# ABSTRACT

Title of Document: DYNAMIC BEHAVIOR OF OPERATING
CREW IN COMPLEX SYSTEMS:
AN OBJECT-BASED MODELING &
SIMULATION APPROACH

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High-risk environments such as the control room of Nuclear Power Plants are extremely stressful for the front line operators; during accidents and under high task load situations, the operators are solely responsible for the ultimate decision-making and control of such complex systems. Individuals working as a team constantly interact with each other and therefore introduce team related issues such as coordination, supervision and conflict resolution. The aggregate impact of multiple human errors inside communication and coordination loops in a team context can give rise to complex human failure modes and failure mechanisms. This research offers a model of operating crew as an interactive social unit and investigates the dynamic behavior of the team under upset situations through a simulation method. The domain of interest in this work is the class of operating crew environments that are subject to structured and regulated guidelines with formal procedures providing the core of their response to accident conditions. In developing the cognitive models for the operators and teams of operators, their behavior and relations, this research integrates findings from multiple disciplines such as cognitive psychology, human factors, organizational factors, and human reliability. An object-based modeling methodology is applied to represent system elements and different roles and behaviors of the members of the operating team. The proposed team model is an extended version of an existing cognitive model of individual operator behavior known as IDAC (Information, Decision, and Action in Crew context). Scenario generation follows DPRA (Dynamic Probabilistic Risk Assessment) methodologies. The method capabilities are demonstrated through building and simulating a simplified model of a steam/power generating plant. Different configurations of team characteristics and influencing factors have been simulated and compared. The effects of team factors and crew dynamics on system risk with main focus on team errors, associated causes and error management processes and their impact on team performance have been studied through a large number of simulation runs. The results are also compared with several theoretical models and empirical studies.

# DYNAMIC BEHAVIOR OF OPERATING CREW IN COMPLEX SYSTEMS: AN OBJECT-BASED MODELING & SIMULATION APPROACH.

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# Preface

# Foreword

# Dedication

*I’d like to dedicate this dissertation to my parents,*

*because they deserve all the love in this world and more.*

# Acknowledgements

I would like to express my gratitude to my advisor, Professor Ali Mosleh, for all his help, support, and encouragement during this endeavor. I especially appreciate the insights and knowledge he shared with me, as well as his constant and invaluable assistance during this process.

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# List of Acronyms

| | |
|---|---|
| BBN | Bayesian Belief Network |
| BFP | Boiler Feed Pump |
| CRM | Crew Resource Management |
| CSDV | Condenser Steam Discharge Valve |
| CST | Coolant Storage Tank |
| CV | Check Valve |
| DDET | Discrete Dynamic Event Tree |
| DPRA | Dynamic Probabilistic Risk Assessment |
| EFP | Emergency Feed Pump |
| EOP | Emergency Operating Procedures |
| HEP | Human Error Probability |
| HERA | Human Events Repository and Analysis |
| HMI | Human Machine Interface |
| HRA | Human Reliability Assessment |
| HSE | Health and Safety Executive |
| HTR | Heater |
| IDAC | Information, Decision and Action within a Crew context |
| IPO | Input Process Output Model |
| J | Pipe |
| LOCA | Loss of Coolant Accident |
| LOFW | Loss of Feed Water |
| NPP | Nuclear Power Plant |
| NPPCR | Nuclear Power Plant Control Room |
| OAT | Operator Action Taker |
| OCT | Operator Consultant |
| ODM | Operator Decision Maker |
| P | Pump |
| PET | Performance Evaluation Method |
| PIF | Performance Influencing Factors |
| PRA | Probabilistic Risk Assessment |
| PSF | Performance Shaping Factors |
| RO | Reactor Operator |
| SA | Situation Awareness |
| SG | Steam Generator |
| SRO | Senior Reactor Operator |
| TMI | Three Mile Island |
| V | Valve |

# Chapter 1: Motivation and Objectives

## 1.1 Introduction

Recent advances in technology have remarkably improved organizations' ability to build and manage hazardous technologies. In the case of high reliability organizations[1], the balance between safe and efficient actions has become a main objective in managing complex systems. In the 1960s, three organizations were considered as high reliability organizations: the US air traffic control system, organizations operating nuclear power stations, and the US Navy nuclear aircraft carrier operations (Juhasz et al., 2011). Recent research on high reliability organizations includes domains in health, public safety, and environmental protection. Much of the research has focused on the performance of the personnel flying aircraft, air traffic controllers, nuclear power stations operators, doctors and nurses in operating rooms and intensive care units, and fire fighters, since the operators in such systems are responsible for the ultimate diagnosis, decision making and control of extremely complex systems (Cacciabue, 2004). High levels of training for the operating crew are required to manage such high-hazard situations efficiently; training focuses on achieving the fundamental professional knowledge about the function of the systems, about events, and about the correct actions (Juhasz et al., 2011). For example while the vast majority of operations in a nuclear power plant (NPP) are highly automated and personnel functions are limited to monitoring, most of the time the task load is at low or moderate levels. However, the personnel need to

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[1] High reliability organization and high risk environment concepts are used interchangeably to describe organizations such as a Nuclear Power Plants (NPPs) where the idea of safety is not just a theoretical concept, and it is an eternal, conscious endeavor to maintain safety in the nature of the high hazard operation and environment (Juhasz et al., 2011).

be aware of possible system malfunctions external factors that threaten the safety and effectiveness of operations, requiring continuous alertness, one of the main causes of high task load in such a complex environments.

In high reliability organizations, operations are technically complex, requiring the knowledge, experience, skills and abilities of more than one person. Hence the professional operating teams play a crucial role in the management of complex operations, where the team members need to interact and integrate their individual capabilities to cope with normal and abnormal operations (Juhasz, 2011). For instance in NPP control rooms, the workflow is totally structured around teams of operators. Clearly, individuals working as a team provide greater resource and power; however, teams introduce new issues such as interpersonal coordination, time and task management. Almost every activity in a power plant control room is time-based and has a time window which in most cases does not exceed a few minutes. Crews consist of highly trained individuals with special skills and knowledge. Each person is responsible for one specific area of the complex system. There is an intensive and constant pressure to perform efficiently and reliably. Also the expectations from the organization are high and this is a source of stress which can alter the way operators work under difficult circumstances.

The existing research shows that the most important contributing factor to accidents and unsafe behavior is not the lack of professional knowledge related to technical aspects of the complex system, but rather to key contributions that come from the failure of efficient teamwork, such as inappropriate communication and coordination (Juhasz, 2011). Human-machine and human-human interactions play a very important role in control rooms, especially after the occurrence of abnormal events. Such interactions are defined as the crew response to cue(s), including alarms and parameter changes. Crew responses are either control manipulations or communications. Response time begins with an observable cue and ends with the operator response to the cue in the form of an observable action (Mengzhuo et al., 1997).

Some control rooms (such as those in NPPs) are highly regulated environments in which the consequence of tasks are safety related, thus each activity inside operating teams is required to be largely coordinated and organized. However, often misunderstandings associated with perspectives characterize interpersonal relations even for teams that interact regularly and are mutually independent. The individuals in a team define, interpret and access the reality that surrounds them with a subjective point of view; social and technical backgrounds determine what one will focus on while interacting with others. Depending on the person with whom one is interacting, different expectations shape the way individuals perceive the situation. Differences in social realities, goals and strategies affect the way people in a team interact.

In recent years the nuclear industry has increasingly recognized the importance of integrating non-technical team skills training with the technical training given to its control room operators. However, little has been done to determine the actual effectiveness of such non-technical training (Levi, 2007 and Harrington et al., 1992). Since critical conditions involve significant human-human interactions, under high-workload and complexities posed by system malfunction, the reliability of such interactions becomes extremely important. Incomplete information, lack of time, stressful conditions and lack of mutual situational awareness can lead to critical human errors.

Research shows that most of past accidents in the nuclear industry have been a consequence of aggregated human error (Reason, 1997), (Gertman et al., 2002), (Carvalho et al., 2006) and (Dietrich et al., 2004). Some researchers such as Gertman et al. (2002) discussed that the impact of multiple human errors inside communication loops can result in major hazards and complex failure modes. In evaluating team performance, not only the standards for the individual operator performance should be considered, but also, new standards need be introduced which reflect a team's perspective. Thus, it is important to study the role that team-related factors can play in systems risk.

## *1.2 Research Motivations*

Human mistakes are rarely built into control room operator training simulators, and research has neglected to systematically study the reliability and accuracy of communication between control room and field operators, between operators within a shift and at shift hand-over. The sensitivity of the group decision process to individual human errors is a critical field of research that has not been studied systematically yet. Such issues apply to most of command and control structures. Research has given little attention to theoretical or conceptual issues on information integration and even less so to consequences of information distribution within groups. Little research has been done on how the individual efforts and skills of group members should be combined when those individuals work together as a group on a given type of task, particularly from a team's perspective (McGrath et al., 1994).

**Figure 1: Operating Crew monitor the Davis-Besse NPP, Ohio, US, 2004[2]**

Systematic approaches to investigate team performance in the context of a high-risk environment such as a NPP use observational methods with limited applications, where results are hard to verify and generalize as discussed by Gibson et al. (2008). It is not always easy to interpret observed behavior, even when the data gathered are fairly specific. In most cases, it appears that more than one interpretation is possible (Pattron et al., 2002). Theoretical approaches leave significant gaps between conceptual models and complexities of dynamic interactions of teams and systems. Moreover, theoretical approaches such as the study by Kim et al. (2003) mostly aim to provide understanding of the work environment and taxonomies of communication-related Performance Shaping Factors (PSFs) as well as their possible outcomes. The real impact of crew interactions on team effectiveness and, consequently, on the entire system has not been fully and quantitatively explored for operating crews in high-risk environments such as NPPs. In fact, existing Human

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[2] http://www.toledoblade.com/Energy/2011/05/12/NRC-task-force-says-review-shows-US-nuclear-reactors-still-safe.html

Reliability Analysis (HRA) approaches have mostly approximated a plant crew as an individual human operator with team effects treated through a set of PSFs. Little has been done to investigate and explicitly model the crew and capture the effects of team factors and team dynamics on system risk. However, since a team is an interactive social system, team-specific issues need to be studied and evaluated by standards that are from a “team perspective” and are based on team dynamics and processes.

Even though research has produced HRA-based techniques in order to improve the group processes and outcomes in general, only a few of researchers such as Petkov et al. (2004) have evaluated the techniques systematically.

Since there are often insufficient resources to conduct empirical studies with human subjects, analytical approaches are required to investigate human performance in complex system contexts. More specifically, considering the large number of parameters and the flexibility needed in examining different configurations to obtain verifiable results, a model-based simulation approach is highly desirable.

A suitable candidate is the class of Dynamic Probabilistic Risk Assessment (DPRA) methods with which the dynamic behavior of the system and crew can be probabilistically simulated by using models of system and crew elements and rules of corresponding external and internal interactions. Simulation-based DPRA focuses on the influence of time and process dynamics on risk scenarios. However, most of the existing representation languages are limited in scope and application. New features need to be integrated into existing DPRA approaches in order to model the dynamics of teams and investigate their contribution to the entire system risk profile.

## 1.3 Objectives

The main motivation for this research is to investigate how team related issues and errors affect complex system risk and how the associated failures reflect the complexity and variety of team characteristics and interactions. To build the theoretical foundations and some of essential means to address the stated need, the following objectives were defined for this research:

1. Develop a crew performance causal model leveraging the existing theoretical concepts and empirical findings, with focus on team characteristics, internal dynamics, and crew-system interaction.
2. Integrate the developed crew performance model into a probabilistic simulation platform capable of generating system risk profiles due to systems and crew failure modes
3. Demonstrate capabilities of the crew model and dynamic simulation platform through an example involving typical control room configurations seen in high reliability complex industrial facilities. Test simulated team macro-behavior for its explanatory power and face validity, and draw insights in comparison with behaviors discussed in existing theoretical models and relevant empirical results.

## 1.4 Methodology

This research applies a systematic method to model and examine information sharing, distribution, and collection, building of shared mental models, team decision making and combined action execution by an operating crew of a complex plant (e.g., NPP), the main focus being the team errors, associated causes, and error management processes.

The dynamic behavior of an operating crew under high workload and upset situations is investigated through the application of simulation methods. An object-based modeling methodology is applied to represent system elements and different roles and behaviors within the operating team. The modeling style aims to be easy to integrate, modify and reconfigure and capable of representing the desired functionality, different roles and behaviors of the individual operators, as well as their dynamic interactions. The object-based methodology captures available sources of knowledge on system elements into representative formal models required for DPRA methods. Three different object categories are included: the hardware system (hardware elements such as pumps and valves); the operating crew composed of individual human operators; and the control panel (alarms and indicators and their activation processes).

Development of representative probabilistic simulation models for system main elements involves a top-down approach for hierarchical decomposition and identifying object classes, and a bottom-up approach for defining object class association links and aggregation. Model implementation stage includes knowledge acquisition for scenario generation and development of model of system dynamics.

The basic ingredients of individual operator behaviors are from the IDAC (Information, Decision, and Action in Crew context) cognitive model (Chang et al., 2007), and the scenario simulations follow typical DPRA methodologies. IDAC decomposes the operator's cognitive flow into: Information-processing (I), Decision-making (D), and Action-execution (A). General characteristics are encapsulated as object class attributes and operations, with the flexibility of being edited to account for personal differences and PSFs. Extended IDAC model proposed by this research classifies team activities into three main categories: "Collaborative information collection", "Shared decision making", and "Distributed action execution". Furthermore, another major category of operator activities is introduced to represent activities related to "error management" including: error detection, error indication and error correction. The approach is demonstrated through a case study for an operating crew of a steam generator feed-water system under a postulated accident scenario (pipe-break).

A configuration of four operators is studied as a reasonable approximation of real operating crews. The team consists of two reactor operators (action-taker), the shift supervisor (decision-maker) and the shift technical-advisor (consultant). Each operator is responsible for a variety of tasks, all following the general cognitive steps of IDAC, with different associated individual characteristics as well as responsibilities.

Human errors are only recognizable within the context by identifying mismatches between internal and external reference points and are categorized by considering their effects. The communication network is centralized around the decision-maker. The developed simulation models for the operating crew and the plant are integrated together via information channels into the complex system simulation model.

The case study aims to demonstrate the proposed modeling and simulation capabilities. A framework is developed inside MATLAB Simulink to accomplish the above tasks. CREWSIM[3], a customized library of pre-defined blocks inside model editor, facilitates model development. The cognitive modules are modeled in Simulink via use of sequential function blocks. The Simulation controller is responsible for data manipulation, information dissemination, inference, calls to external routines and command implementation. The dynamics of behavior is captured by using a local controller inside each object structure, responsible for branch generation. The simulation algorithm generates a dynamic event tree based on branch points associated with the internal and external error reference points and the lowest level functionalities of each simulated module. Each branch in the simulation scenario represents distinct combinations of system and operator states. Once a system end-state is reached the scenario ends. A study is conducted on simulation results of different cases associated with different configuration of teams and team factors in order to provide face validity of validate the model and demonstrate the capabilities of the approach.

## *1.5 Research Contributions*

This research proposes a framework to study the dynamic behavior of an operating crew and to explore the complexities arising from their interactions, using model-based simulation. Extended IDAC, the framework designed and developed in this research, focuses mainly on the team aspects of operating crew behavior. It not only adds features to models of individual operator cognitive processes and the team's

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[3] CREWSIM is a developed tool by this research inside MATLAB Simulink environment that performs realistic, high-fidelity simulation which is relevant to real life situations.

shared problem-solving activities, but also adds communication-related aspects and additional model elements to cover error management activities at the individual operator and team levels. The domain of interest in this work is the class of operating crew environments that are subject to structured and regulated guidelines with formal procedures providing the core of their response to accident conditions.

The Extended IDAC also introduces a significantly expanded model of PSFs that characterize the individual and team responses, and form the basis for quantification of human error probabilities in team context.

