the rear side of the control panel, paying attention to such indicators requires extra physical effort for operators in the front side. It consequently reduces the operator's attention to such indicators, and results in (3) excessive demand for applying resource. For example, poor Human–System-Interface could provide too much information to the operator distracting him from paying adequate attention to the task.

Attention to Surrounding Environment is affected by the operator's stress level, Work-Environment (e.g., illumination and work place design), and Safety-and-Quality-Culture.

Bias: Biases are likely to arise from heuristics [22]. Heuristics are activated due to symptom matches between operator memorized information and perceived information.

Three types of heuristics and their influencing factors are discussed here:

- Representativeness heuristic: Using similarity and connotative distance to compare essential features (or key properties) between the compared instances [83] or similarity-matching [84]. Similarities between Memory-of-Recent-Diagnoses-Actions-and-Results and Knowledge/Experience (in Memorized Information) could trigger representativeness heuristics.
- Availability heuristic: instances of large classes are recalled better and faster than instances of less frequent classes [83]. Knowledge/Experience and Memory-of-Recent-Diagnoses-Actions-and-Results are the related factors.
- Adjustment and anchoring heuristic: Inappropriate selection of the start value combines with insufficient adjustment to cause final estimation error. Knowledge/Experience (causing incorrect first estimation) combined with (low) Self-Confidence (causing insufficient adjustment) is one of the likely causes.

Stress also could affect Bias. For example, an individual under stress tends to persevere longer with an inappropriate or rigid solution [37,85].

The above discussions focus on the internally caused biases which are the preference or inclination in judgment due to a pre-existing strong belief based on the operator's experience and knowledge. There are also externally caused biases resulting from Organizational Factors and Team-Related Factors (e.g., an organization culture, management, or team leader's tendency to weigh production higher than safety).

5.1.2. *Emotional arousal*

Frustration Stress results from the feeling that a goal is not being achieved, despite the effort. Any persistent obstacle in reaching a goal could result in frustration. For this reason Physical-Abilities, Communication-Availability, Tool-Availability, Procedure-Availability, and Work-Process-Design-Tasking-and-Directions are factors affecting Frustration Stress.

Pressure Stress results from perception of imbalance between demand and resource in steering an undesirable situation back to a desired state. Thus, Pressure Stress is dependent on Time-Constraint-Load, Task-Related-Load, and Passive-Information-Load.

Conflict Stress results from inappropriate resource distribution. Thus, Non-Task-Related-Load is an influencing factor since it depredates resources from steering the system to the desired state.

Uncertainty Stress results from not understanding the situation, thus Perceived-Familiarity-with-Situation, Perceived-System-Confirmatory/Contradictory-Responses, and Confidence-in-Performance are the main influencing factors.

5.1.3. *Strains and feelings*

Since the PIFs within this category relate to an individual's feelings, Self-Confidence (an indicator of an individual's intrinsic adaptability to the demand of the external world) is a common factor affecting all PIFs within "Strain and Feeling" category.

Time Constraint Load: Since Time-Constraint-Load is related to the rate at which the situation moves towards the moment at which negative consequences materialize [32], it depends in part on the operator's perception of the various dynamic parameters of the system. The effect of such parameters is reflected in Perceived-Criticality-of-System-Condition, Perception-of-Alarms-Quantity, and Perception-of-Alarms-Intensity, which in turn are factors influencing Time-Constraint-Load. Different people have different levels of adaptability to time pressure [31,48]; experienced operators are more confident than inexperienced operators in facing the same scenarios [49], and a novice will be more affected by time pressure than a skilled person [86]. Such an effect represents self confidence accumulated through operation and is covered by PIF Self-Confidence. Studies also suggest that uncertainty [31] (covered by Perceived-Familiarity-with-Situation) and potential loss and unpredictable consequences [87] (covered by Perceived-Severity-of-Consequences-Associated-with-Current-Diagnosis and Perception-of-Alarms-Importance) could contribute to Time-Constraint-Load. It is also expected that Perception-of-Problem-Solving-Resources, which indicates the additional help that the operator might have, would affect Time-Constraint-Load.

Task-Related Load: represents the operator's perception of cognitive and physical efforts required to meet the demands resulting from the quantity, intensity, complexity, and "fault tolerance" of tasks needed to be performed simultaneously.

From the demand perspective, if the difficulty, number, rate, complexity, or accuracy of the demands imposed on an operator is increased, workload is assumed to be increased [37]. The demands can be surrogated by Perceived-Criticality-of-System-Condition, Perceived-Task-Complexity, Perception-of-Alarms-Quantity, Perception-of-Alarms-Intensity, and Perception-of-Alarms-Importance.

The perception that additional tasks might be required following an error could also increase Task-Related-Load. For example according to [37], pilots sometimes anticipate that additional errors could follow those already committed, requiring additional tasks to recover, which translates into perception of workload increase. Hart and Bortolussi [88] found that, on average, the pilot's workload increased 6, 30, and 16 percent when adding routine task, encountering system failure, and committing an error, respectively. In IDAC Memory-of-Recent-Diagnoses-Actions-and-Results stores such error/recovery sequences, and is therefore an influencing factor to Task-Related-Load. Morale-Motivation-Attitude determines the individual's self-requirements on the quality of task completion and as such it could affect the Task-Related-Load.

From a resource perspective, individual differences (i.e., Intrinsic Characteristics) could affect the Task-Related-Load. Work-Process-Design-Tasking-and-Directions, Team Coordination, Tools Adequacy and Quality, Procedures Adequacy and Quality, and Perception-of-Problem-Solving-Resources could also affect Task-Related-Load.

Non-Task-Related Load: Additional personnel present in the control room or placing calls to management to report the current situation could induce Non-Task-Related-Load. Work-Process-Design-Tasking-and-Directions is the dominant demand source in Non-Task-Related-Load.

Passive Information Load: Passive-Information-Load depends on the quantity and rate of the information perceived, therefore Perception-of-Alarms-Quantity and Perception-of-Alarms-Intensity are the influencing factors. An overwhelming level of Passive-Information-Load could jam the operator information perception and processing as witnessed during the first few minutes of the Three Mile Island accident [38]. Self-Confidence is an influencing factor of Passive-Information-Load as it represents among other things the accumulated level experience as an operator.

Confidence in Performance: "With additional but redundant information, people become more confident in their decision" [32], implying that Perceived-System-Confirmatory/Contradictory-Responses and Perceived-Familiarity-with-Situation could affect Confidence-in-Performance. Self confident operators tend to overestimate the control capabilities in risky situations [32,89] and the probability of a favorable outcome [90]. It implies that Self-Confidence is an influencing factor of Confidence-in-Performance.