This research implemented the Extended IDAC framework as a series of sequential cognitive and action blocks, with the behavioral effects of PSFs captured via influence diagram PSFs for each human activity. In developing the cognitive models for the operators and teams of operators, their behavior and relations, this research integrates findings from multiple disciplines such as cognitive psychology, human factors, organizational factors, and human reliability.

The error management framework was introduced and used with a set of associated PSF models to support additional branching events in dynamic simulation of the team response, while providing a more explicit causal explanation of the crew behavior. Except for a few theoretical frameworks, error management activities have not been considered fully and explicitly in previous efforts. Collaborative information collection method developed and implemented in this research simulates the contributions of various team members in gathering important information under the supervision of the team leader.

A team decision-making model responsive to dynamic changes in situational context was also designed and implemented, covering team discussions and consultation activities inside the team. In addition, a distributed action execution model was also defined and implemented to cover the complexities associated with assigning tasks to team members and the effect of including redundancy in operator's roles on team performance.

To provide a rich contextual environment for the team response, the Extended IDAC model simulation was fully integrated with a detailed hardware model in order simulate accident scenarios involving hardware and crew interactions. The resulting simulation platform (CREWSIM), developed by applying object-based methodologies is a practical tool for simulating crew behavior in response to system abnormalities.

Extensive simulation runs and quantitative and qualitative examination of the resulting scenarios provided ample evidence of face validity of the proposed team model and simulation platform. Further, while performing experiments with real crews and real scenarios to validate the model was not feasible due to resource limitations and other practical constraints, the International Empirical Study conducted at Halden Laboratories in Norway provided an opportunity to perform a limited comparison of the proposed model behavior with actual performances of the crews participating in the exercise.  This comparison showed the explanatory power of the proposed model with respect to some observable aspects of the crew performance. Finally, the simulated scenarios in the case study of this work reproduce a number of macro-level behaviors identified in several of the theoretical frameworks discussed in the literature.

## *1.6 Overview of Dissertation*

Following this introductory Chapter, Chapter 2 reviews the literature, related efforts and current state of research on team behavior. Chapter 3 introduces the proposed modeling framework for the operating crew, describing the “Extended IDAC” model, its basic concepts and the fundamentals. The Chapter end with a comparison of the proposed model and simulation approach with the methods and frameworks reviewed, highlighting the contributions of this research to the field. Chapter 4 provides details on the implementation of Extended IDAC, and the development of CREWSIM platform (in MALAB Simulink). This chapter also offers an overview of the various causal models proposed for “Team Error Management”, “Team PSFs” and “Team Communication”. Chapter 5 explains the design of the case study and corresponding simulation models. Chapter 6 provides details on designing and conducting simulation runs and qualitative and quantitative analyses of the results, with the objective of verifying reasonableness of the macro-behavior of the integrated team model. It also offers a limited validation case using data from an experiment involving real operating crews. Chapter 7 discusses the findings, concluding remarks and recommendations as well as directions for future work.

# Chapter 2: Review of Team Behavior Research

Figure 2: Safety is a major concern in high reliability organizations[4]

This chapter provides a summary of the existing research results on team issues. The scope of this review is the research on high reliability organizations in general, and NPPs in particular. The existing literature has been studied and classified to better understand the finding on various aspects of team behavior. The main categories of literature covered are human error in complex systems, team behavior including communication and coordination, team PSFs, supervision and leadership, and team performance.

## 2.1 Human Error in Complex Systems Operation

Safe operation of complex systems requires close coordination between the human operators and the physical hardware. Bocanete et al. (2007) have stated that 90% of

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[4] Flin et al., 2008

all workplace accidents have human error as a cause. Flin et al. in their book, “Safety at the sharp end” (2008), mention that the analysis of a number of industrial sectors has indicated that up to 80% of accident causes can be attributed to human factors.

In a high-risk environment such as a NPP, the primary functions are usually performed by a team of operators which collaborate with each other to achieve system goals. While most of operating teams are professional and tightly coordinated, under high-workload and upset situations, unexpected events happen and the interaction among operators becomes extremely crucial. Since operators working under high risk are subject to the cognitive and psychological changes imposed by external stressors, almost 65% of commercial nuclear system failures have been considered to involve human error (Carvalho et al., 2006) and (Dietrich, 2004).

Managing the processes in such a safety critical system is very stressful for the front line personnel since every little deviation from the safe operational state, if not effectively monitored and managed, would lead to catastrophe. Incomplete information, little time and stressful conditions usually lead to critical errors. The Health and Safety Executive (HSE) of United Kingdom has considered “communications” and “interfaces” among the top ten human factor issues (Health and Safety Executive of GB, 2005). Since a number of operators are involved during most accidents, it is the aggregate impact of multiple human errors that results in major hazards. While typical consequences are decreased efficiency and revenue, some operational failures in a complex environment such as a NPPCR, pose a threat to public safety (Carvalho et al., 2006). For instance, on March 28, 1979, Reactor No.2 at the Three Mile Island (TMI) nuclear power plant suffered a partial meltdown because an event occurred that resulted in melted fuel, prior to the situation being brought back under control (US Department of Commerce report, 1980). One of the most important problems at TMI is considered to have been a total failure of communication. Internal radioactivity levels, for example, were reported as outdoor air readings. As the situation unfolded, operating and monitoring personnel continuously failed to recognize critical information cues and to coordinate their responses accordingly.

Similarly, on April 25, 1986, several years after the TMI accident, the unit No.4 reactor at the Russian Chernobyl power plant installation exploded during the test of the plant's turbine generator system, resulting in 30 fatalities and widespread radioactive contamination (International Nuclear Safety Advisory Group, 1986). During the course of the events an operator error caused the reactor's power to drop below specified levels, setting off a catastrophic power surge that caused a major accident. Among the human factors issues contributing to the disaster, failures in preplanning for coordination requirements inside teams for such an incident, poor marking of roles and responsibilities and breakdown in communication among team members have been listed. In these two of the world's most serious NPPs accidents, operator error relating to loss of situation awareness and poor decision-making played a major role (Flin et al., 2008).

Similarly problems in communication and coordination were identified in the Vogtle-1 nuclear plant incident (Patrick et al., 2003). In March 1990, the plant faced a near miss accident. The incident was in form of Loss of Offsite Power during shutdown and the main reason for this situation was that the emergency diesel generators did not start.

## 2.2 Team Related Issues

Today’s complex systems are operated by teams of individuals whose interactions must be taken into account (Pew et al., 2007) and (Firth-cozens, 2004). Team related issues in recent years have become the subject of increasing interest for the organizations that rely on teamwork (Banbury et al., 2004). Many problems and issues in team performance are potentially answerable by research; however, the issue of group structure and functions has been ignored for a long time in systematic research except for the psychology context where a variety of investigators have been interested in how a group of people interact to accomplish their goals and tasks Examples are Interactionism[5] Psychology (Bland, 2001), (Druckman et al., 1991) and (McGrath et al., 1994). However experimental psychology has not systematically addressed important team related variables such as information sharing and coordination (Waern et al., 1998).

In the nuclear industry, research on teamwork has also been limited. Most of the existing literature in the human reliability field is focused on the individual operator’s cognitive processes and the crew as a unit, as opposed to an interactive social system of individual operators. Teams are complex, adaptive and dynamic systems embedded in organizations and they are responsive to situational contexts (Ilgen et al., 2004). Many studies have explored systematic approaches to investigate team behavior in the context of high-risk environments using field studies and observational methods

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[5] "Interactionism" is an American sociological current that analyzes the social interaction.

(Juhasz et al., 2007), (Bust, 2008) and (Carvalho et al., 2008). Such methods have articulated a number of important questions but have provided limited applications and are not reproducible. Since finding comparable groups is difficult, it is hard to verify and generalize the results. Theoretical approaches mostly aim to provide understanding of the work environment and taxonomies of performance shaping factors as well as their possible outcomes (O'Hara et al., 2004). Ilgen et al. (2004) reviewed existing literature on team performance and concluded that the domain of empirical studies is less cohesive and coherent than is theory and method. They also mention that the importance of dynamic conditions experienced over time is accepted by all. The empirical work is only beginning to consider the implications of time in research designs. Hence the authors conclude that theoretical and methodological approaches are preferred over solely empirical research.

The real contributions of interpersonal relationships on team effectiveness and consequently on the entire system has not been fully and quantitatively addressed for groups interacting with complex technology in high-risk environments such as NPPs. Even though a number of studies have developed HRA-based techniques in order to improve the group processes and outcomes in general, only a few have been evaluated systematically (Boring, 2006) and (Petkov et al., 2004), and the available evidence does not provide clear support for the techniques.

Most of the studies address the team skills, cognitive skills, or the ergonomic considerations of NPP control room personnel. GIHRE (Dietrich et al., 2004), was a joint research project between linguistics, psycholinguistics, psychologists and specialists from the fields of aviation, surgery, intensive care and nuclear reactor safety conducted from 1999 to 2004. GIHRE highlighted governing factors in relation to how people work together and handle technology in a high-risk environment. The main objective of GIHRE was to identify what governs the way in which people work together and handle technology in a high-risk environment.

Improvement in training programs, education, control room procedures, norms and interfaces and ultimately the safety of process has been considered as major results of conducting research on team performance in control rooms. Waller et al. (2004) conducted a study on control room crews using simulation and examined adaptive behaviors and shared mental model development. Healey et al. (2006) studied teamwork behavior via a set of "behavioral constructs". Carvalho et al. (2005) examined how control room supervisors make decisions and Patrick et al. (2003) measured differences in situation awareness among six control room teams.

Considering the large number of parameters involved it is difficult to explore and determine how the various factors, constructs, and assumption, give rise to the "macro-behavior" of the team anticipated or assumed by the theoretical, or observed through experiments and actual operating data. This points to the potential value of systematic simulation approach to investigate team behavior.

## *2.3 Performance Shaping Factors*

Performance Shaping Factors (PSFs) characterize the roots and facets of human error and provide a basis for calculating human error probability and tailoring the values to specific contexts. The importance of these factors has been recognized by most researchers in the field and there is a large body of research on NPP operators with a focus on the factors that threaten their performance, such as effects of overconfidence on team capabilities in the Chernobyl disaster and communication conflicts caused by overgeneralization of the roles and responsibilities (Dietrich et al., 2004) and (Orasanu, 2003). The effect of the nature of team differences, their consistency and training implications on situation awareness was the subject of interest of Patrick et al. (2003) where observational methods were used in particular to study the effects of quality of communication and team coordination.

A list of PSFs, based on field data, is presented by Groth (2009). This study regards communication, direct supervision, team coordination, and team cohesion and role awareness as the most important PSFs for teams. Taxonomies for team and organization PSFs are provided by Gibson (2008), and Kim (2003). The IDAC model for cognitive modeling and investigation of the NPP operating crew as well as implementation of the effect of individual PSFs are fully developed by Chang et al. (2007). In this study the effects of PSF sets that influence human cognitive processes are studied for different cognitive stages. Most of the research in this area is focused on classifying the factors and obtaining taxonomies rather than developing quantification methods to be used in simulation approaches. Such taxonomies consider the human operator vs. the hardware system, the situation and environment, the cognitive stressors and personal capabilities, the organization and the rest of operating crew.

O’Conner et al. (2008) developed a nuclear team skills taxonomy including shared situation awareness, team focused decision-making, communication, co-ordination and collaboration. They used interviews and reviewing documentations in order to provide taxonomy. Sasou et al. (1999) provided taxonomy on team errors by introducing an error making process and a model for error recovery. Sasou's research provided the fundamental and basics for the team error management model used in this research. Taxonomy for team and organization PSFs has been provided by Bust (2008). Bocanete et al. (2007) categorized PSFs as external, internal and team related. They listed lack of communication, inappropriate task allocation and excessive authority gradient and over trusting as major categories of team PSFS. They focused on the relationship between team errors and PSFs and failures in team error recovery process.

The considerations for creating a dynamic HRA framework necessary for simulation have been highlighted by Boring (2006); he studied the use of MIDAS, a NASA design and analysis system in simulation and modeling of human contributions to risk in NPPs and listed major PSFs as available time, stress, stressors, complexity, experience, training, procedures, ergonomics, HMI (Human Machine Interface), fitness for duty and workspace.

Requirements and guidelines are provided by Mosleh et al. (2004) for the human reliability analysis methods that are used for probabilistic safety assessment of nuclear power plants. The training simulator for NPPs deficiencies has been investigated and those deficiencies have been identified via observation by Carvalho et al. (2006). The issue of simulation of human operator behavior and advanced knowledge-based systems powered by influencing factors for computer aided operator support system is studied by Takano et al. (2000).

Sasangohar et al. (2010) studied the sources of complexity in the control room and listed environmental, organizational, interface complexity, and cognitive complexity as the main categories. Mengzho et al. (1997) studied real operators at both experienced and less experienced levels and observed their response, actions and communication. They used a questionnaire for different scenarios to study effects of crew experience, stress and quality of interface and found operators training level, experience and cultural background to be the most effective factors.

The effect of the nature of team differences, their consistency and training implications on situation awareness is the subject of interest of Patrick et al. (2006); they used observational assessment of situation awareness, team differences and training implications and observed five teams in three scenarios using three observers. They listed planning, problem solving, team coordination, attention, communication and knowledge as the main factors contributing to building Situational Awareness (SA).

Patrick et al. (2009) examined different aspects of situation assessment for understanding, analyzing and developing it using existing observed data and literature. They categorized main team activities as to achieve and maintain SA, to decide over a course of action and to perform the action. They listed the reasons of failure to detect the information from system to be poor instrumentation, ineffective communication and cognitive fixation.

O’Conner et al. (2008) developed the nuclear team skills taxonomy with a focus on shared situation awareness, team focused decision making, communication, coordination and collaboration. Blackman et al. (2008) provided definition of a predefined set of PSFs and a method to quantify human error using those PSFs.

### 2.3.1 Communication inside Team

Hirotsu et al. (2001) reported that 25% of human error incidents in Japanese NPPs were due to communication failure. There is a significant body of research on the importance of communication inside a team and its effect on team performance. Most of such research used recorded data from real life control rooms in real or simulated situations. Lee et al. (2011) states that poor communication or communication error have been either a major or minor reason for incidents from 2001 to 2007 in NPPs in Korea (20 out of 27 cases). They present a qualitative and a quantitative method to analyze communication errors. They list communication errors, error modes and types with respect to timing, channel, contents, and sequence. They also classify possible causes as person, technology and organization related. They investigated the effect of these factors on communication by investigating a known failure scenario. Kolbe et al. (2009) provided taxonomy of coordination activities in the operating rooms (medical applications) and emphasized on the effects of “non-explicit communication” inside such environments. Strater {(2002), (1999)} realized that the importance of communication varies for different cognitive activities. His study is based on field data from actual control room operators. The researcher has divided the cognitive activities into six basic categories and has provided relative measures for importance of communication in each step. It has been found that the importance of communication is relatively high in activities such as coordinating, imagining, associating and identifying (Dietrich, 2004).

Park (2011) used a social network analysis technique to investigate crew communications in NPPs. The communication data of an operating crew under simulated off normal conditions were collected, analyzed, and compared with existing knowledge of communication characteristics from literature. The research results show that the amount of communication declines with respect to increase in the level of workload; however, in a good performance crew the amount of communication related to observation and announcement increases. The crew performance scores are proportioned to the levels of communication cohesion in the network.

Juhasez et al. (2011) studied the data available from a Hungarian NPP located in Paks along river Danube and empirical research on NPPs operating crews; they concluded that a high task load situation would increase communication. They linked team coherence to mental and cognitive processes. The importance of cooperation and stress management on communication quality is emphasized by this study using field observations and experiments as well. They provided an overview of IPO (Input-Process-Output) models for team performance and investigated the relationship of team assertiveness and team agreeability to communication and emphasized the importance of implicit communication in order to save resources.

Entin et al. (2001) used a variety of team-based measures to assess teams in simulation environments. They used observer and participants' quantitative assessments. They characterized and analyzed team performance using these measures. Their work is based on qualitative ratings mostly on communication aspects. Firth-Cozens (2004) studied the reasons that communication fails in control rooms and listed team instability, poor teamwork and organizational policies, and resources. They have also listed individual causes such as personality, authority, language and the amount of shared training and knowledge. Stachowski et al. (2009) compared the high performance crew with the low performance crew based the complexity of the interaction patterns. In their research, the higher performance group exhibited fewer interaction patterns and less complex interaction, fewer behaviors such as verbal communication and fewer actors and less back and forth communication.

A method is introduced by Petkov et al. (2004) to evaluate teamwork in accidents based on the concept of human performance shifts and is practiced using famous scenarios such as TMI and Chernobyl. However, the data sources that are used are very limited.  The communications within control room crews based on empirical data are analyzed and the study finds that operators use informal verbal exchanges (as opposed to procedural and formal communications) to solve plant problems and resolve conflicting goals in bringing stability to system performance.

Other field studies such as a study by Vicente et al. (2001) have emphasized that information obtained via communication with local operators is of great importance. Carvalho et al. (2006) analyzed the communication within control room crews in shift changeovers and in the form of verbal exchange to determine the role of such communications in providing resilience and stability in system operation. They investigated how cultural and cognitive issues related to the work of NPP's operators in control room impact plant safety. Carvalho et al. (2008) gathered empirical data from control rooms, using audio and video records, and investigated the content of their communication. They highlighted the criticality of verbal exchanges for the adequate use of written documents and showed that people deal with the non-compliance during the normal operation using porous communications to achieve a consensual coordination of actions and behaviors. Waller et al. (2004) conducted a study of 14 operators under simulators and examined effects of adaptive behavior and shared mental models on performance. They realized that group communication, when all team members are located in one room and engage in face-to-face communication, is more effective as they are more able to communicate verbally and non-verbally. The importance of implicit (nonverbal) communication was highlighted by their research.

### 2.3.2 Supervision & Leadership

The importance of supervision and leadership inside the operating team has been addressed and explored implicitly inside the existing literature on team performance shaping factors. Harrington et al. (1993) investigated the effect of team skill training on behavioral markers such as communication, feedback, conflict resolution, workload management and leadership with real operating crews and pilots using questionnaires and realized individuals show more positive attitude post training. One of their fundamental findings was that the NPPs operating crews believe that the responsibility for the safe operation rests more with Senior Reactor Operator (SRO) than with the crew.

Petkov et al. (2004) studied the performance evaluation method (PET), which uses two reliability models for cognitive processes and group communication. They used data from a full scope simulator of the NPP during training session for operator teams and compared them with PET algorithm. They highlighted the role of the supervisor as the center of the communication network inside the team of operators.

Carvalho et al. (2005) observed control crews in control room during simulator training and used post-scenario interviews to see how cultural and cognitive issues affect the performance. They noticed that the supervisor holds the ultimate responsibility for team activities in the eyes of rest of the crew and serves as the main communication channel for inside and outside activities. (They also recommended the use of a senior operator to help the supervisor with his tasks).

Brennen et al. (2007) studied the most appropriate team structure for the most effective performance; they used existing literature to derive theoretical concepts and formulated the concepts and implemented them by computer modeling. They listed monitoring, feedback and backup as main team activities. The result of their study shows that decreasing level of knowledge increases time to complete the task and engaging in positive team activities such as feedback decreases that time. Their conclusion was that the optimum case of knowledge distribution inside the team for highest performance is when the knowledge of the supervisor is the maximum.

Broberg et al. (2008) used the simulator experiment to investigate the effects of PSFs on operator performance in a NPP steam generator tube rupture scenario both quantitatively and qualitatively. They mention the shift supervisor leadership style as the major factor in qualitative evaluation of PSFs. Effective leadership style is defined as good situational awareness and quick responses without consultation, and is considered a driving factor to success or failure of team activities. However, they did not find any clear patterns in communication style of fast and slow groups and concluded that it cannot explain the differences in performance among crew behavior all by itself.

## 2.4 Team Performance

Theories directed at teams (small groups) provide different frameworks for addressing team behavior (Ilgen et al., 2004). Some researchers have used analytical and computational developments to handle more effectively the complexities of multilevel problems (Klein et al., 2000). There are also mathematical and computational models for aiding the understanding of organizational behavior in teams and other settings (Arrow et al., 2000), (Hulin et al., 2000) and (Losada 1999). These theories and methods provide a firm foundation for investigating team performance.

Sebok (2000) compared the effectiveness of interface design and staffing levels on various aspects of team performance in the control room. It was also revealed that NPP crew cognitive activities are strongly related to successful NPP safety performance, particularly for emergency situations. He found that the workload is higher in smaller groups and in conventional plants, the normal crews performed better than minimum sized groups with higher situational awareness and lower workload. However, advanced interface increased the workload of a team.

Petkov et al. (2004) studied safety investigation of team performance in accidents and developed a method based on well-known observed scenarios. The performance evaluation method (PET) had two reliability models for cognitive processes and group communication. They used data from a full scope simulator of the NPP during training sessions for operator teams and they compared these data using PET algorithm. They also emphasized the role of team supervisor as the center or communication model.

Boring et al. (2008) studied the effect of reduced staffing levels in advanced control rooms from a team performance perspective using simulations. Stachowski et al. (2009) focused on demographics & team effectiveness factors for evaluating team performance. They compared high and average-performing groups based on the complexity of their interaction patterns. They used exploratory study and investigated frequency and complexity of patterns. Better performing groups showed less systematic pattern for communication and less complex interaction with fewer actions.

Sasangohar et al. (2010) studied team interactions as one of the sources of complexity in advanced NPP's control rooms and developed a method to investigate their effect on performance levels. Smith et al. (2007) provided descriptive reviews of the methods and measures used for measuring task and mission performance in virtual environments. They considered measuring the individual performance, team performance and communication analysis.

Su Ha et al. (2007) considered plant performance, personnel task performance, situation awareness, workload, teamwork and psychological factors for the human performance evaluation and introduced measures in each category. Furta et al. (1999) constructed an operator model (OCCS) based on the conceptual model of human activities and a knowledge base and used simulation in order to evaluate the operator performance in three different layouts of control rooms.

Waller et al. (2004) conducted a study on a number of NPPs control crews as they faced routine and non-routine situations and found out that higher performance groups do a much better job in information collection and building the shared mental model as well as multi-tasking which is considered to be the reason for the better performance.

Lang et al. (2001) followed empirical investigation by Roth et al. (1994) and revealed that the NPP crew’s cognitive activities, which are the basis for crew performance, are strongly related to successful NPP safety performance, particularly for emergency situations. Flin et al. (2002) described the basic principles to enhance operational performance such as leadership, situation awareness, decision-making, teamwork and communications.

Paris et al. (2000) provided a summary of research on human performance in a team setting, to identify team level elements of success and to measure these characteristics. They specified three important factors in performance as team selection, task design and team training and summarized the most effective PSFs. They also provide a taxonomy for human performance measures.

Stanton et al. (2000) investigated the impacts of change in the company on system and team performance. Observing different teams at different stages of team development working in the same control room, they realized newer teams (with less experience as a team) engage in more sharing of information than older teams. They provided a summary of the approaches that use this framework and realized that the wheel network is the optimized type of communication for faster performance inside control room. However, it can be overloading for the person in the hub (center), which would lead to censoring and poor decision making. They also emphasized the importance of informal communication.

As mentioned earlier, Brennen et al. (2007) explored the most appropriate team structure for most effective performance; their conclusion was that the optimized case for knowledge distribution inside the team for highest performance is the knowledge of the supervisor.

### 2.4.1 Team Performance Models

Team performance has been the subject of study by many researchers, including Massaiu et al. (2011), Sasou et al. (1999), Kim et al. (2003), O'Conner et al. (2008), Helmreich et al. (1993), and Klein et al. (2010), who have studied. Many have developed taxonomies of Team PSFs as part of their approach. In this section the proposed models for performance evaluation are reviewed.

One of the most relevant of the current literature on crew performance is work done by Massaiu et al. (2011). They developed the Guidance-Expertise Model (GEM) to model NPP control room crews in emergency response situations. GEM introduces two cognitive control modes that the operating crew uses during emergency situations: 1) narrowing and 2) holistic. The control modes are affected by external PIFs, such as the quality of the emergency procedures, and internal PSFs, such as the quality of the crew's teamwork. The outcome behaviors are generic types of crew activity that typically impact the performance of tasks. Their research was conducted at the Halden Reactor Project[6] and the researchers used observations to derive a preliminary list of behavioral outcomes.

Sasou and Reason (1999) put the emphasis on team errors in their research and offered definitions of team errors and team error taxonomy. Four types of error are: independent individual errors, dependent individual errors, independent shared errors, and dependent shared errors. They defined three major error categories in a team context: Failure to detect, Failure to indicate, and Failure to correct. They reviewed events that occurred in the nuclear power industry, aviation industry and shipping industry and concluded the proposed definition and taxonomy were useful in categorizing team errors. The analysis also reveals that deficiencies in communication, resource/task management, and excessive authority gradient and excessive professional courtesy are likely causes of team errors.

Helmreich et al. (1993) developed a Crew Resource Management (CRM) program which is a training program created for the aviation industry that attempts to improve crew coordination and flight deck management. CRM is an input-process-output model, whereby inputs translate roughly into PSFs. Similarly, many of the process functions in the CRM model describe the nature and quality of the emergent psychological mechanisms of team performance, such as communications, team formation and leadership, planning, and coordination of tasking. In addition, Helmreich (1999) proposed an Error Threat Taxonomy to further characterize team or crew performance.

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[6] The Halden Reactor Project (Norway) provides facilities, crews, and expertise to collect and analyze simulator crew performance data.

Team Process Model by Pascual et al. (2001) has its origin in the team model concept by McGrath et al. (1994). The model consists of a series of input, team work processes and output variables. Input factors shape the way in which the team operates and the nature of teamwork required. Outcome factors are domain-specific and are measurable.

Boring (2008) discusses that that control room simulators do not offer the only effective way to gather data about crew performance and Simulation studies—involving virtual crews and virtual control rooms—offer an increasingly powerful way to predict crew performance. Additionally, he discusses that data collection tools such as the US NRC's Human Events Repository and Analysis (HERA) system are an effective way to evaluate human performance based on event reports. He recommends using a collection of methods such as research simulator studies, training simulator studies, control room simulations, and event reporting to create a powerful approach to understanding crew performance.

## *2.5 Summary of Findings*

This section highlights the issues identified by this research based on the review of related literature on modeling and investigation of team behavior, and describes the way this research addresses such issues.

The issue of group structure and functions has been ignored for a long time as the subject of systematic research except for the psychology context. However, experimental psychology has not systematically addressed important team related variables such as shared information and coordination. This research applies a systematic method to explicitly model team behavior and incorporate the effect of individual and team influencing factors on the operator and team errors. Individual operators' cognitive activities, team error management, communication and the causal influence of performance shaping factors are being explicitly modeled and integrated together as a single team model, and being investigated under different circumstances using simulation.

Many studies have explored systematic approaches to investigate team behavior in the context of high-risk environments using field studies and observational methods. Such methods have provided limited applications and are not reproducible. Since finding comparable groups is difficult, it is hard to verify and generalize the results. Theoretical approaches mostly aim to provide understanding of the work environment and taxonomies of performance shaping factors as well as their possible outcomes. The empirical work is only beginning to consider the implications of time in research designs. The real contributions of interpersonal relationships on team effectiveness and consequently on the entire system have not been fully and quantitatively addressed. Even though a number of researchers have developed HRA based techniques, only a few have been evaluated systematically. Considering the large amount of parameters and the required flexibility for configuration to obtain verifiable results, a systematic simulation approach to investigate team behavior is highly desirable. This research addresses such issues by using a simulation method to explore the complexities associated with the dynamics of the crew behavior with focus being on timing properties and error management activities.

Most of the research in the area of team PSFs is focused on classifying the factors and obtaining taxonomies rather than developing quantification methods to be used in simulation approaches. Such taxonomies consider the human operator vs. the hardware system, the situation and environment, the cognitive stressors and personal capabilities, the organization and the rest of operating crew. This research conducted a full study on the existing literature on individual and team PSFs and developed detailed causal models which have been used in quantification of human error probabilities.

Communication failure has been identified as have major contribution to incidents involving human error in NPPs. There is a significant body of research on the importance of communication inside teams and its effect on team performance. Most of such research has used recorded data from real life control rooms in real or simulated situations (Park, 2011). Some researchers have emphasized the effects of "non-explicit communication" inside environments such as control rooms and operating rooms in medical applications (Kolbe et al., 2009), ,however, this research did not model non-explicit communication inside control rooms. The effect of workload on communication inside teams has been studied by different researchers; however, the results are contradictory and differ for expert and non-expert teams. Some researchers (Stachowski et al., 2009) used the number of communication patterns and number of people involved as a measure for the complexity of team activities. This research has adapted the most popular idea from the existing research such as Stanton et al. (2000) and has used a star (wheel) communication network to pattern for operating crews. Furthermore the effects of device-based communication have been considered by this research in modeling the communication between operator located inside the plant and the control room crew.

The importance of supervision and leadership in the operating team not only has been discussed and explored implicitly in the existing literature by using associated PSFs, but also has been highlighted explicitly by some researchers such as Petkov et al. (2004) and Carvalho et al. (2005). They realized that the knowledge and the leadership style of the supervisor have significant impacts on team performance. Our work uses a case study and explores the effect of such factors on team performance as part of the model validation process.

There is a large body of research on team performance and contributing factors which has been fully studied by this research in order to collect a comprehensive set of those factors. Most of the existing team performance models are in the form of I-P-O (Input Process Output) models and define different performance measures such as number of goals achieved, number of completed actions, and timeline for those actions. This research used the response time and successful completion of tasks as team performance measure, and the same metrics were used comparison among different simulated teams.

# Chapter 3: The Fundamentals of the Crew Model

This chapter provides a high level view of the Crew Model from a conceptual perspective. To this end the basics of the model are reviewed and definitions for technical terms are provided. The origin of the model is introduced and related methods applied in this work are discussed. A review of the fundamentals applied for the simulation approach is provided at the end of this chapter.

## *3.1 Task-Oriented Teams*

Organizations are shifting toward team-based operations, which are based on the cooperation of people with different expertise and capabilities. Consequently, there is an increasing reliance on teams to respond to non-routine events in times of crisis. Team members work interdependently to accomplish goals and have the power to control at least part of their operations. Druckman et al. (1991) lists the general focus in studying teams as the team processes, organizational structures, and operating procedures that are required for optimal task performance. Teams, the tasks they accomplish, and the environment in which they operate are diverse, hence the problems associated with team performance and the means of solving those problems are specific to the task and work environment. Since this research is focused on the operating crew and the control room environment, team success is associated with the concept of "Task Completion". Such teams are considered "task-oriented" teams. Task-oriented teams have structured and interdependent relationships, interactions, and mutual influence (Levi, 2007). Figure 3 illustrates important features of task-oriented teams. Task oriented teams are composed of a group of people with the right level of knowledge, skills, abilities and authority, and necessary group process skills that are compatible with the task. The task should also be suitable for teamwork. The team must combine resources effectively to complete the task.

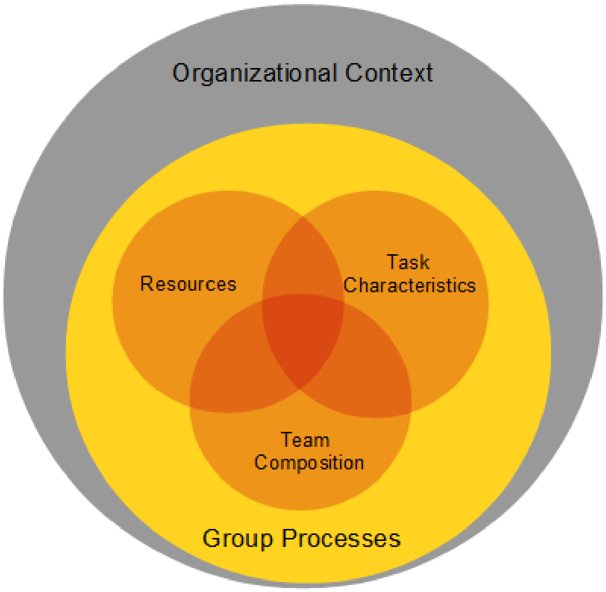

Figure 3: Task oriented teams

A successful team has clear directions and goals, appropriate leadership, suitable tasks, necessary resources to perform tasks, and organizational support. In addition to these factors, an open and supportive communication climate ensures emotional comfort and focus. The characteristics of quality group communication listed by Pattron et al. (2002) include: atmosphere of the group, clear objectives and acceptance of roles, reaching consensus (cohesion and conformity), and balanced power. In studying teams, the group size, level of group cohesion, trust and cooperation are important factors.