5.1.4. Perception and appraisal

Perceived Severity of Consequences Associated with Current Diagnosis/Decision could be assessed by the operator's instinctive appraisal on the severity level of a diagnosis; thus, Perceived-Severity-of-Consequences-Associated-with-Current-Diagnosis depends on the current diagnosis or decision that the operator has in mind. For example, a NPP operator would have different scores of Perceived-Severity-of-Consequences-Associated-with-Current-Diagnosis for diagnoses "loss of coolant accident" and "steam generator tube rupture". Memory-of-Recent-Diagnoses-Actions-and-Results (representing recent diagnosis, decisions, and actions) and Knowledge and Experience (representing the operator's engineering knowledge) are also among the influencing factors.

Perceived Criticality of System Condition is represented by the distance, moving rate, and direction (moving close to or away from the nominal value) of the key parameters with respect to their safe boundaries. Memory-of-Incoming-Information (representing the perceived system related information) and Knowledge/Experience are the contributing factors.

Perceived Familiarity with Situation: "When an event unfolds as planned and the well-rehearsed sequence of actions can be relied on, the individual has lower cognitive demands and better performance" [37]. This indicates that Memory-of-Incoming-Information (representing perceived system information) and Knowledge/Experience (representing the memorized simulator exercises similar to the current situation) are the contributing factors.

Perceived System Confirmatory/Contradictory Responses depends on the results of diagnoses and the perceived system response that confirms or contradicts the operator's expectations. As a result, Memory-of-Recent-Diagnoses-Actions-and-Results, Memory-of-Incoming-Information, and Knowledge/Experience are the influencing factors.

Perception of Alarms Quantity, Intensity, and Importance: A benefit of the simulation-type approach to operator response modeling is that the properties of each piece of information generated by the external world can be precisely captured. This applies to putting real operators in simulator exercises or performing computer simulations as Accident Dynamic Simulators (ADS [82,91,92]). For example, the time of the incoming information generated and the priorities of activated alarms can be precisely identified. Alarm quantity is the total number of alarms being perceived. Alarm intensity is the highest number of alarms perceived in a fixed time lapse. Alarm importance is the sum of the importance of each perceived alarm. Clearly the states of these factors can change in the course of an event. In simulation implementation of IDAC and in certain other applications of the model (e.g., data taxonomy and event analysis), the values of these parameters are captured (or recorded) and then used in the model to assess impact. Therefore, these values are external input to the rest of the IDAC PIFs and model elements.

Perceived Decision Responsibility: The greater the role an operator plays in making a decision, the higher the level of responsibility and accountability felt by that operator with respect to the consequences of the decision. In the IDAC model, such responsibility is linked to the problem-solving strategy implemented by the operator. IDAC identifies nine types of problem-solving strategies that covers a wide spectrum from simple direct association of the problem to a ready made solution or action, from "*Direct-Matching*" and "*Instinctive-Response*", to more complex systematic search/selection of a solution among possible candidates, "*Inductive-and-Deductive Reasoning*". The list of strategies of course includes the favored strategy of "*Follow- Written-Procedure*" and "*Follow-Oral-Instruction*", but also "*Wait-and-Monitor*", "*Ask-for-Advice*" and "*Trial-and-Error*", as well as hybrid strategies mixing, for example, Inductive-and-Deductive-Reasoning and Follow-Written-Procedure to form a more human-like problem solving strategy of "*limited reasoning*".

The ranked order of Perceived-Decision-Responsibility for various strategies, in the context of NPP accident conditions, is as follows:

1. *Follow oral instruction*. In this strategy, the operator interacts with the system by following another operator's

instruction (e.g., the supervisor). The decision maker is the supervisor rather than the operator who follows instructions. The operator has little responsibility as long as the supervisor's instructions are strictly followed. As a result, the Follow-Oral-Instruction strategy has the lowest Perceived-Decision-Responsibility.

2. *Following written procedure* is executing procedural instructions step by step. The operator's responsibility is to correctly choose and execute the procedure. Other than that, the responsibility lies on the procedure writers rather than the operator.
3. *Instinctive response* is selected when the situation compels the operator to feel that an immediate action is required in order to save an endangered system or component. The required response in such situations is usually stated in the "immediate response procedure", or learned from training and work experience. There is usually a good reason for the decision, thus the Perceived-Decision-Responsibility of the Instinctive-Response is low, but higher than Follow-Written-Procedure.
4. *Ask-for-advice* is to obtain consensus on a decision to be taken. As a result, it represents a shared responsibility among the operating crew. However, the decision maker still has to take most of responsibility for the outcome. As a result, the operator carries a more significant amount of responsibility for his/her decision, compared to for example Follow-Oral-Instruction.
5. *Limited-reasoning* is a hybrid strategy with the decision resting on Follow-Written-Procedure and Inductive-and-Deductive-Reasoning strategies. Inductive-and-Deductive-Reasoning is a knowledge-based problem solving strategy, thus the operator is more fully responsible for the decision resulting from the strategy. The Perceived-Decision-Responsibility of Limited-Reasoning is therefore between Follow-Written-Procedure and Inductive-and-Deductive-Reasoning.
6. *Wait-and-monitor* is used when the system information does not provide clues for diagnosis and the operator continues to monitor the system until more information becomes available to help in diagnosis. Wait-and-Monitor could result in reducing the response time margin and as such the decision to follow such strategy in general carries a burden. However, NPPs are designed with multiple layers of safety to prevent a situation from evolving into an undesired consequence. Some plants even suggest that operators keep their hands off during the first 30 minutes into an event to let the safety systems control the situation automatically in the situations in which the operators do not have a clear picture of the event [93]. In short the burden of this strategy is the result of a balance between premature decision and lost opportunity for action, with the added uncertainty that the needed clues may or may not become available. For these reasons we have ranked the Perceived-Decision-Responsibility of Wait-and-Monitor higher than Limited-Reasoning.
7. *Inductive-and-deductive-reasoning* represents a thorough knowledge-based reasoning process in situations in which no procedure is applicable. Thus the operator is fully responsible for any consequences resulting from the decision. However, since a thorough reasoning has been performed, the operator would usually have good justification and explanation for the decision. Thus Perceived-Decision-Responsibility of Inductive-and-Deductive-Reasoning is relatively high, but not the highest.
8. *Direct-matching* jumps to a conclusion (i.e., a situation diagnosis) before going through a procedure-based or knowledge-based investigation process. Such heuristics could result in wrong diagnosis and reduce the available time for action. The operator has to take full responsibility for the decision. Since the cognitive process of Direct-Matching is very limited, the operator's responsibility for the decision is higher than that of the Inductive-and-Deductive-Reasoning.
9. *Trial-and-error* takes actions with little knowledge of the current plant state and under a great deal of uncertainty. The hope is that through interaction with the system some clues could be found for assessing the plant states. The actions could result in the commission of errors that worsen the situation. The operator would be fully responsible for the consequences. As a result, Trial-and-Error has the highest Perceived-Decision-Responsibility among the strategies.

The second column of Table 2 shows the sample scores of Perceived-Decision-Responsibility of different strategies. The rules for determining how a strategy is selected are discussed in Paper 3 of this series [4].

Perceived Complexity of (Problem Solving) Strategy: Different strategies demand different levels of mental effort. Strategy complexity can be assessed by the types of cognition required by the strategy. Three types of cognitive activity identified with cognitive complexity, from

Table 2
Example values of the Perceived decision responsibility and perceived complexity of strategy

Problem-solving strategy	Perceived complexity of Strategy	Perceived decision responsibility
Instinctive response	1	2
Direct matching	1	8
Follow oral instruction	2	1
Follow written procedure	3	1
Limited reasoning	5	5
Ask for advice	6	4
Wait and monitor	6	5
Inductive and deductive reasoning	8	6
Trial and error	9	9

The scores range from 0 to 10. The larger values indicate greater responsibility or greater task complexity.

simple to complex, are skill-based, rule-based, and knowledge-based. Instinctive-Response and Direct-Matching are highly skill-based. Therefore, they have the least strategy complexity. Follow-Oral-Instruction and Ask-for-Advice have different degrees of skill-based and rule-based cognitions. Follow-Written-Procedure is rule-based. Wait-and-Monitor and Limited-Reasoning have different degrees of rule-based and knowledge-base cognitions. Inductive-and-Deductive-Reasoning and Trial-and-Error are fully knowledge-based cognitions. Trial-and-Error is a knowledge-based strategy used in a highly confusing situation, thus it has the highest strategy complexity. The third column in Table 2 shows an example of the relative scores of complexity (on 0–10 scale) for different strategies.

Perceived Task Complexity: The demand aspect of the Perceived-Task-Complexity can be measured by conventional methods. For example, the "step complexity measure" [39] evaluates task complexity with three indicators: information complexity, logic complexity, and size complexity. The resource aspect of Perceived-Task-Complexity is measured in terms of the operator's Knowledge/Experience level since more knowledgeable and more experienced operators have a higher tolerance to task complexity as observed in [94] "experience reduces the difficulty with which a task may be resolved".

Perception of Problem-Solving Resources is a combined indication of the operator's perception of the internal and external resources that the operator might have for solving a problem. The operator's knowledge and memorized event history (represented by Memory-of-Recent-Diagnoses-Actions-and-Results) could affect the operator's perception of internal resources. The perception of the resources to which the operator can count on (e.g., remote technical support center and teammates) to help solve the problem, if necessary, is the perception of external resources. Team coordination and task planning (i.e., Work-Process-Design-Tasking-and-Directions) relate to the external resources. Communication-Availability-and-Quality is also an influencing factor since it affects teamwork.

Awareness of Role/Responsibility: An operator's awareness of his/her responsibilities is influenced by the primary (formally assigned) and subsidiary (informal mutual assistances between crews) responsibilities. Formal assignment of responsibility is represented by Work-Process-Design-Tasking-and-Directions. The informally assigned responsibilities are represented by the operator's knowledge and Safety-and-Quality-Culture. The Good Samaritan behavior or being a good organizational citizen [51] results from awareness of the subsidiary responsibilities.

5.1.5. Intrinsic characteristics

Self Confidence: could be determined by the number of years of operation experience of the operator. For example, the observation "experienced operators have a greater repertoire of strategies available to perform a given task and greater familiarity with the stressors to cope with the stress effect than inexperienced (operator)" [95] indicates that the differences between senior and junior operators are not only in system-related knowledge but also in psychological dimensions e.g., self confidence, accumulated through their exposure and appertaining experience.

Problem Solving Style: could be determined by an assessment questionnaire, such as the personality traits survey. Problem-Solving-Style would assess the degree to which a person's problem- solving style matches for instance *Hamlet* type (see discussion in Section 3.1.5).

Morale-Motivation-Attitude can be measured by the degree of satisfaction and commitment of an individual to his/her job. Herzberg et al. [96,97] identify 16 of the most common factors affecting job satisfaction in order of importance: (perception of) job security, personal interest in the job, (perception of) opportunity for advancement, appreciation (from the supervisor), company and management, intrinsic aspects of the job (excluding ease), wages, intrinsic aspects of the job, supervision, social aspect of the job, working conditions (excluding houses), communication, working conditions, ease (from intrinsic aspects of the job), and benefit. Fink [98] indicates that job commitment can be measured by three indicators of an individual: identification with work, identification with co-workers, and identification with the organization. Seaburg et al. [99,100] indicate that an individual's ability to perform a job must be accompanied by a willingness or motivation to do the job. Such willingness is affected by work values that consist of the following attributes: "achievement (environments that encourage accomplishment), comfort (environments that are comfortable and not stressful), status (environments that provide recognition and prestige), altruism (environments that encourage harmony and service to others), safety (environments that are predictable and stable), and autonomy (environments that stimulate initiative)."

5.2. Memorized information

Knowledge, Experience, and Skills: The PIFs have two facets that require somewhat different assessments. The first facet is the operator's *general* knowledge, experience, and skills which are generally applicable for various situations. The second facet is the *specific* knowledge and skill to solve a particular problem. Depending on the level and requirements of the implementation of IDAC modeling for HRA use, Knowledge, Experience, and Skills could be anywhere from simply an aggregate assessment of training and experience level, to a full fledged knowledge base to support computer simulation of operator response.

Memory of Recent Diagnoses, Actions and Results: Refers to the set of information stored in short-term memory (i.e., Working Memory and Intermediate Memory, see discussion in Paper 1[1]) during the course of an event, and as such it is highly dynamic and strongly context-dependent. Depending on the level and requirements of the implementation of IDAC model for HRA use, the content of Memory-of-Recent-Diagnoses-Actions-and-Results could be a simple indicator (e.g., success or failure of previous actions), or a detailed memory of scenario history to support computer simulation of operator response.

5.3. Physical factors

Fatigue: can be assessed at two levels: fatigue prior to the event and fatigue accumulated during the event. The initial fatigue level can be determined through an assessment of an operator's initial physical condition. Some useful auditing points include:

- Work shift and schedule (causing sleep loss and circadian disruption), work load and time on task, and degree of automation. These have been mentioned as the three main influencing factors of concern in the aviation industry, but certainly are applicable to the nuclear power industry
- Lifestyle and individual differences in physical strength [43,57,101].
- Human Factors characteristics of the work place and operating environment (e.g., room temperatures and noise) [43,101]. Factors related to the operating environment are covered by Work-Environment, thus initial fatigue is influenced by Work-Environment.
- The operator's level of motivation [58]

Fatigue accumulated during the event can be assessed dynamically through:

- Amount of stimulations coming from the environment [58]
- Work load and time on task, and degree of automation
- Individual differences in physical strength
- Human Factors characteristics of the work place and operating environment (e.g., room temperatures and noise)
- The operator's level of motivation

Physical Abilities: can be assessed by the degree to which the operator's physical characteristics (e.g., height, weight) are relevant to performing his tasks for a given "nominal" work place setup. Human–System-Interface design guidelines (e.g., [60,102]) can be used as a reference to assess Physical-Abilities.