In evaluating team performance, both technical and non-technical skills of the members should be considered. Non-technical skills are defined as the cognitive "hard" and social "soft" skills of the team members. The cognitive "hard" skills are related to problem-solving activities,, and include professional knowledge, problem solving abilities and standard compliance. The social "soft" skills are team-relevant skills such as task load management, cooperation and communication (Juhasz et al., 2011). In general, team interaction involves "soft" skills such as motivation and leadership style in contrast to technical skills directly needed for the job at hand. Team interactions take place in form of discussion and interpretation, negotiation, and argument. Communication is essential to any team interaction and activity. It is through team interactions which involve "soft" skills (such as discussion and interpretation, negotiation, and argument), that shared mental models are developed.

### 3.1.1 Shared Mental Models

All team activities are centered on building a shared mental model. Building a shared mental model lowers the load of coordination activities. Under high workload conditions communication inside a team becomes very important. Shared mental model means the shared cognition and understanding of the current situation. "Shared contextual knowledge" and "shared situational awareness" are alternative terms used to describe the mutual knowledge and beliefs about the ongoing situation, knowing each other's goals, current and future activities and intentions. Team communication is essential in building a shared mental model, which in turn significantly lowers the load of coordination activities.

Team members are involved in information collection activities and collaborate to build a shared mental model that provides a mutual assessment of the system state. In addition team members use a consensual decision-making approach and agree on the solution for any emerged problem. Finally each team member is responsible for a part of the action course.

All these activities involve loads of communication and interaction among team members. Furthermore, since technical operating teams are usually led by a supervisor, all team activities are monitored and feedbacks are provided. Hence team members most likely face error recovery activities as well. These features are considered building blocks of the crew model developed in this research, while the basic ingredients of individual operator behavior of the proposed crew model are from the IDAC (Information, Decision, and Action in Crew context) cognitive model (Chang et al., 2007) and the scenario simulations follow typical DPRA methodologies.

## *3.2 IDAC Model*

Since the development of IDA (Information, Decision and Action) cognitive model and error taxonomy (Smidts et al., 1997), extensive research was conducted on this framework which ultimately resulted in full development of IDAC model in 2007 (Chang et al., 2007). IDAC (Figure 4) decomposes an operator's cognitive flow into three main processes: Information Processing, Decision Making, and Action Execution. IDAC model specifically targets domains with highly trained operators, and highly regulated and risky environments.

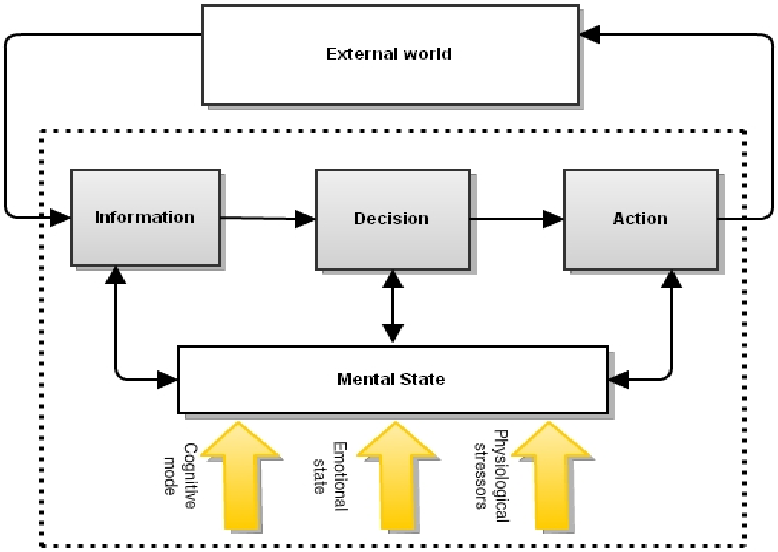

Figure 4: IDAC Framework

In IDAC, the crew is modeled as a team of individuals working on different assigned tasks and communicating with one another. The individuals differ by the content of their knowledge bases, by their mental state, and by the goals and strategies they employ (Coyne, 2009). In IDAC the major focus is on developing the a model of individual operators. The IDAC cognitive model has been applied as the underlying framework for individual operator's behavior in this research. The dynamic human response is derived from certain cognitive rules and physical and psychological factors that influence the behavior.

"Information processing" stage in IDAC model represents the limitations of human perception and refers to the operator's situational awareness of the external world. In "Decision-making" stage, the operator develops a situational assessment of the current plant state based on perceived information of the previous stage. In this stage, the operator uses the situational assessment to guide further activities and selects an appropriate problem-solving strategy. Therefore it includes diagnosis of the system state and selecting a proper action package. In the “Action execution” stage, the operator performs the action that is required. These processes are supported and influenced by the operator’s mental state (Coyne, 2009). The mental state is represented by a set of performance influencing factors and acts as an internal filter (Chang et al., 2007).

A typical control room is staffed by a group of four people: two operators, a foreman, and a shift supervisor. When a malfunction of any subsystem occurs, the control room crew is required to recognize that a malfunction is occurring, to work through the requisite diagnostics, and to take the necessary corrective actions; all of which need to be done in a limited amount of time through a number of interpersonal interactions. There are and step-by-step procedures to guide the operations through unfamiliar situations. Each member of the team has a different function, but the members are interdependent with respect to addressing the larger problem. The original form of IDAC introduced three roles inside the team: Operator-Decision Maker (ODM), Operator-Action Taker (OAT), and Operator-Consultant (OCT). ODM is the shift supervisor and the leader of the operating team. Figure 5 lists the roles of operators often considered in studying the operating crew behavior. These roles include: equipment operators, senior operator, shift supervisor and instructors.

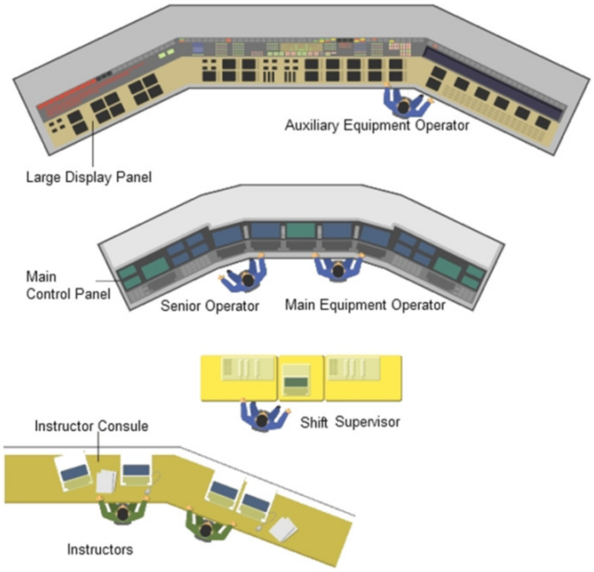

Figure 5: An example of NPP control room arrangement

### 3.3 Extended IDAC Framework

This research introduces “Extended IDAC” framework (Figure 6) to model operator activities in a team context. The model incorporates different aspects of teams and a number of theories on team dynamics into an integrated model of macro behavior. Extended IDAC summarizes team activities into three basic steps: “Collaborative Information Processing”, “Shared Decision Making” and “Distributed Action Execution”; all of which involve team interactions and generate a shared mental model, a consensual decision, and a coordinated action sequence at different stages. In this framework individual operators are modeled based on the IDA methodology while their activities follow Extended IDAC guidelines. Features of Extended IDAC can be summarized as:

- Extended IDAC is customized for teams. IDAC-based human cognitive processes are implemented and encapsulated as internal sequential processes in object models for each operator. The object models also include an underlying network of PSFs which characterize the way operator accomplishes tasks. Together they form the operational profile of the operator. These object models are then integrated together via communication model to develop the model for the operating team.

- In Extended IDAC there are three different categories of PSFs: Individual factors, Team factors and Organizational/Environmental factors. A combination of multiple factors through a mechanism of influence determines the availability of the operator and the probability of failure of operator's functions. Extended IDAC develops a "PSFs model" and applies it to calculate human error probabilities; it captures the effect of static PSFs as well as dynamic PSFs such as information load and time load.
- In Extended IDAC, individual cognitive activities are accomplished in parallel and independently by every team member and then merged through team dynamics.
- Extended IDAC adds another team member to the current IDAC configuration to explore the communication related factors such as the quality of communication device. The additional team member is an equipment operator who is located inside the plant (outside of the control room) and takes an Operator Action-Taker (OAT) role.
- In addition, since control room operations are all monitored by the shift supervisor, and the human errors are considered correctable inside the team, Extended IDAC introduces "Error Management" model and integrates this model into each step of team and individual activities.

Extended IDAC Framework and the development of the Error Management and PSFs models are fully reviewed in the next chapter. In order to better understand the capabilities of Extended IDAC, next sections provide detailed information on theoretical concepts such as team error management, team performance shaping factors, and object based modeling approach as the core model building method adopted in this research.

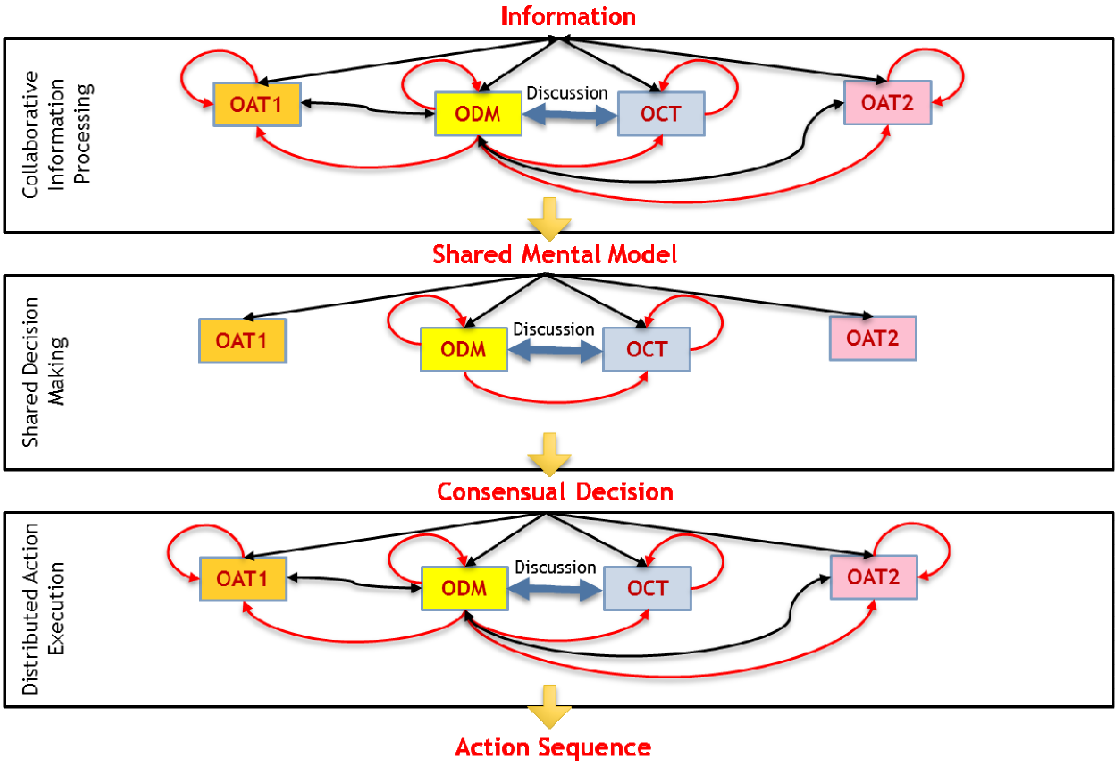

Figure 6: Team behavioral model in Extended IDAC

## 3.4 Team Error Management

Human errors have been embraced as the price of including human operators in technical systems and the focus has always been on dealing with the consequences of human errors. Most of the human errors which occur within the team of operators are usually caught and reversed or perhaps compensated. Rather than questioning the likelihood of error in a statistical sense, a more important issue to be addressed is the identification of factors that limit human ability to adapt to or change a situation. The rate of human error in design and operation is high, but a vast majority of such errors are reversible once the operator realizes his mistake, and only cost the operators in terms of wasted time. Hence, the recognition of human error and managing it is of great importance.

Figure 7 illustrates a general classification of human error. An error of Omission is to forget or not to perform a task or sub-task. In case of control room operators we define these errors as missed actions (human functions), e.g. operator missed the message. Error of Commission is doing the task incorrectly and in our case is related to errors of planning and execution. For control room operators, we define these errors as actions performed incorrectly with respect to timing, direction, sequence and object, e.g. operator pushed the wrong button.

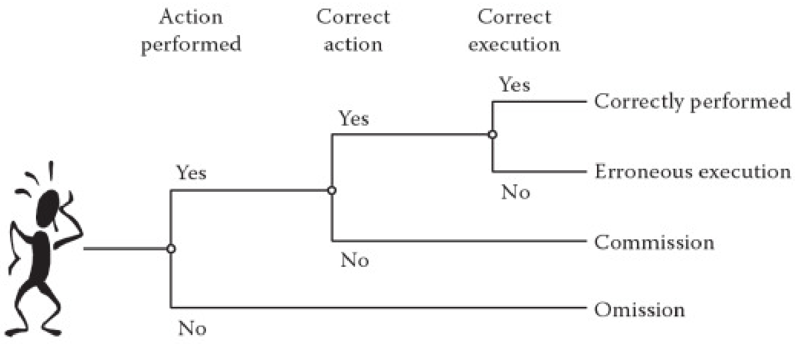

Figure 7: Errors of omission and Errors of commission

Sasou et al. (1999) proposed a model for error management inside a team structure (Figure 8). The goal was to develop definitions and error taxonomy and an analysis that determines the relationship between the team errors they defined and related PSFs. They listed deficiencies in communication, resource-task management, and excessive authority gradient as causes of team errors. Their study introduces three broad categories for human error from a team's perspective: Individual, Shared and Team errors;

- When an individual makes an error without the participation of any other team member it is called an individual error.
- Errors that are shared by some or all of the team members, regardless of whether or not they were in direct communication, are classified as shared errors.
- Team error is defined as human error made in group processes.

Since most human work is performed by teams rather than individuals, when other team members fail to indicate or correct individual or shared errors (despite being noticed), there may be influences of team factors and how the team members interact. Figure 8 provides details on the error management activities inside teams. These activities include: Error Detection, Error Indication and Error Correction.

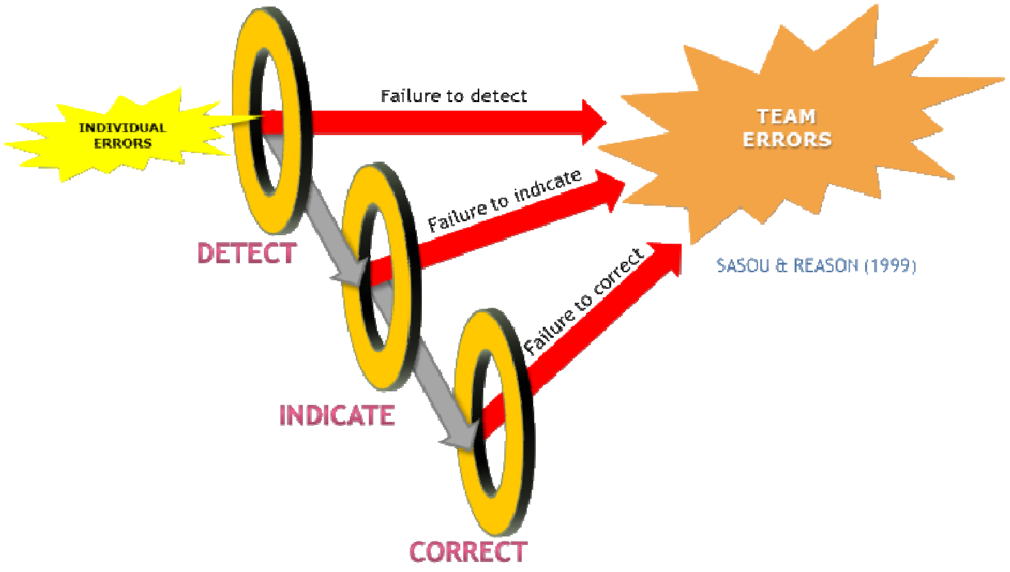

Figure 8: Sasou's model for Team error management (1999)

Based on this framework, three different categories of team errors are identified; "failure to detect" an error, "failure to indicate" the occurrence of an error to the rest of the team and "failure to correct" the error. Hence the first step in recovering errors is to detect their occurrence via self-review or peer-check process. If the remainder of the team does not notice errors, they will have no chance to correct them. Once detected, the recovery of an error will depend upon whether the team member who discovers it brings it to the attention of the rest of the team. This is the second barrier to team error making. An error that is detected but not indicated may remain uncorrected. The last barrier is the actual correction of errors. Even if the remainder of the team notices and indicates the errors, the errors remain unless actual steps are taken to correct them, by the person(s) who made the error or by those who discover it.

Figure 9: Monitoring, feedback and fixing together for error management

In general, team error handling process involves three different phases: “Monitoring”, and “Feedback”, as well as “Fixing and Backing up” (Figure 9). Monitoring is the process of tracking activities through watching and speaking or listening to colleagues. Feedback is when a team member offers an opinion and advice to a colleague. Fixing and backing up is when a team member intervenes to assist a colleague when the need for help is perceived. All of these phases involve communication in order to exchange information concerning the task and the control of the task (Brennen et al., 2007).

## *3.5 Team Performance*

### 3.5.1 Team Performance Shaping Factors

To achieve a quantitative estimate of the human error probability, most of the HRA (Human Reliability Analysis) methods utilize PSFs (PIFs[7] ) which are a collection of factors that represent different aspects of human performance. PSFs characterize the roots and facets of human error and provide a numerical basis for calculating the error probability (Smith et al., 2007). Modeling these PSFs along with the system allow

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[7] Performance Shaping Factors & Performance Influencing Factors are terms which can be used interchangeably.

simulation-based assignment of their levels, and help to obtain a more realistic model for simulation. However, to identify and quantify the PSFs is a highly subjective task.

While most of the influencing factors are designed to capture human performance at a specific point in time, there are factors that evolve over time and the consequence of their evolution needs to be considered by an appropriate dynamic approach. The former group is known as “Static PSFs”, and in most cases they are assumed to be nominal at the outset of a scenario. The latter group, known as “Dynamic PSFs”, however, is usually set initially for the scenario and their value is frequently changed as a result of change in the system state. Since this research aims to observe system behavior over time, the dynamic PSFs as well as the static PSFs need to be considered.

It should be noted that Team PSFs (TPSFs) are different from individual PSFs; Team PSFs are factors affecting the performance of a team and their subsequent effectiveness, arising from the fact that a group of people are working together in a team and on a common task; In contrast, individual PSFs are defined for each individual in general. For a team member, a new set of individual PSFs are defined which directly address the team-related aspects of individual characteristics. Examples are “Training for the role” and “Motivation for the role”.

As discussed earlier, existing research on PSFs mostly is in the form of taxonomies. Researchers such as Hendrickson et al. (2010), Groth et al. (2009), Bust (2008), Dawson (2007) and O’Hara et al. (2004), consider the human operator vs. the hardware system, the situation and environment, the cognitive stressors and personal capabilities, the organization and the rest of operating crew in order to categorize PSFs. Depending on the specific scenarios that are being simulated and the nature of the system under study, usually a subset of PSFs are modeled and applied (Patrick et al., 2006), (O'Hara et al., 2004) and (Mengzhuo et al., 1997). Since model developed in this research is inspired by NPP operating crews and their team failure modes, the applicable set of PSFs have been addressed by research on existing literature in the nuclear power HRA domain.

Among individual PSFs, stress, attention, task complexity, availability of information, the quality of interface, the person's experience/training, and time pressure (time constraint) have been research spotlights (Boring, 2006), (Mengzhuo et al., 1997), (Bust, 2008), (Hendrickson et al., 2010). Clearly defined roles and duties, standard communication structure and protocols, and the quality of procedures and leadership have been of great interest in existing research in this domain (Bust, 2008), (Hendrickson et al., 2010), (Groth et al., 2009).

Although the number of group members is intuitively a very important factor, it is not been mentioned to have a significant difference, perhaps because the size of an operating team is usually the same in most cases (Bust 2008).

The quality of verbal communications has been found to make a significant difference in providing resilience and stability in system operation as it affects knowledge sharing, problem solving, selection of goals and action processes by Carvalho et al. (2008) and Patrick et al. (2006). The importance of communication, cooperation and stress management on communication quality is emphasized by Juhasz et al. (2007)

using observational experiments. Since communication is essential to any team activity, one of the most common team PSFs is “Deficiency in Communication”. An observational method has been applied in the study by Patrick et al. (2006) where the effects of quality of communication and the team coordination have been studied in particular. Other field studies have shown that in addition to the control room indicators and alarms, the information obtained via communication with local operators has a major impact on the quality of operator actions (Vicente et al., 2001), (Mumaw et al., 2000) and (Vicente et al., 1998).

Bust (2008), Dietrich et al. (2004), and Starter et al. (2002) realized that the importance of communication varies for different cognitive activities. They have found that the importance of communication is relatively high in activities like coordinating, imagining, associating and identifying. Firth-cozens (2004) lists team instability, poor teamwork and organizational policies and resources as reasons for communication failure in teams; in addition, individual causes such as personality, authority, language and the amount of shared training and knowledge. Many of the recent studies such as Groth (2009), Carvalho et al. (2008), Dawson (2007), Patrick et al. (2006), Boring (2006), O’Hara et al. (2004 ) and Kim et al. (2003) are dedicated to the study of systematic construction of PSF sets for NPP HRAs. All of these studies have mentioned team cohesion, coordination and cooperation, and communication quality as the most notable Team PSFs.

This research follows the guidelines and high level classification proposed by Groth et al. (2009) (Figure 10) for major categories of TPSFs and expands the level of details for those factors using the existing literature. These categories include: Team

Cohesion, Role-Awareness, Team Coordination, Communication and Direct Supervision. Details of the team PSFs model proposed by this research is discussed in Chapter 4.

#### 3.5.1.1. Communication

Communication refers to the ability of team members to pass information to each other (Groth, 2009). Communication can be verbal, non-verbal, and device-based or via writing. Communication assists team members to build knowledge of a shared situation. It is often considered from two perspectives: Communication Availability and Communication Quality, meaning that no information is passed from sender to receiver, or the information passed is less than adequate, or miscommunicated. Communication is related to the Information Availability. The availability of information could be directly caused by less than adequate communication; however other organizational factors may interfere.

#### 3.5.1.2 Direct Supervision

Direct Supervision serves as the link between management and the team members. Often direct supervision and management are collectively referred to as leadership (Paris et al., 2000). In this research, direct supervision and leadership terms are used interchangeably since the supervisor plays the role of the team leader. The direct supervisor is a member of the team with additional authority and responsibility and has a key role in the team. The supervisor has the dual responsibility of setting goals for the group and also working with group members to accomplish these goals (Groth, 2009).

Figure 10: Major categories of team PSFs

### 3.5.1.3 Team Coordination

Team Coordination refers to the overall interactions of the team, including distribution of responsibilities and ability to work as a unit (Barnes et al., 2001). Communication and Direct Supervision can be considered as aspects of Team Coordination, but Team Coordination also involves additional factors that contribute to overall team performance. This includes planning and scheduling on the team level and decisions made during team discussions (Groth, 2009). Poor communication and other factors such as lack of knowledge and poor teamwork could be responsible for the poor coordination.

### 3.5.1.4 Team Cohesion

Team Cohesion refers to the way that team members interact with each other (Hoegel et al., 2001). Groth (2009) mentioned that team cohesion has been referred to as group morale, interpersonal attraction and team compatibility. Team cohesion is closely related to most of other team PSFs such as coordination; less cohesive teams are more likely to have less effective in coordination. Team Cohesion includes group morale and group attitude toward the task. Mullen et al. (1994) provide the characteristics of cohesive teams as interpersonal attraction of team members, commitment to the team task, and group pride and team spirit.

### 3.5.1.5 Role Awareness

The distribution of roles and responsibilities is very important in a team. How each team member perceives his/her duties, responsibilities, and role as a team member is called Role Awareness and is a critical factor in team performance. It is related to how the team divides tasks and how team members interact (Paris et al., 2000). Role Awareness requires workers to be aware of their place in the team and to act according to the expectations of the role (Groth, 2009). Operators in NPPs have defined roles; the compliance of each operator to the expectations of his/her role is mandatory. Groth (2009) distinguished two main functions of Role Awareness: to ensure that tasks are completed and to enhance team coordination. In order to reduce conflict inside the team and ensure the completion of all tasks, proper role awareness for all members including the leader is necessary.

Since factors such as team cohesiveness and role awareness are necessary for almost every team activity, team PSFs are considered to be interdependent by this research. This interdependency has been captured using a hierarchy of factors and will be discussed in Chapter 4. Figure 11 illustrates the visualization of this interdependency.

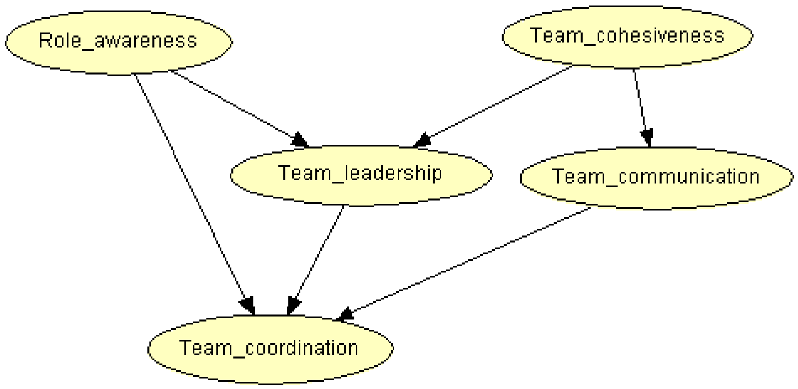

Figure 11: Team PSFs are interdependent

The development of a causal map offers a way of highlighting both the complexity within and the interconnection between the Team PSFs, in terms of their influence on each other. Causal maps highlight the relationships between team factors and the path of influence; hence it can be clearly seen that altering one factor will have an impact on others. Causal maps are modeled using Bayesian Belief Networks (BBNs)[8]. The performance of the team can be further characterized using the following classification of team factors:

- Internal Team PSFs
- External Team PSFs

Internal team PSFs include factors that are related to: Task and situation (such as Cognitive load, Perceived workload, Work shift), Personal technical skills (such as Problem solving), Personal social skills (such as Communication), Team operational skills (such as Decision making), Team generic skills (such as Coordination), Team soft skills (such as Negotiation), Team structure (such as Goals) and Team roles (such as Leadership). On the contrary, External team PSFs are factors that are related to

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[8] A Bayesian belief network (BBN) is a directed graph, together with an associated set of probability tables. Such networks are based on conditional probabilities to model causal uncertainty.

environment / workspace (including physical, social environment, and working conditions), and Organization (including organizational operations, atmosphere, work content and instability). Team PSF Model in Extended IDAC and the quantification process are discussed in details in Chapter 4.

### 3.5.2 Team Performance Model

Most of the team performance models in the literature are in the form of Input/Process/Output (IPO) models. The IPO model posits that a variety of inputs are combined to influence processes, which in turn affect team outputs (Juhasz et al., 2011). Figure 12 illustrates a typical IPO model, which consists of:

- Inputs: Individual, team related, task related and organizational factors
- Processes: Team working and team activities
- Outputs: Team performance and outcomes

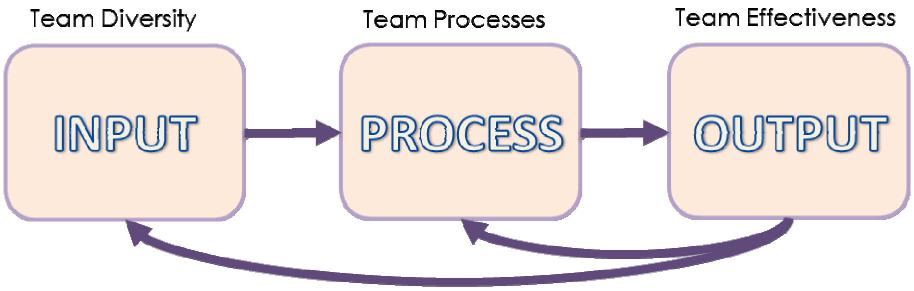
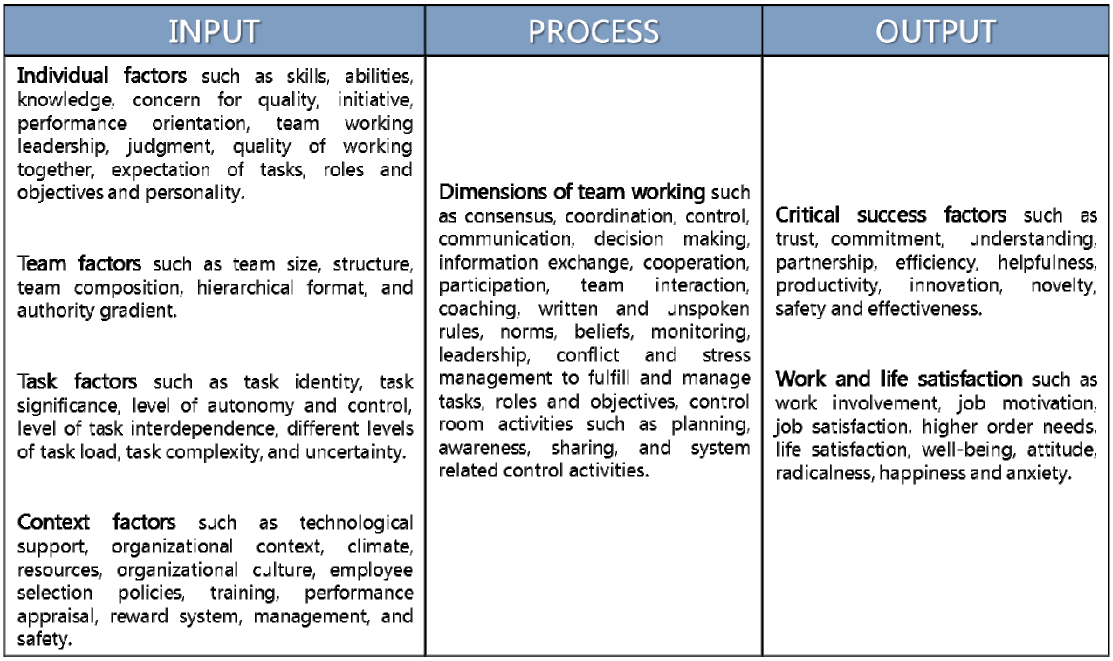


Figure 12: Typical IPO model

Table 1 lists examples of inputs, processes and outputs of the IPO model. Inputs are classified as individual factors such as personality, attributes, skills, knowledge and abilities, team-related factors such as team size, team structure and team composition, task-related factors such as task significance and complexity and context-related factors such as support, resources and culture (Juhasz et al., 2011). In the case of NPP operator teams, the emphasis is on the team members' professional knowledge, although the team members need to possess social skills and abilities for teamwork. Task characteristics are considered as: level of autonomy and control; level of task interdependence; different levels of task load, task complexity, and uncertainty. The different levels of task load that control room operators are faced with require a continuous behavioral adaptation from the team members. The organizational factors are organizational culture, training, performance appraisal, and reward system. In a NPP environment safety is the key concept and is the main focus of any organizational factor.