5.4. External factors

The external PIFs can be assessed by an auditing system. Table 3 provides suggestions on auditing points.

6. General form of equation for calculating PIFs states

Currently the state of most IDAC PIFs is quantitatively represented by a score between zero and ten. These are either assessed directly or as a function of other PIFs. For the directly assessed PIFs (e.g., procedure quality), a questionnaire is used to assess their states. For the PIFs whose states are function of other PIFs, Eq. (1) is used to calculate their scores.

$$\text{PIF Score} = \overbrace{\left[\prod_{i=1}^{N}\left(\sum_{j=1}^{M_i} w_j(\text{PIF}_j)\right)^{u_i}\right]}^{\text{Main Bracket}}[\text{AF}]. \tag{1}$$

The w_j's and u_i's are positive normalized constant weight factors such that

$$\sum_{i=1}^{N} u_i = 1, \quad \sum_{j=1}^{M_i} w_j = 1. \tag{2}$$

The equation allows PIFs to affect a PIF score individually or in groups. Three types of influences are represented in Eq. (1) and are summarized in Table 4. The first type of influence, *Individually-dominant* (denoted as 'I' in Table 4), allows a single PIF to have a pronounced effect on the PIF depending on it. For example, as shown in Table 4, Non-Task-Related-Load could have a deterministic influence on the Conflict-Stress of the Emotional Arousal. The second type of influence, *Collectively-dominant* (denoted as 'C' in Table 4), is the case where a group of PIFs acting together have the same kind of influence as the first type. For example, as shown in Table 4, the four types of stress together could have a deterministic effect on the Attention-to-Current-Task in the Cognitive-Tendencies-and-Modes. Types 'I' and 'C' influences are covered by the main bracket of Eq. (1). Identical numerical subscripts indicate membership in the same group of influencing factors' influences. The third type of influence, *Adjustment* (denoted as 'A' in Table 4), results from the fact that some PIFs have some degree of influence on a PIF; however, the degree of influence is not as significant as in types one and two. They mainly function as an adjustment factor, as seen in Eq. (1). A proposed form for calculating the effect of the Adjustment Factors (appropriate for scores in the 0–10 range) is shown in

$$\text{AF} = (1-\alpha) + 0.2\alpha \cdot \left(\sum_{k=1}^{N} v_k(\text{PIF}_k)\right),$$
$$0<\alpha<1 \quad \text{and} \quad 0 \leqslant \sum_{k=1}^{N} v_k(\text{PIF}_k) \leqslant 10, \tag{3}$$

where v_k is the normalized weight of PIF_k and N is the total number of adjustment PIFs.

For the same value of α, the actual linear adjustment to the base score, x, depends on the value of x. The value of α is between 0 and 1 determining the adjustable range. For a given α, the value of Adjustment Factor is between $(1-\alpha)$ and $(1+\alpha)$. This will cause a basic score 'x' calculated from the main basket of Eq. (1) to vary between $x(1-\alpha)$ and $x(1+\alpha)$ due to the effects of Adjustment Factor (Fig. 6).

Table 3
Examples of factors to be considered in the assessment of the external factors

Group	PIF	Example assessment factors
Team-related factors	Cohesiveness	Frequency with which the crew is trained or performs duty as a team Mutual assistant behavior Willingness to sacrifice the right judgment for maintaining team cohesiveness [103]
	Coordination	Frequency with which the crew is trained or performs duty as a team The level at which different individual roles and responsibilities (including backup responsibilities) are clarified to each team member.
	Composition	Team size, homogeneity/heterogeneity, and compatibility [10] The team stability or turnover rate (For example, if too many members are replaced, particularly when replaced by less skilled members, team performance is likely to degrade [10].)
	Communication availability	The sufficiency and availability of communication means for use The physical proximity of operators and communication equipment (if any) Failure or functional unavailability of communication system (e.g., signal jam due to a high volume of communication signals) The likelihood that communication equipment is unmanned
	Communication quality	Distorted signal or degradation of the equipment due to equipment faults (e.g., old or poorly maintained equipment) Human fault (e.g., heavy accent, linguistic ambiguity, and unclear instruction).
	Leadership	Ascendancy, rank, experience, and reliability of the decision maker [29] Leadership quality, comprising of three elements: direction-setting, gaining followers' commitment, and overcoming obstacles to change situation [67] The level of commitment could be measured in three dimensions: identification with work, identification with co-workers, and identification with the organization [98]
Organizational factors	Work Process design, tasking & direction	Work sequence/schedule Completeness and correctness of task description Timeliness of work assignment
	Human-system interface	Quality of system design for ease and accuracy of visual, audio, and cognitive information perception. (Examples of design guidelines are [60,102]) Appropriateness of workload distribution between automation and operator manual controls
	Safety & quality culture	Policy (i.e., clear emphases on safety/quality policy) [71] Senior management commitment to safety/quality [71] Response and commitment of individuals to the above Violations and errors recorded in operation log Investigation of accidents or near-miss events
	Work environment (physical)	Control room habitability (e.g., illumination, temperature, humidity, vibration, noise) Sufficient work space
	Tool availability	Needed tools are available, well organized, and accessible
	Tool adequacy and quality	Availability of specially designed tools for certain tasks
	Procedure availability	Existence and accessibility of procedures Content accessibility (e.g., document indexing) [12]
	Procedure quality and adequacy	Document fidelity (e.g., adequacy of the level of detail, completeness, and correspondence of procedures to actual tasks) [12] Legibility and readability (e.g., page layout) [12] Usability (e.g., provision for check-listing) [12] Easiness for distinguishing different procedures Reference [104] provides some principles for writing good procedures
Environmental factors	Physical access	Security access control (management, software and hardware controls) Manmade and natural obstacles
Conditioning events	Pre-existent system problem	Potential for latent human errors (quality of maintenance work) Potential for Dormant or hidden system faults Provisions for detecting and recovery from the above Quality of vendors' and suppliers' products, and outsourced system maintenance and upgrades

Table 4
Summary of PIF inter-dependencies

Dependent PIFs[a]		Cognitive modes and tendencies				Emotional arousal				Strains & Feelings					Perception & appraisal									
Independent PIFs[a]		Alertness (1)	Attention to current task (2)	Attention to Sur. Envi. (3)	Bias (4)	Frustration (5)	Conflict (6)	Pressure (7)	Uncertainty (8)	Time-constraint load (9)	Task-related load (10)	Non-task-related load (11)	Passive-information load (12)	CiP (13)	14	15	16	17	18–20	21	22	23	24	25
Emotional arousal	Stress–Frustration (5)		C1	C1																				
	Stress–Conflict (6)		C1	C1																				
	Stress–Pressure (7)		C1	C1																				
	Stress–Uncertainty (8)		C1	C1																				
Strains & feelings	Time-Constraint Load (9)							C1																
	Task-Related Load (10)							C1																
	Non-Task-Related Load (11)						I																	
	Passive Information Load (12)							C1																
	Confidence in Performance (13)								I															
Perception & appraisal	Perceived Severity of Consequence Associated with Current Diagnosis/Decision (14)					I																		
	Perceived Criticality of System Condition (15)									I														
	Perceived Familiarity of Situation (16)									A				C1										
	Perceived System Confirmatory, Contradictory Responses (17)													C1										
	Perception of Alarms Quantity (18)	C1								A	C1		I											
	Perception of Alarms Intensity (19)	C2								A	C1													
	Perception of Alarms Importance(20)	C3								A	C1													
	Perceived Decision Responsibility (21)																							
	Perceived Complexity of Strategy (22)										C2													
	Perceived Task Complexity (23)										C2													
	Perception of Problem-Solving Resources (24)									A	C3													
	Awareness of Role/Responsibility (25)																							

Table 4 (*continued*)

Dependent PIFs[a]		Cognitive modes and tendencies				Emotional arousal				Strains & Feelings					Perception & appraisal									
Independent PIFs[a]		Alertness (1)	Attention to current task (2)	Attention to Sur. Envi. (3)	Bias (4)	Frustration (5)	Conflict (6)	Pressure (7)	Uncertainty (8)	Time-constraint load (9)	Task-related load (10)	Non-task-related load (11)	Passive-information load (12)	CiP (13)	14	15	16	17	18–20	21	22	23	24	25
Intrinsic characteristics	Self-Confidence (26)									A	A	A	A	A										
	Problem Solving Style (27)																							
	Morale-Motivation-Attitude (28)										A													
Memorized information	Knowledge/Experience (29)				C2										I	I	I			I	I	I	C1	I
	Skills (30)																							
	Memory of Recent Diagnoses, Actions, and Results (31)										A				I			I					C1	
	Memory of Incoming Information (32)				C2											I	I							
Physical factors	Fatigue (33)	I																						
	Physical Abilities (34)					A																		
Team-related factors	Cohesiveness (35)	A																						
	Coordination (36)										C3												C1	
	Communication Availability (37)	A				A																	A	
	Communication Quality (38)	A																					A	
	Composition (39)																							
	Leadership (40)				C3																			
Organizational factors	Work Process Design, Tasking, and Directions (41)					A					C3	I											C1	I
	Human–System Interface (42)		I																					
	Safety and Quality Culture (43)			C2	C3																			A
	Work Environment (Physical) (44)			C2																				
	Tool Availability (45)					A																		
	Tool Adequacy and Quality (46)										C3													
	Procedure Availability (47)																							
	Procedure Adequacy and Quality (48)					A					C3													
Environmental factors (49)																		I						
Conditioning events (50)																								

I: Individually dominant factors; C: Collectively dominant factor; A: Adjustment factor.

[a] The PIF identifying numbers correspond to the numbering system in Fig. 5.

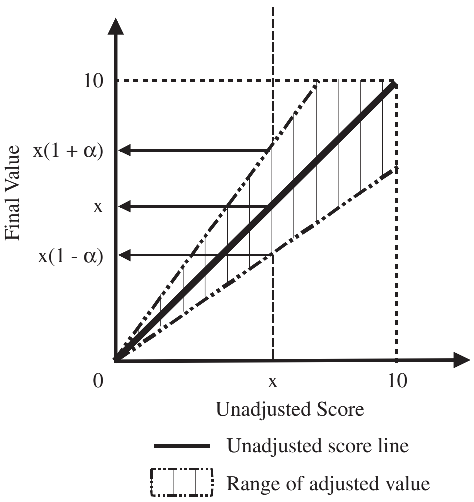

Fig. 6. The score adjusting range of adjustment factors.

The PIFs relationships shown in Table 4 are based on the authors' current state of knowledge. As more evidence is perceived, the content of the table would be enhanced.

As an example we apply this scoring approach to Time-Constraint-Load. Using the demand-and-resource concept, the perceptions of time sufficiency and rate at which the situation moves towards negative consequences are the demands. We associate the time urgency with the time characteristics of the operator's diagnosis of current situation. The higher the criticality of system condition (i.e., the amount of safety buffer of the system), the higher is the assessment of time urgency. Perception-of-Alarms-Quantity, Perception-of-Alarms-Intensity, and Perception-of-Alarms-Importance are the subsidiary demands. High alarm activation rate usually indicates short available time for response, and can be considered as an adjustment factor on Time-Constraint-Load. On the resource side we have Perception-of-Problem-Solving-Resources, Perceived-Familiarity-with-Situation, and Self-Confidence. The Perception-of-Problem-Solving-Resources (e.g., remote technical support center) gives the operator an alternative for help.

Based on these factors a Time-Constraint-Load score can be expressed as

$$\text{Time Constraint Load} = \text{Min.}\left\{\begin{array}{l} 10, \\ \text{Criticality of System Condition}\times \\ \left\{(1-\alpha)+0.2\alpha\left[\begin{array}{l} V_1\times\text{Perception of Alarms Quantity}+ \\ V_2\times\text{Perception of Alarms Intensity}+ \\ V_3\times\text{Perception of Alarms Importance}+ \\ V_4\times(10-\text{Perception of Problem Solving Resources})+ \\ V_5\times(10-\text{Perceived Famility with Situation})+ \\ V_6\times(10-\text{Self Confidence}) \end{array}\right]\right\} \end{array}\right\}, \tag{4}$$

where V_1, V_2, V_3, V_4, V_5, V_6, and α are positive constants, and $V_1+V_2+V_3+V_4+V_5+V_6=1$, $0\leqslant\alpha<1$

In Eq. (4), Criticality-of-System-Condition by itself has a deterministic effect (i.e., I-type influence) on Time-Constraint-Load since zero in the score for Criticality-of-System-Condition would result in a zero score for Time-Constraint-Load. The other PIFs shown in Eq. (4) such as Perception-of-Alarms-Quantity represent Adjustment type of influences. They could adjust the final score of Time-Constraint-Load but could not cause the score of Time-Constraint-Load to become zero. The user adjusts the value of α to restrict the magnitude of influence of the Adjustment type of influence.

The PIFs, form and values of parameter in Eq. (4) are provided as an example. As more evidence collected the PIFs and their influences on Time-Constraint-Load could change accordingly. As mentioned before, quantitatively assessing PIFs' states is an ongoing research. Currently, a Bayesian Belief Net (BBN) type of approach (e.g., [103,104]) for assessing PIFs' states and influences is under development.