Intergroup processes refer to interactions that take place among the team members and include conflict, efforts toward leadership and those communication patterns that differentiate teams from each other (Juhasz et al., 2011). Each team has its own communication style depending on the environment they are working in. "Team Processes" are basically different dimensions of team working; hence consensus, coordination, decision-making, information exchange, cooperation, participation, monitoring, conflict and stress management, and control room activities are all considered as team processes. For NPPs operating crew process variables include all the written and unspoken rules, norms, and beliefs.

Table 1: IPO factors for teams extracted from existing literature



| INPUT | PROCESS | OUTPUT |
|---|---|---|
| **Individual factors** such as skills, abilities, knowledge, concern for quality, initiative, performance orientation, team working leadership, judgment, quality of working together, expectation of tasks, roles and objectives and personality.<br>**Team factors** such as team size, structure, team composition, hierarchical format, and authority gradient.<br>**Task factors** such as task identity, task significance, level of autonomy and control, level of task interdependence, different levels of task load, task complexity, and uncertainty.<br>**Context factors** such as technological support, organizational context, climate, resources, organizational culture, employee selection policies, training, performance appraisal, reward system, management, and safety. | **Dimensions of team working** such as consensus, coordination, control, communication, decision making, information exchange, cooperation, participation, team interaction, coaching, written and unspoken rules, norms, beliefs, monitoring, leadership, conflict and stress management to fulfill and manage tasks, roles and objectives, control room activities such as planning, awareness, sharing, and system related control activities. | **Critical success factors** such as trust, commitment, understanding, partnership, efficiency, helpfulness, productivity, innovation, novelty, safety and effectiveness.<br>**Work and life satisfaction** such as work involvement, job motivation, job satisfaction, higher order needs, life satisfaction, well-being, attitude, radicalness, happiness and anxiety. |

Team output refers to team outcomes associated with productivity, and performance as well as capability of team members to continue the work cooperatively (Juhasz et al., 2009). Examples of outputs in team performance model include critical success factors such as trust, commitment, efficiency, productivity, and innovation; work and life satisfaction factors such as work involvement, job motivation, life satisfaction, well-being, and happiness. Output variables are the quantitative and qualitative aspects of team performance, effectiveness, efficiency, productivity, team members' satisfaction, wellbeing, and commitment. The current and the future performances predict the capability whether the team continues to work together as a unit or not. The most important measure of team effectiveness is the current performance assessment of the team, which is based on either supervisor ratings of team productivity or objective indicators of team quantity and quality of productivity.

### 3.5.3 Performance Measurement

A number of performance measures (calculated per unit of time) are introduced by Smith et al. (2007) and Entin et al. (2001), which reflect the quantity, directionality, timing and type of such processes. Some examples of these measures include measures for quality of team communication such as number of requests and transmissions of information per unit of time, number of requests for information-action per unit of time, frequency and complexity of interaction patterns that are used for sharing knowledge, directing attention, and determining next step, with respect to the number of team members that are involved and number of communication loops.

The performance measures on team outcomes include: Accuracy of performance which usually considers the number of goals achieved, Timeline for action including the time to initiate and the time to complete important tasks, Number of errors (with respect to timing, sequence, and taking inappropriate or unnecessary actions) and Deviation in system parameters. Among these measures, Accuracy of team actions (with respect to timing, sequence, and taking inappropriate or unnecessary actions) and Time for action completion have been used in this research.

## *3.6 Simulation Approach*

### 3.6.1 Simulation-Based Human Reliability Analysis (HRA)

Among the advantages of using simulation studies is the possibility to adjust and change parameters repeatedly according to the aim of the researcher. Since this study is focused on the investigation of team behavior and interactions in the specific domain of a NPP, the application of simulation methods in human reliability analysis is of great interest. Figure 13 illustrates a combined HRA approach. Qualitative HRA is focused on the identification of the human error and its contributors and is usually the result of task analysis or incident investigation while quantitative HRA is focused on translating identified event or error into a Human Error Probability (HEP). Qualitative and quantitative HRA are complementary however not all of the events are always well enough understood to be quantified. The ultimate purpose of the majority of human reliability analysis methods is to identify human responses and errors, estimate the response probabilities, and identify causes of errors to support development of preventive or mitigating measures (Kirwan, 1994).

Figure 13: HRA approach

In order to achieve such goals, these methods need to apply a systematic procedure for generating reproducible results, based on human cognitive and behavioral processes. A set of performance shaping factors and a structure that provides traceable links between its input and output forms a model; but no model is credible without real data, thus reliable sources of data should be available (Mosleh et al., 2004). The application of computer simulation is necessary to support the study of time-dependent behavior of performance influencing factors. Computer simulations provide more precise and detailed information on scenario evolution and context for human response and explore a wider range of accident conditions. Since communication is considered to be a relevant factor for managing abnormal events in

NPPs, the empirical studies of such situations can best be carried out by analyses of carefully chosen simulator sessions.

### 3.6.2 Dynamic Probabilistic Risk Assessment

In practice, risk assessment is performed by first identifying how a system might deviate from its intended performance, second deciding how probable these deviations are, and third determining what the consequences of these deviations might be (Kaplan et al., 2001). Dynamic PRA basically involves the simulation of dynamic behavior of the system by using models of system elements and rules of their external and internal interactions. Simulation-based DPRA focuses on the influence of time and process dynamics on risk scenarios. DPRA methods are created and designed in order to study complex and dynamic systems (Chang, 1999). The goal is to generate scenarios involving the failure of a combination of subsystem and components with different nature by using simulation. Before studying a technical system, it has to be described and formalized. Hence, obtaining a formal representation of the system and its behavior is an essential part of any DPRA approach. Figure 14 shows the essential parts of any model-based simulation approach. The formal representation of the system consists of models of its elements and the model of system dynamics. The simulation controller is responsible for actuating accident initiating events and different failures as well as setting up sequence termination criteria. Based on simulation results, the influence of time and process dynamics are investigated on risk scenarios. Probability estimation and consequence determination processes are affected by the influence of the dynamics of the system on the failure rates and failure mechanisms of the components of the system.

Dynamic event-based systems evolve in time by the occurrence of events at possibly unknown irregular time intervals. These systems are modeled using discrete events which cause the system to change from one state to another. Stochastic events are time based or demand based. For time-based events, the timing of the occurrences of the events is random, following a probability density function of the time of occurrence of events. For demand-based events, the outcomes of that point of time are random, with a probability of occurrence of each set of outcomes.

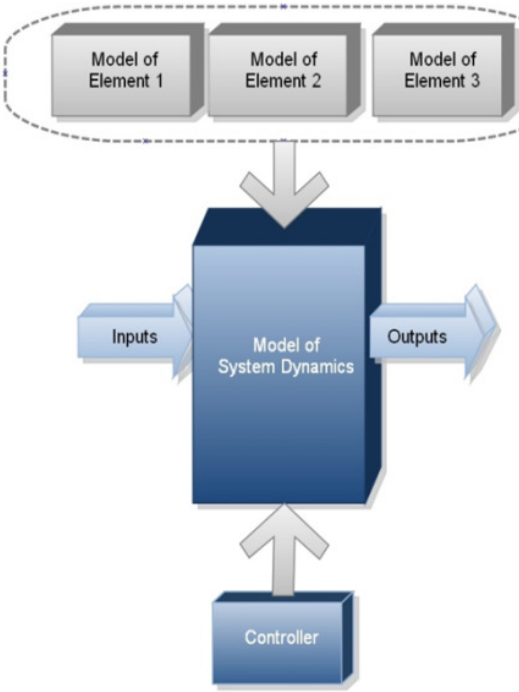


Figure 14: Model-based simulation

The idea is to dynamically change the states of various subsystems, components and operators' responses within the system and generate possible time dependent scenarios. Discrete-event simulation models typically have stochastic components that mimic the probabilistic nature of the system under consideration. In this research such events are mostly demand-based events.

The simulation algorithm generates a dynamic event tree based on the simulation model and the predefined branch points. The accident scenarios are created once certain conditions are met and associated branching points are activated. Each branching point includes two or more individual event branches, each of which represents distinct combinations of system and operator states. Once a system end-state is reached the scenario ends. Branch points in the simulation model are associated with the error reference points and the lowest level of functions for each simulated module. At each time step some of the branch points are triggered, modifying the generated scenario. Together, the branch points describe the topology of a DDET which is associated with an initiating event. A specific accident sequence is defined by the unique path through the DDET branching points from the initiating event to an end state. Model based simulation techniques are becoming popular in system risk analysis. However, most of the existing representation languages are limited in scope and application. For instance, conventional methods and tools for DPRA do not fully account for the risk involved with the interpersonal relationships of the operating crew in the context of a complex system. New features need to be integrated into existing DPRA approaches in order to model the dynamics of such interactions and investigate their contribution to the entire system's risk profile. To this end, this research chooses to apply an object-based modeling methodology for representation of different system components. This methodology is discussed in Chapter 4.

## *3.7 Features of Proposed Model in Comparison with Other Models of Team Behavior*

In this section a summary of existing models of team behavior is provided and their characteristics and features are discussed and compared and contrasted against the team behavior model developed in this research. The models are discussed under two categories: Theoretical Models and Simulation Methods.

### 3.7.1 Theoretical Models: Team Cognition Models

#### 3.7.1.1 Macro-cognition Model

Letsky and his colleagues (Letsky et al., 2007) introduced a "macro-cognition" model for team collaboration. The model was introduced for military applications. It identified macro-cognitive processes as: asynchronous, distributed, multi-cultural, and hierarchical (Figure 15). The model includes four major team collaboration stages (knowledge construction, collaborative team problem solving, team consensus, and outcome evaluation and revision). The conceptual aspects of this model are helpful in developing a NPP-specific model for team behavior; however since nuclear power operations are highly regulated and are strongly governed by procedures, not all of the decision making aspects provided in this model may apply. This model has strong theoretical ties to the psychological literature. This model has roots in four general categories of research: externalized cognition, team cognition, group communication and problem solving, and collaborative learning and adaptation; i.e. how and why a team uses tools and decision aids such as procedures or computers to help solving complex problem. This model provides guidelines on how teams use technology to assist in their coordination and generate a common understanding of the situation, task, and/or problem; how team dynamics and group processes can affect the assumptions team makes about the situation, tasks, and problem space; and finally, how teams work together to create new knowledge.

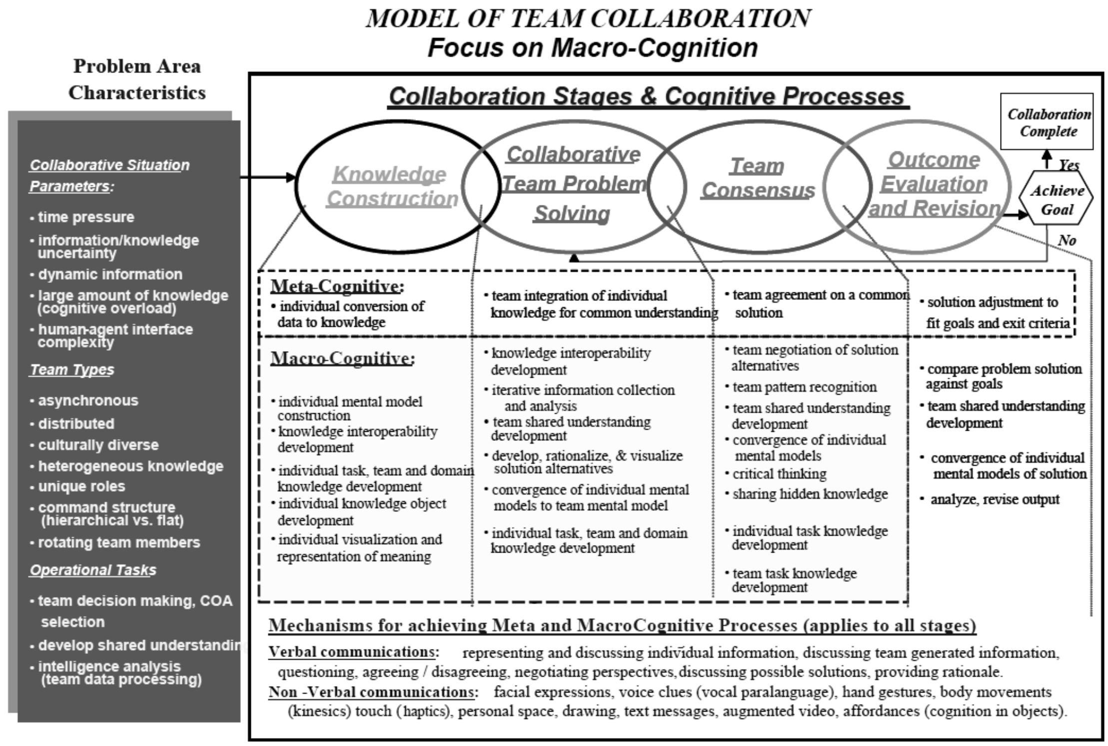


Figure 15: Macro-cognitive model of team collaboration (Letsky et al., 2007)

### 3.7.1.2 Macro-cognitive Function Model

Klein et al. (2003) has presented an initial set of primary macro-cognitive functions and supporting macro-cognitive processes that are used as means for achieving the primary functions. The macro-cognitive functions include: Naturalistic decision making, Situation assessment, Planning, Adaptation/Re-planning, Problem detection and Coordination. The focus of their research is to encourage research at the macro-cognitive level rather than to introduce a complete, validated list. In Figure16, the blocks in the middle represent the macro-cognitive functions, while the items in the surrounding circle represent the macro-cognitive processes that support the functions.

All of these processes are supposed to be shared by all of the functions. Therefore, these functions and processes work together in a continuous loop. This model has been used as a starting place and was adapted for a specific domain of Space Shuttle missions.

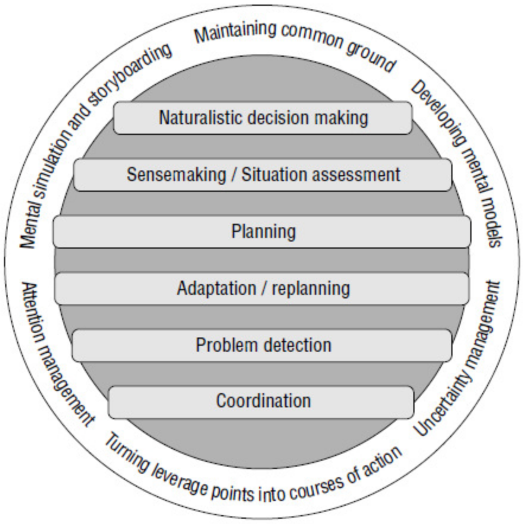


Figure 16: Macro-cognitive functions for individuals & teams (Klein et al., 2003)

### 3.7.1.3 A Macro-cognitive Model for NPP Control Room Operations

John O'Hara and his colleagues developed a generic NPP operator performance characterization that has been applied in some of the NRC HFE guidance development efforts (O'Hara et al., 2008). This model describes the basic categories of operator activities to accomplish control room tasks. O'Hara referred to these categories as generic operator tasks. According to O'Hara, operators perform two types of tasks: primary tasks and secondary tasks. Primary tasks (Figure 17) include activities such as monitoring plant parameters, following procedures, responding to alarms, and operating equipment (e.g., starting pumps and aligning valves). The secondary tasks of interest are "interface management tasks." Figure 17 is a diagram of O'Hara's model.

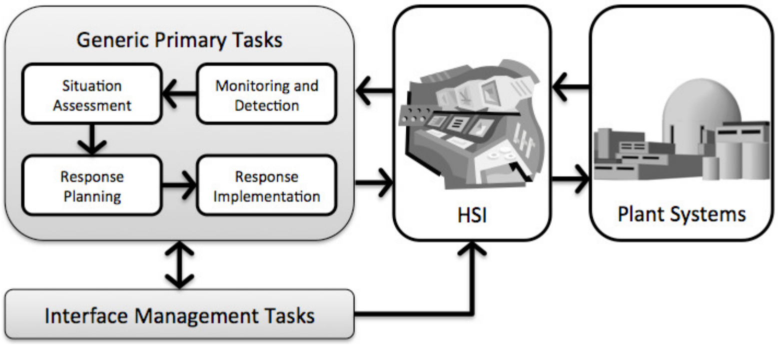


Figure 17: Cognitive model of control room operations by O'Hara et al. (2008)

Monitoring/Detection, Situation assessment, Decision and planning, Action implementation; this is different from Klein's view that the cognitive process can start from anywhere of the loop. This difference may reflect a fundamental difference between the NPP and aviation/military operations: NPP operations are procedure-driven; therefore, human responses to events typically begin with monitoring/detection; and aviation and military operations are often driven by goals or missions, thus operational personnel can begin their cognitive activities by first making a decision or plan then seeking information to refine the decision/plan.

### 3.7.1.4 Summary of Observations

Among all the macro-cognitive models discussed here, Extended IDAC framework has some shared features with the Macro-cognitive model of team collaboration introduced by Letsky et al. (2007). In team macro-cognition model, each member of the team is involved in their own independent process of collecting data in parallel and converting that data into information. These parallel individual processes, called “individual knowledge building processes”, merge together and become the “team knowledge building processes”. Different stages of macro-cognitive model of team collaboration, i.e., Knowledge Construction, Collaborative Team Problem Solving, Team Consensus, Outcome Evaluation and Revision are similar to the stages of our proposed model; however, this model is a conceptual model with many psychological details, with a scope is limited to military applications. Hence it is hard to use it as a general purpose model. In addition, the last stage of this model is focused on building new knowledge and team learning instead of error management, which is an important feature of our proposed model.

## 3.7.2 Theoretical Models: Team Performance Models

### 3.7.2.1 Crew Resource Management by Helmreich ( 1999)

Crew Resource Management (CRM) is a model and training program created for the aviation industry that attempts to improve crew coordination and flight deck management (Helmreich, 1999). It focuses on team and managerial aspects of flight operations. CRM attempts to optimize the person-machine interface and execute a timely and appropriate action. In addition this model takes into account interpersonal activities such as leadership, effective team construction and maintenance, problem-solving, decision-making, and maintaining situational awareness. CRM is an input-process-output model, in this model inputs are characteristics of individuals, groups, and the organizational/operational environment that affect the performance of the team. Many of the factors identified for this model are relevant to NPP crew performance, and translate into PSFs. CRM identifies group composition, organizational culture, and regulatory requirements as “crew performance input factors" as PSFs that can affect crew performance. Group composition means the type of people that are working together in a team and their level of skill and experience. Similarly, many of the "crew and mission performance functions" in the CRM model consider "team processes" such as communication skills, leadership, planning, prioritization, and coordination of tasking. Figure 18, shows some of PSFs that have been identified by CRM. CRM model is similar to our proposed model since it is in the form of an Input-Process-Output model and the model is focused on team aspects such as communication and leadership.

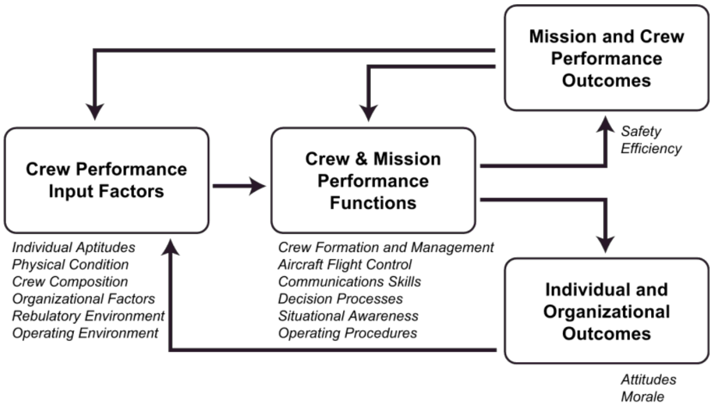


Figure 18: CRM model and the influencing factors, (Helmreich et al., 1999)

### 3.7.2.2 Model of Team Effectiveness by Shanahan (2001)

Shanahan (2001) developed this model which has four main elements: Process, Inputs, Outputs and Structure. Process has been considered to be the heart of this model. A dynamic set of demands and a set of resources such as information and platforms are input to processes. The process uses resources to handle demands. Outputs collectively determine team performance and team effectiveness based on mission objectives. Process is divided into three parts (Figure 19): task work, teamwork and leadership. It is the primary function of task work to turn inputs into outputs (team performance). Particular task work responsibilities are defined for each member in the team. The quality of task work is influenced by teamwork, and team leadership. The overall process is influenced by a variety of structural factors. These are physical resources (e.g., technical equipment, workspaces, buildings) or the results of prior organizational processes (e.g., selection, training, and planning) (Essens, 2005). These factors are assigned properly to cover the teamwork and leadership dimensions. Team effectiveness is measured through comparing team performance with the initial objectives of the team mission.

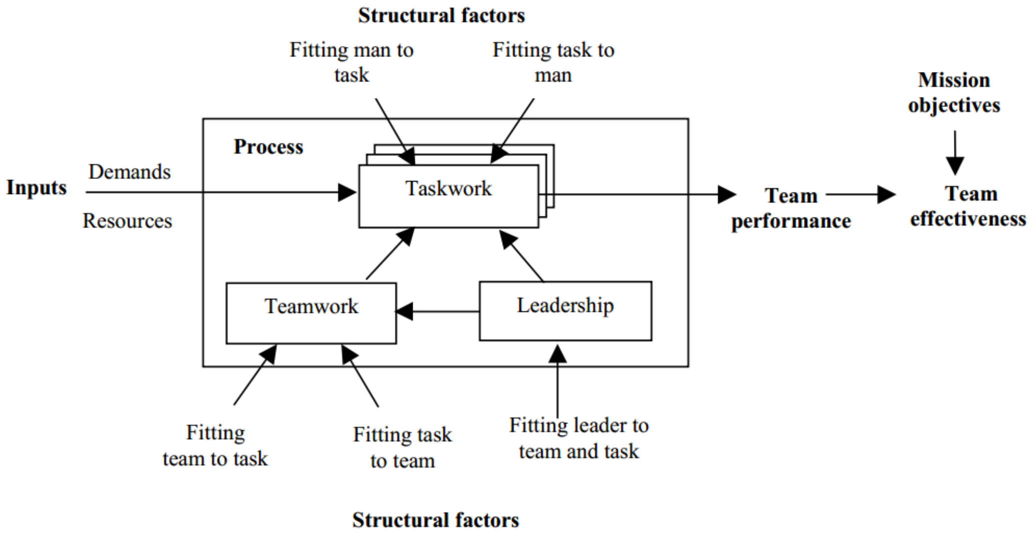


Figure 19: Level model of team effectiveness, Shanahan (2001)

### 3.7.2.3 Team Process Model by Rasker et al. (2001)

This model proposed by Rasker et al. (2001) defines team effectiveness as the predefined concepts such as accuracy, timeliness, and the extent to which the goals are satisfied (Figure 20). The process criteria such as motivation and satisfaction are also considered to be important indicators of effectiveness. The operational context of the team is defined by five factors; a set of specific variables defines these concepts.

Situational factors are factors imposed on the team from the outside world (e.g., uncertainty of the task, and time stress). Organizational factors are variables outside of the team which provide both direction and limitations on the functional abilities of the team (e.g., objectives, reward systems, support, and rules). Task factors (e.g., complexity, structure, interdependency, and load) are those factors that comprise what the team must do to achieve their goals (Essens, 2005). The final two factors represent the human elements of the model both at the team (e.g., size, structure, cohesion, leadership, composition) and individual level (i.e., knowledge, skills, and attitudes). Teamwork has two kinds of behavioral aspects: task-related activities and team-related activities. Task activities include all of those individual behaviors directly related to the job at hand. Team activities include all of those behaviors which help to strengthen the quality of functional cooperation aspects of team members (e.g., communication and coordination).

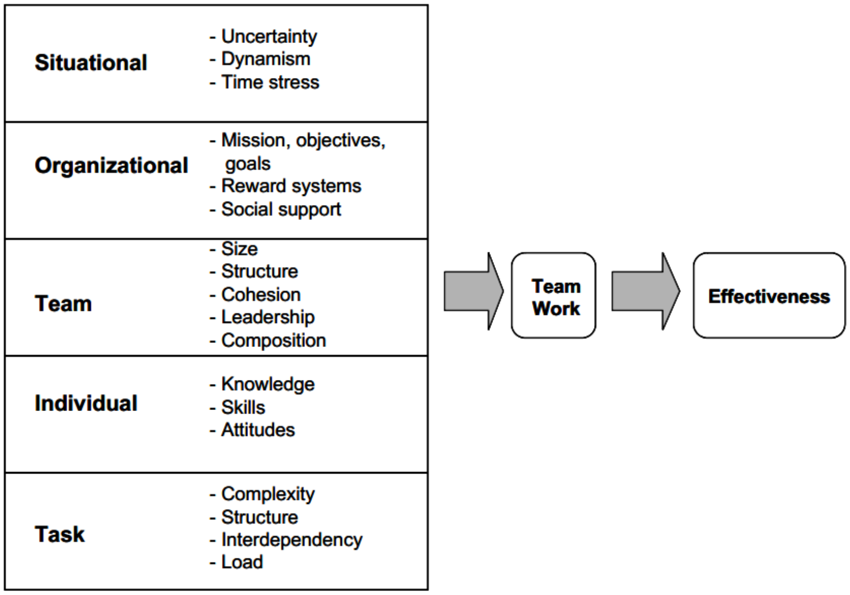


Figure 20: Team Process Model by Rasker et al. (2001)

### 3.7.2.4 Team Process Model by Blendell et al. (2001)

This model was introduced as the result of a ‘Workshop on Team Modeling’ conducted at TNO[9] Human Factors, in the Netherlands (Essens, 2005). The basic objective of the workshop was to communicate and develop modeling concepts for understanding the effects of team organization and interaction. The input factors of this model (e.g., leadership style, experience, team composition, etc.) impact, or influence the process factors that are within the team, and the process factors in turn, impact the activities conducted by the team i.e., the output factors (e.g., team satisfaction, error rates, etc.). in this model (Figure 21) the emphasis is placed on the process factors that occur within the team (i.e., Knowledge, Leadership, Behaviors and Attitudes) and the identified input factors and output factors have been provided as examples and do not follow a specific structure (e.g., individual characteristics, environment, etc.).

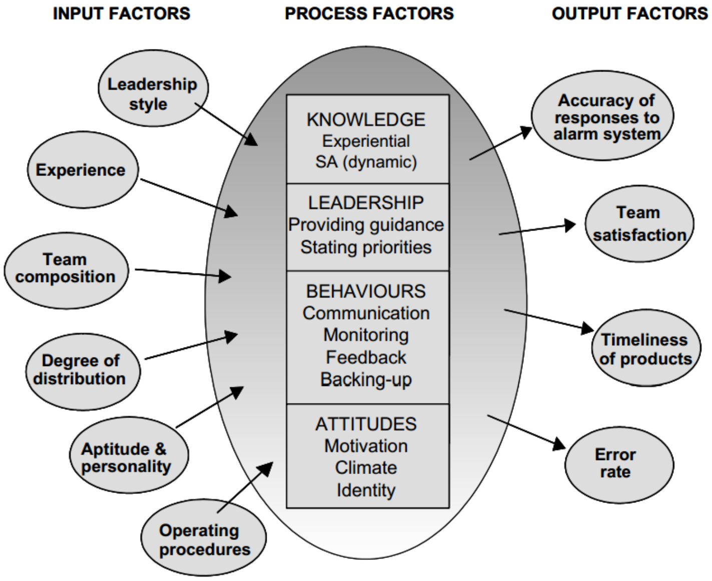


Figure 21: Team Process Model by Blendell et al. (2001)

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[9] Netherlands Organization for Applied Scientific Research

### 3.7.2.5 Summary of Observations

Most of the theoretical models discussed in this section were in the format of IPO models and describe how a set of inputs (influencing factors) affects team processes and as a result affect team outputs and performance. The model for team performance used in our approach has many aspects in common with the team process model introduced by Rasker (2001). However, in our approach team processes are explicitly modeled and the dynamics of crew and context are incorporated via a simulation approach, making it much more comprehensive and integrative model incorporating in an explicit manner many aspects of team performance, causal paths of error, influence of context. Table 2, presents a list of key elements of team models introduced in the reviewed research and shows the extent to which those elements or constructs our covered by our proposed model.

**Table 2: Comparison among team performance models**

| Category | Elements for Effective Teams | Shanahan (2001) | Rasker et al.(2001) | Blendell et al. (2001) | Extended IDAC |
|---|---|---|---|---|---|
| Individual | Skills | √ | √ |  | √ |
|  | Personality |  |  | √ | √ |
|  | Knowledge | √ | √ | √ | √ |
|  | Attitude | √ | √ |  |  |
|  | Training | √ |  |  | √ |
|  | Level of Stress | √ |  |  | √ |
|  | Experience |  |  | √ | √ |
| Team | Norms | √ |  | √ | √ |
|  | Size |  | √ |  |  |
|  | Composition | √ | √ | √ | √ |
|  | Cohesion |  |  |  | √ |
|  | Leadership | √ | √ | √ | √ |
|  | Team Training | √ |  |  | √ |
|  | Coordination | √ |  |  | √ |
|  | Communication |  |  | √ | √ |
|  | Conflict Management |  |  |  | √ |
|  | Decision Making |  |  |  | √ |
|  | Problem Solving |  |  |  | √ |
|  | Objectives and Goals | √ |  | √ | √ |
|  | Motivation |  | √ |  | √ |
|  | Monitor, Feedback, Audit |  | √ |  | √ |
|  | Mutual Trust |  |  | √ | √ |
|  | Clear Role and Responsibilities |  |  | √ |  |
| Task | Organizational Support | √ | √ |  | √ |
|  | Workload | √ | √ |  |  |
|  | Complexity |  | √ |  |  |

### 3.7.3 Simulation Models

This section provides an overview on a couple of approaches for modeling and simulating of the crew behavior. The models include Performance Evaluation of Teamwork (PET) introduced by Petko et al. (2004) and CREAM-based Communication Analysis Method (CEAM) for NPP crew communication, introduced by Lee et al. (2011).

#### 3.7.3.1 Performance Evaluation of Teamwork (PET) Method

This method, introduced by Petkov et al. (2004), attempts to identify and analyze the potential errors of commission by using three basic concepts which determine the reliability of human performance: violated, cognitive, and executive erroneous actions. PET method performs context quantification for analysis and prediction of these errors and introduces a measure based on the occurrence of deviations from expected paths. The PET method consists of two reliability models (Figure 22); one for human operator cognition, and the other for representing communication inside a team of four operators. These models are represented as directed networks which are solved by analysis of topological reliability of digraphs (ATRD) method. The current limitations are related to the equal weights of different paths in the accident and the action execution error probability.  In this model the team decision-making process is seen as a superstructure of the individual cognition. The decision-maker makes the correct decision when the situation is cleared up for him. In this case the group process is reduced only to the communication process. The project lists fundamental characteristics of decision-making as cognition and communication and indicates the crucial role of decision-maker.