7. Concluding remarks

This paper provides detailed discussions of two important modeling elements of IDAC. First we have identified a set of PIFs that are essential for linking crew behavior to context and personal characteristics. The list of PIFs is intended to be as complete as possible within the scope of IDAC. Each PIF is given an as clear as possible definition, with minimum or no overlap with other PIFs within the same PIF group. The paper provides supporting evidence found in literature for the selection and organization of these PIFs into groups. Secondly, the important topic of PIF interdependencies has been tackled, resulting in a PIFs influence diagram linking externally observable inputs and outputs to internal PIFs. A complementary discussion also presented in the paper is on the methods for assessing the states or values of the individual PIFs.

In order to facilitate the use of these models in a dynamic PRA framework, the qualitative PIF dependencies are transformed into quantitative representations using a simple generic equation, resulting in an explicit and quantitative causal model. This would set a foundation for integration of further evidence and an orderly improvement of the accuracy and completeness of the causal model. A procedure for root causes analysis of human errors can be developed from such a causal model and the PIFs' effect on operators' behavior discussed in Paper 4 [2]. By applying the causal model to the simulation based dynamic PRA framework, various general or specific situational contexts can be more precisely specified. This would certainly increase the accuracy and reduce the complexity of applying advanced HRA methodologies. Besides the formal mathematical relations used in quantifying PIF values and interdependencies, other methods such as the Bayesian Belief Network (BBN) could also be used.

Armed with the above results and modeling tools, we are prepared for Paper 3 of this series [4] which focuses on relating the states of the PIF influence diagram to various phases of operator behavior according to the IDAC model.

It is evident that many assumptions have been made in developing the building blocks presented in this and companion papers. Testing and validating these assumptions, beyond what is presented in paper 5 [3] is the subject of ongoing research by the authors.

The number of PIFs identified and the complexity of their dependencies discussed in this paper effectively means that the conventional paper-and-pencil approach for HRA is not practical in the case of full scope IDAC. The authors are in the process of simplifying a version of the IDAC model application for non-simulation applications.

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References

[1] Chang YHJ, Mosleh A. Cognitive modeling and dynamic probabilistic simulation of operating crew response to complex system accidents—part 1 overview of the IDAC model (in press). Reliab Eng Syst Saf 2006.

[2] Chang YHJ, Mosleh A. Cognitive modeling and dynamic probabilistic simulation of operating crew response to complex system accidents—part 4 IDAC causal model of operator problem-solving response (submitted). Reliab Eng Syst Saf 2006.

[3] Chang YHJ, Mosleh A. Cognitive modeling and dynamic probabilistic simulation of operating crew response to complex system accidents—part 5 dynamic probabilistic simulation of IDAC model (submitted). Reliab Eng Syst Saf 2006.

[4] Chang YHJ, Mosleh A. Cognitive modeling and dynamic probabilistic simulation of operating crew response to complex system accidents—part 3 IDAC operator response model (submitted). Reliab Eng Syst Saf 2006.

[5] Swain AD, Guttmann HE. Handbook of human reliability analysis with emphasis on nuclear power plant applications. NUREG/CR-1278: Nuclear Regulatory Commission. 1983.

[6] Woods DD, Roth EM, Pople Jr. HE, Embrey D. Cognitive environment simulation: an artificial intelligence system for human performance assessment (summary and overview). NUREG/CR-4862 (vol. 1). Washington DC.: US Nuclear Regulatory Commission; 1987.

[7] Lewis GW. Critical incident stress and trauma in the workplace: recognition…response…recovery. Muncie, Indiana: Accelerated Development Inc.; 1994.

[8] Hollnagel E. Cognitive reliability and error analysis method (CREAM), 1 ed. Amsterdam: Elsevier; 1998.

[9] Gertman D, Blackman HS, Marble J, Byers J, Haney LN, Smith C. The SPAR-H human reliability analysis method. NUREH/CR-6883. Washington DC: US Nuclear Regulatory Commission; 2005.

[10] Paris CR, Salas E, Cannon-Bowers JA. Teamwork in multi-person systems: a review and analysis. Ergonomics 2000;43(8):1052–75.

[11] Whitehead D. Recovery actions in PRA (probabilistic risk assessment) for the risk methods integration and evaluation program (RMIEP). Washington DC.: US Nuclear Regulatory Commission; 1987.

[12] Malone TB, Kirkpatrick M, Mallory K, Eike D, Johnson JH, Walker RW. Human factors evaluation of control room design and operator performance at Three Mile Island-2. 1979, NUREG/CR-1270, vol. 1. Nuclear Regulatory Commission.

[13] Reason J. Managing the risks of organizational accidents. Ashgate Publishing Company; 1997.

[14] Hansen E. Emotional processes: engendered by poetry and prose reading. Sweden: ACTA UNIVERSITATIS STOCKHOLMIENSIS: Stockholm Studies in Psychology IV; 1986.

[15] Bach M. Stream of consciousness: affective content. Dissertation abstracts international, 1974.

[16] Sträter O. Evaluation of human reliability on the basis of operational experience, in economics and social sciences. The Munich Technical University; 2000.

[17] Kirwan B. A guide to practical human reliability assessment. London: Taylor & Francis; 1994.

[18] Kirwan B. The development of a nuclear chemical plant human reliability management approach: HRMS and JHEDI. Reliab Eng Syst Saf 1997(56):107–35.

[19] Barnes V, Haagensen B, O'Hara J. The human performance evaluation process: a resource for reviewing the identification and resolution of human performance problems. NUREG/CR-6751. Washington DC.: US Nuclear Regulatory Commission; 2001.

[20] Shorrock ST, Kirwan B. Development and application of a human error identification tool for air traffic control. Appl Ergon 2002; 33(4):319–36.

[21] Manktelow K. Reasoning and thinking. Psychology Press Ltd.; 1999.

[22] Tversky A, Kahneman D. Judgment under uncertainty: heuristics and biases. Science 1974;185:1124–31.

[23] Baron J. Thinking and deciding, 3 ed. New York: Cambridge University Press; 2000.

[24] Barriere MT, Wreathall J, Cooper SE, Bley DC, Luckas WJ, Ramey-Smith A. Multidisciplinary framework for human reliability analysis with an application to errors of commission and dependencies. NUREG/CR-6265. Washington DC.: US Nuclear Regulatory Commission; 1995.

[25] Williams J. HEART: a proposed method for assessing and reducing human error. In: The 9th advances in reliability technology symposium. University of Bradford, 1986.

[26] Gaillard AWK. Comparing the concepts of mental load and stress. Ergonomics 1993;36(9):991–1005.

[27] Kaplan RM, Saccuzzo DP. Psychological testing: principles, applications, and issues, 2 ed. Pacific Grove, California: Brooks/Cole Pub. Co.; 1989.

[28] Kim B, Bishu RR. On assessing operator response time in human reliability analysis (HRA) using a possible fuzzy regression mode. Reliab Eng Syst Saf 1996(52):27–34.

[29] Sasou K, Takano Ki, Yoshimura S. Modeling of a team's decision-making process. Saf Sci 1996;24(1):13–33.

[30] Svenson O, Maule AJ, editors. Time pressure and stress in human judgment and decision making. New York: Plenum Press; 1993. p. 333.

[31] Rastegary H, Landy FJ. The interaction among time urgency, uncertainty, and time pressure. In: Svenson O, Maule AJ, editors. Time pressure and stress in human judgement and decision making. New York: Plenum Press; 1993.

[32] Wickens CD. Engineering psychology and human performance. 2nd ed. Harper Collins Publishers; 1992.

[33] Maule AJ, Maillet-Hausswirth P. The mediating effects of subjective appraisal cognitive control and changes in affect in determining the effects of time pressure on risk-taking. In: 15th research conference on subjective probability, Utility and Decision Making (SPUDM15). 1995. Jerusalem.

[34] Fagerjord M. Human reliability assessment. In: Department of production and quality engineering. Norwegian University of Science and Technology; 1999. p. 124.

[35] Lawton R. Not working to rule: understanding procedural violations at work. Saf Sci 1998;28(2):77–95.

[36] Julius JA, Jorgenson EJ, Parry GW, Mosleh A. Procedure for the analysis of errors of commission during non-power modes of nuclear power plant operation. Reliab Eng Syst Saf 1996;53:139–54.

[37] Huey BM, Wickens CD, editors. Workload transition: implications for individual and team performance. Washington DC.: Commission on Behavioral and Social Sciences and Education, National Research Council; 1993.

[38] United States, Report of the President's commission on the accident at the Three Mile Island 1979. 1980.

[39] Park J, Jung WD, Ha J. Development of the step complexity measure for emergency operating procedures using entropy concept. Reliab Eng Syst Saf 2001;71(2):115–30.

[40] Nixon HL. The small group. Prentice-Hall Series. In: Smelser NJ, editor. Sciology. 1 ed. Englewood, NJ: Prentice-Hall, Inc.; 1979.

[41] Embrey DE, Humphreys P, Rosa EA, Kirwan B, Rea K. SLIM-MAUD: an approach to assessing human error probabilities using expert judgment. NUREG/CR-3518. Washington, DC.: Nuclear Regulatory Commission; 1984.

[42] Kirwan B. Human reliab assess. In: Wilson JR, Nigel Corlett E, editors. Evaluation of human work: a practical ergonomics methodology. Bristal, PA: Taylor & Francis Inc.; 1990. p. 706–54.

[43] Dougherty EM. Is human failure a stochastic process? Reliab Eng Syst Saf 1997;55:209–15.

[44] Ornstein R. The roots of the self: unraveling the mystery of who we are. New York: HarperCollins Publishers; 1993.

[45] Dictionaries TAH, editor. The American heritage dictionary of the english language. 4 ed. Boston: Houghton Mifflin Co.; 2000.

[46] Tupes EC, Christal RE. Recurrent personality factors based on trait ratings. Journal of Personality 1992;60(2):225–51.

[47] Woods DD, Roth EM, Pople Jr. HE, Embrey D. Cognitive environment simulation: an artificial intelligence system for human performance assessment (Cognitive Reliability Analysis Technique). NUREG/CR-4862 (Vol. 3). Washington DC.: US Nuclear Regulatory Commission; 1987.

[48] Freedman JL, Edwards DR. Time pressure, task performance, and enjoyment. In: McGrath JE, editor. The social psychology of time. Newbury Park: Sage Publications; 1988.

[49] Decortis F. Operator strategies in a dynamic environment in relation to an operator model. Ergonomics 1993;36(11):1291–304.

[50] Steers RM, Porter LW. Motivation and work behavior. McGraw-Hill series in management, 2 ed. New York: McGraw-Hill Professional Publishing; 1979.

[51] Brief AP. Attitudes in and around organizations. In: Whetten D, editor. Foundations for organizational science: a Sage publication series. Thousand Oaks, California: SAGE Publications, Inc.; 1998.

[52] Eagly AH, Chaiken S. The psychologies of attitudes. Fort Worth, TX: Harcourt Brace Jovanovich; 1993.

[53] Triandis HC. Attitude and attitude change. In: Encyclopedia of human biology. San Diego, CA: Academic Press; 1991. p. 485–96.

[54] Borman WC, Hedge JW, Ferstl KL, Kaufman JD, Farmer WL, Bearden RM. Current directions and issues in personnel selection and classification. Research Methods in Personnel and Human Resources Management 2003;22:287–355.

[55] German D, Hallbert BP, Parrish MW, Sattision MB, Brownson D, Tortorelli JP. Review of findings for human error contribution to risk in operating events. INEEL/EXT-01-01166. Idaho Falls: Idaho National Engineering and Environmental Laboratory; 2001.

[56] Connon-Bowers JA, Salas E. Reflections on shared cognition. Journal of Organizational Behavior 2001;22:195–202.

[57] Marcil I, Vincent A. Fatigue in air traffic controllers: literature review. TP-13457: Transportation Development Centre of Transport Canada. 2000.

[58] Rosekind MR, Gander PH. Fatigue in operational setting: examples from the aviation environment. Human Factors 1994;36(2):327–38.

[59] Wylie CD, Shultz T, Miller JC, Mitler MM, Mackie RR. Commercial motor vehicle driver fatigue alertness study. FHWA-MC-97-002. Washington DC: Federal Aviation Administration of US Department of Transportation; 1996.

[60] Wickens CD, Gordon SE, Liu Y. An introduction to human factors engineering. New York: Addison-Wesley Educational Publishers Inc.; 1997.

[61] Mullen B, Copper C. The relation between group cohesiveness and performance: an integration. Psychological Bulletin 1994;115(2): 210–27.

[62] Hoegl M, Gemuenden HG. Teamwork quality and the success of innovative projects: a theoretical concept and empirical evidence. Organization Science 2001;12(4):435–49.

[63] Homans GC. The human group. New York: Harcourt, Brace, Jovanovich, Inc.; 1950.

[64] Crosbie PV. Interactions in small group. New York: Macmillan Publishing Co.; 1975.

[65] Rognin L, Blanquart J-P. Human communication, mutual arareness and system dependability. Lesson learnt from air-traffic control field studies. Reliability Engineering and System Safety 2001;71: 327–36.

[66] Paradise M, Unger PM, Haas PM, Terranova M. Development of the NRC's human performance investigation process (HPIP). NUREG/CR-5455. Washington DC: US Nuclear Regulatory Commission; 1993.

[67] Paglis LL, Green SG. Leadership self-efficacy and managers' motivation for leading change. Journal of Organizational Behavior 2002;23(2):215–35.

[68] Kecklund LJ, Svenson O. Human errors and work performance in a nuclear power plant control room: association with work-related factors and behavioral coping. Reliability Engineering and System Safety 1997(56):5–15.

[69] Cook RA, Burack EH. Measuring norms and expectations with the OCI, Organizational culture inventory, Level V manual. Chicago, Illinois: Human Synergistics; 1987.

[70] IAEA, Safety Culture. IAEA Safety Series No 75—INSAG 4, Vienna (A): International Atomic Energy Agency. 1991.

[71] Sorensen JN. Safety culture: a survey of the state-of-the-art. NUREG-1756. Washington DC.: US Nuclear Regulatory Commission; 2002.

[72] Flin R, Mearns K, O'Connor P, Bryden R. Measuring safety climate: identifying the common features. Safety Science 2000; 34(1–3):177–92.

[73] Rundmo T. Safety climate, attitudes and risk perception in Norsk hydro. Safety Science 2000;34(1–3):47–59.

[74] Bourrier M. Elements for designing a self-correcting organization: examples from nuclear power plants. In: Hale AR, Baram M, editors. Safety management: the challenge of change. Netherlands: Elsevier Science Publishing Company, Inc.; 1998. p. 133–46.

[75] Williamson AM, Feyer A-M, Cairns DR. Industry differences in accident causation. Saf Sci 1996;24(1):1–12.

[76] National Transportation Safety Board, In-Flight Electrical System Failure and Loss of Control, Jet Express Services, Raytheon (Beechcraft) Super King Air 200, N81PF, Near Strasburg, Colorado, January 27, 2001. 2003, NTSB/AAR-03/01; NTIS/PB2003-910401, Washington DC: National Transportation Safety Board.

[77] Roth E. Crew performance in complex simulated emergencies: what simulator data can tell us about contributors to human reliability and human error. In: Workshop on human reliability models: theoretical and practical challenges. Stockholm, Sweden: 1994, August 22–24, 1994.

[78] Hughes D. Incidents reveal mode confusion. Aviation Week & Space Technology 1995;142(5):56.

[79] Phillips EH. NTSB: mode confusion poses safety threat. Aviation Week & Space Technology 1995;142(5):63–4.

[80] Chang YH, Mosleh A. ADS: a computer program for dynamic probabilistic risk assessment. In: International topical meeting on probabilistic safety assessment. Detroit, Michigan: American Nuclear Society; 2002 October 6–9.

[81] Chang YH, Mosleh A. ADS-IDACrew: dynamic probabilistic simulation of operating crew response to complex system accidents. In: PSAM 5—probabilistic safety assessment and management November 27–December 1. 2000. Osaka: JapanUniversal Academy Press, Inc.; 2000.

[82] Chang YH, Mosleh A. Cognitive modeling and dynamic probabilistic simulation of operating crew response to complex system accidents (ADS-IDACrew). CTRS-B6-06. College Park, Maryland: Center for Technology Risk Studies, University of Maryland; 1999.

[83] Tversky A, Kahneman D. Availability: a heuristic for judging frequency and probability. Cognitive Psychology 1973;5: 207–32.

[84] Reason J. Human error. Cambridge: Cambridge University Press; 1990.

[85] Cowen EL. The influence of varying degrees of psychological stress on problem-solving rigidity. Journal of Abnormal and Social Psychology 1952;47:144–58.

[86] Wickens CD, Stokes A, Barnett B, Hyman F. The effects of stress on pilot judgment in a MIND simulator. In: Svenson O, Maule AJ, editors. Time pressure and stress in human judgement and decision making. New York: Plenum Press; 1993. p. 271–92.

[87] Janis IL, Mann L. Decision making. New York: The Free Press; 1977.

[88] Hart SG, Bortolussi MR. Pilot errors as a source of workload. Human Factors 1984;26(5):545–56.

[89] Mosneron-Dupin F, Reer B, Heslinga G, Strater O, Gerdes V, Saliou G, et al. Human-centered modeling in human reliability analysis: some trends based on case studies. Reliability Engineering and System Safety 1997;58(3):249–74.

[90] Yates FJ, Stone EF. Risk appraisal. In: Yates FJ, editor. Risk taking behavior. Chichester: Wiley; 1992. p. 49–85.

[91] Hsueh K-S. An integrated simulation model for plant/operator behavior in accident conditions. In: Materials and nuclear engineering. College Park, Maryland: University of Maryland; 1992.

[92] Chang YH, Mosleh A. ADS-IDACrew: an integrated system for performing dynamic probabilistic risk assessment. in: Society for risk analysis 2000 annual meeting "Applications of Risk Analysis in Industry and Government". 2000. Arlington, Virginia: December 3–6, 2000.

[93] Laumann K, Braarud PØ, Svengren H. The task complexity experiment 2003/2004. HWR-758. Halden, Norway: Instututt for energiteknikk; 2005.

[94] Svenson O. A decision theoretic approach to an accident sequence: when feedwater and auxiliary feedwater fail in a nuclear power plant. Reliability Engineering and System Safety 1998;59:243–52.

[95] Wickens CD, Hollands JG. Engineering psychology and human performance. 3rd ed. Englewood, NJ: Prentice-Hall Inc.; 1999.

[96] Yuzuk RP. The assessment of employee morale: a comparison of two measures. Columbus, Ohio: The Ohio State University; 1961.

[97] Herzberg F, Mausner B, Peterson RO, Capwell DF. Job attitudes: review of research and opinion. Pittsburgh: Psychology Service of Pittsburgh; 1957.

[98] Fink SL. High commitment workplaces. New York: Quorum Book; 1992.

[99] Seaburg DJ, Rounds JB, Dawis RV, Lofquist LH. Values as second order needs. in: Annual Meeting of the American Psychological Association. Washington DC: August 1976.

[100] Schmitt N, Chan D. Personal selection—a theoretical approach. In: Whetten D, editor. Fundation for Organizational Science. California: SAGE Publications, Inc.; 1998.

[101] Co EL, Gregory KB, Johnson JM, Rosekind M. Crew factors in flight operations XI: a survey of fatigue factors in regional airline operations. NASA/TM-1999-208799. Moffett Field, CA: Ames Research Center; 1999.

[102] O'Hara J, Brown WS, Lewis PM, Persensky JJ. Human-system interface design review guidelines. NUREG-0700, Rev. 2. Washington DC.: US Nuclear Regulatory Commission; 1996.

[103] Jensen FV. Bayesian networks and decision graphs. New York: Springer; 2001.

[104] Pearl J. Probabilistic reasoning in intelligent systems: networks of plausible inference, 2 ed. San Franciso, California: Morgan Kaufmann Publishers; 2001.