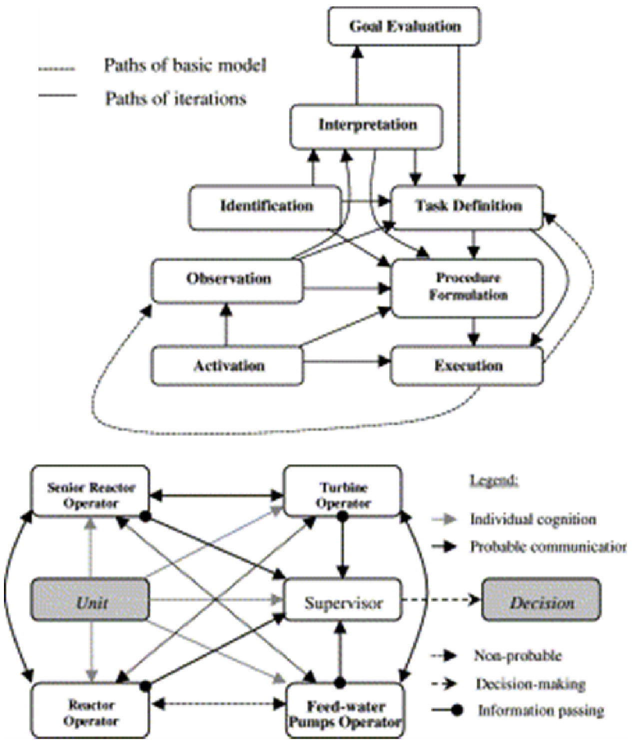


Figure 22: Human cognitive & communication model (Petkov et al., 2004)

### 3.7.3.2 CREAM-based Communication Analysis Method (CEAM)

The descriptive model of the human communication process introduced by Lee et al. (2011) for NPPs operators defines the important elements as the sender, the channel, and the encoding and decoding phases of sender and receiver. It also considers factors affecting each process. The effects of influential factors either increase or decrease communication performance. These factors are situation awareness, long term memory (expertise) and stress (psychological state), attitude, time pressure which can contribute to the success of the communication process. There are also other factors, namely short-term memory, mutual awareness and stress (psychological state), attitude, time pressure, which can negatively affect this process and can contribute to either the success or failure of communication. Whether each factor ultimately contributes to good or bad human performance depends on environmental conditions.

They analyze the environment in which human communication is conducted to better understand and characterize this process and introduce context conditions such as adequacy of organization.

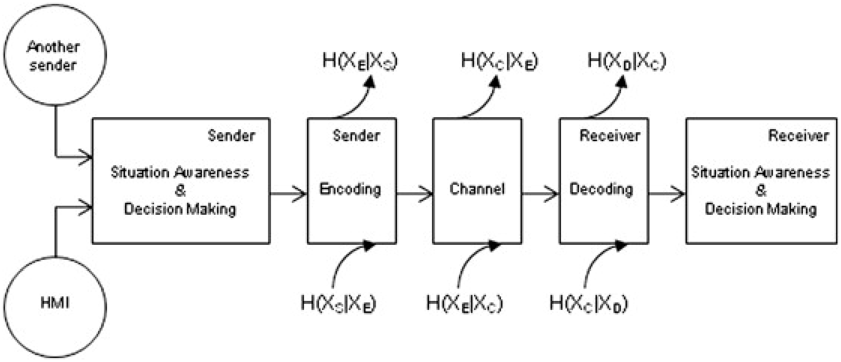


Figure 23: Descriptive model of communication (Lee et al., 2011)

### 3.7.3.3 Summary of Observations

Table 3 presents a comparison among the discussed models and the model introduced by this research for operating crew behavior. The similarities and differences among the discussed models are highlighted based on the key features that have been modeled and simulated. Note that PET (Petkov et al., 2004) claims to address commission errors in the context but does not introduce a separate model for errors based on team tasks.

Table 3: Comparison among simulation models

| Index | Features | PET | CEAM | Extended IDAC |
|---|---|---|---|---|
| 1 | Operator Cognitive Model | √ | | √ |
| 2 | Team Model | √ | | √ |
| 3 | Communication Model | √ | √ | √ |
| 4 | Leadership | √ | | √ |
| 5 | PSFs Model | | √ | √ |
| 6 | Error Model | | | √ |
| 7 | Performance Evaluation | √ | √ | √ |

# Chapter 4: Proposed Model & Implementation Approach

This chapter describes the structural details of the Crew Performance Model introduced in this research, and the approach taken to use the mode in a probabilistic simulation of crew response to accidents and abnormalities in the systems they operate. The model details cover four sub-models: 1) Extended IDAC model, 2) Communication model, 3) Error management model, and 4) PSFs model. In addition the methodology adopted for probabilistic simulation of crew-system interactions and associated risk scenarios is described at the end of this chapter. The specific realization of the simulation method in the context of a case study will described in Chapter 5.

## *4.1 Extended IDAC*

Chapter 3 provided insights to IDAC model and an overview of the Extended IDAC framework. The original form of IDAC introduced three roles inside the team: Operator-Decision Maker (ODM), Operator-Action Taker (OAT), and Operator-Consultant (OCT). The shift supervisor takes the team leader role in a typical control room setting. He is also the person who takes the most responsibility for the outcome of the operator's activities.

In "Extended IDAC" framework (Figure 15), the model of human cognitive processes is developed based on IDAC methodology guidelines and has been encapsulated into the object models for each operator as internal processes. Developed object models for operators are stored in the CREWSIM library in MATLAB Simulink. CREWSIM can be used to define any configuration of such object models for future applications. The object models have been then integrated together to develop the model for the operating team. The “Extended IDAC” adds another team member to the current configuration to highlight the communication related factors such as the quality of communication channel; an equipment operator who is located inside the plant takes the Operator-Action Taker (OAT2) role.

Extended IDAC summarizes team activities into three basic steps illustrated in figure 15:

1. Collaborative information processing
2. Shared decision making
3. Distributed action execution

All of the above steps are accomplished on a sequential basis and involve team discussion and collaboration among team members, meaning that at each step two or more operators are involved actively. At step one, active members are ODM, OCT, OAT1 and OAT2. OAT1 and OAT2 provide the information and ODM recognizes the system state. If ODM is unable to recognize it, he would ask OCT for advice on the system state. Hence, after this step is accomplished the system state is considered known. Collaborative information processing is necessary to build a shared mental model inside the team to portray the system state. However, in order to have an accurate guess for the system state the information collected from the equipment operators needs to be complete. This step may include back and forth communication between ODM and the rest of the crew (Figure 24);

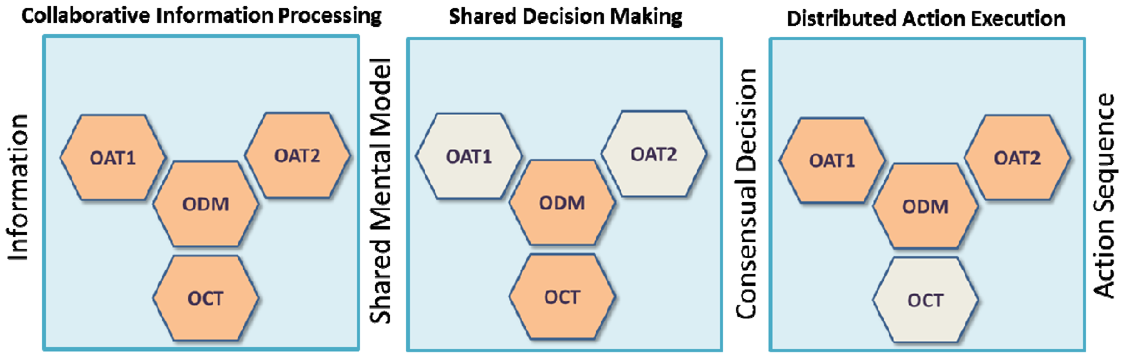


Figure 24: Extended IDAC framework

At step two, ODM and OCT are considered active operators; based on the shared mental model, a decision needs to be made about the required plan for action. If ODM is unable to make the decision he would be involved in a conversation with OCT and ask for advice for the decision. The outcome of this step is the consensual decision, meaning that ODM and OCT have agreed on such a decision.

Step three involves ODM and the equipment operators, and includes a request for action on the system and associated acknowledgment of the operation (Figure 24).

In Extended IDAC model, individual cognitive activities accomplished in parallel and independently by every team member are merged through team dynamics. Major operator activities in Extended IDAC are:

- Performing system control (corresponding to “Action” in IDAC framework); Equipment Operators
- Human cognitive activities
- Error management (detecting, indicating and correcting errors using the communication network)
- Communicating with each other (sending and receiving messages)

The content of messages being exchanged among operators is:

- A request for performing action or providing advice
- An observation on the system in the form of a report
- A judgment/advice on the system state or judgment/advice on decision
- Confirmation/acknowledgement for performing required action

In Extended IDAC framework the individual cognitive steps and human functions as well as error management activities have been represented by sequential blocks, each of which are associated with a probability of failure on demand. These blocks are preceded by a chance for the operator to be available or not when demanded. These probabilities are the result of a set of related contributing PSFs. The mechanism of influence of these factors has been captured and is being discussed in section 4.3.

## 4.2 Errors in Extended IDAC

To understand the causes of human error, it is necessary to link the actions that lead to an error event back to the underlying cognitive model. In IDAC framework, individual errors are defined based on internal and external reference points. IDAC associates the human error with the failure to meet a plant need; the basic idea is to identify mismatches between internal and external reference points.

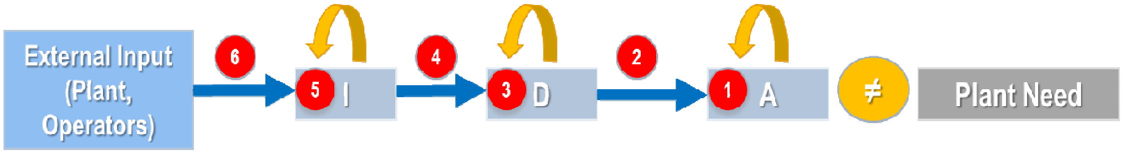


Figure 25: Errors in IDAC framework

Internal reference points are different cognitive stages within the IDAC model and include information collection, diagnosis/decision, and action processes. These produce:

- Error in information collected due to receipt of incomplete information from the plant or from another crew member or an information filtering error;
- Incorrect or incomplete assessment of a situation or solution to problem due to failure to adequately define the problem or error in problem solving strategy selection;
- Decision error due to inappropriate selection of the solution from equivalent alternatives or selection of incorrect decision criteria;
- Error in action execution due to high operator workload or poorly human factored environment.

The possible mismatch between plant needs and actions are skipping steps, delayed or premature actions or action on the wrong object. These mismatches, based on IDA framework would be due to Failure of A (Error in Execution) or Failure of A due to Error in D, Error in D is caused by a Failure in D or Failure of D due to Failure of I, Error in I is caused by Failure in I or Incorrect I from External Source (Steps 1 to 6). Hence, the probability of Human Failure Event (HFE) would be the logical or of I+D+A (Figure 25).

External reference points are defined as the plant system, procedures, and the operators (Chang et al., 2007). Errors in this category include: Plant-Crew Mismatch:

caused by erroneous or incomplete information from plant or operator observation error; Procedure-Plant Mismatch: caused by erroneous or incomplete procedure; Crew-Plant Mismatch: caused by diagnosis, decision, or execution errors; Crew-Procedures Mismatch: caused by procedure inadequacy from a human factors viewpoint or crew lacking knowledge to understand procedure; Crew-Crew Mismatch: caused by erroneous or incomplete communication. Errors in Extended IDAC framework have been identified using a "comprehensive task analysis" and including Individual and team level errors. For a list of emergency operating procedures which have been used as the basis for determining the accuracy of actions in this research, see appendix D.

### 4.2.1 Error Management Model

Sasou et al. (1999) introduced a model for error management in 1999. The objective of their research was to develop definitions and error taxonomy and perform an analysis that determines the relationship between the team errors they defined and PIFs (PSFs). They defined error types as: independent individual errors, dependent individual errors, independent shared errors, dependent shared errors. They defined the error recovery process and classified the team failures as Failure to detect, Failure to indicate, and Failure to correct individual errors. The method they used was to test their hypothesis by reviewing events that occurred in the nuclear power industry, aviation industry and shipping industry. They concluded that their proposed definition and taxonomy are useful in categorizing team errors. They listed deficiencies in communication, resource/task management, excessive authority gradient, and excessive professional courtesy as likely causes of team errors. They also noted that modeling team errors provides an opportunity to reduce human errors. This research has used their idea and has developed an error module inside each of the operators that is responsible for error recognition and handling.

Based on Sasou's model, our research suggests that the process of team error management consists of the following major team activities:

- Error Detection
- Error Indication
- Error Correction

Error detection includes active exploration, review and monitoring. Error identification is accomplished by using an error reference list and previous knowledge of likely consequences. Error indication within a team is accomplished using feedback and communication. Finally error recovery includes a selection of appropriate control, repetition or back up actions. Such team processes are supported by dynamic knowledge (i.e., information from and about the situation at the time) and experiential knowledge (i.e., knowledge that an individual brings to the situation based on training and previous experience).

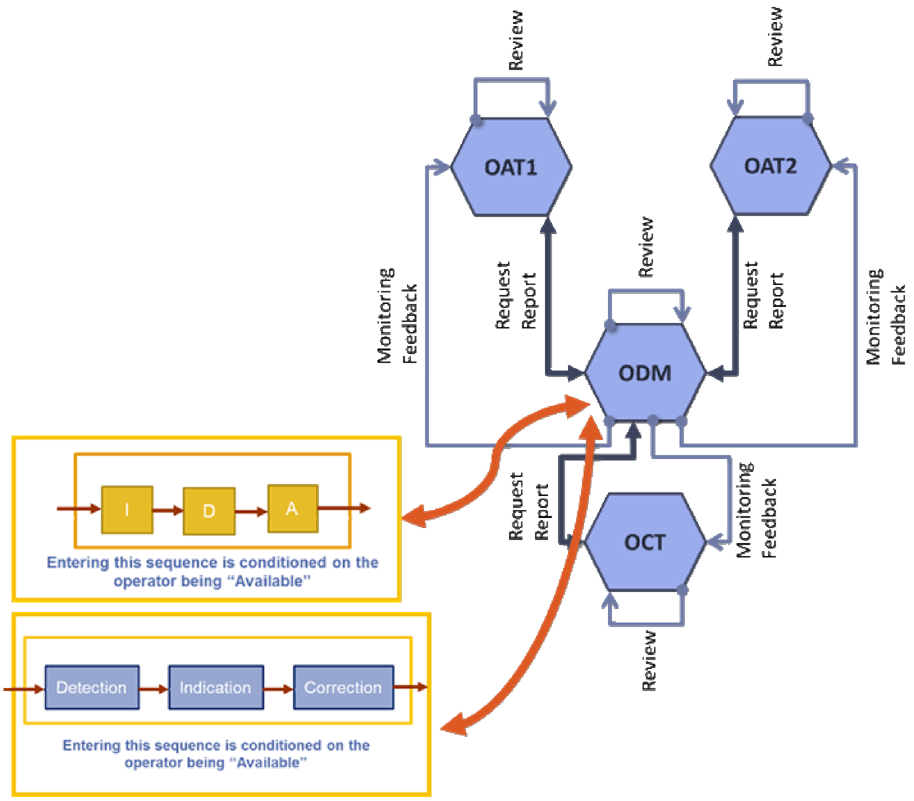


Figure 26: Error management in Extended IDAC

Error management in Extended IDAC is a closed loop of reviewing, providing feedback and correction activities and involves extra communication inside the team. Each person reviews his/her own action, lets the rest of the people know in case there was an error and has a chance to correct it (Figure 26). In addition, since the decision maker (shift supervisor) is the leader of the team, all actions are monitored by him and he is supposed to recognize errors, provide feedback on them and ask for a fixing action. These activities, along with the messages that are exchanged regarding the error management process inside the team, are called "recovery actions" and "recovery messages". The error management module is designed in a sequential fashion and consists of three sequential blocks, including "Detection", "Indication" and “Correction”. Each of these blocks is associated with a probability of failure that is calculated based on the associated performance shaping factors with the failure of each block. Entering this sequence is conditioned on the operator being “Available”.

The application of these blocks introduces new errors modes that are directly a result of the nature of working in a team. These errors and consequently failure modes do not necessarily impose a system failure but have a potential to contribute to it; errors that can occur in the process of team error management are being considered among team errors.

### 4.2.2 Team and Individual Operator Error Classification

An essential element of the proposed team behavior model and simulation platform is a list of relevant errors at individual and crew levels. Such taxonomy forms the starting point for identification of communication, coordination, and action “failure mechanisms” and associated PSFs. Failure mechanisms provide the link between the PSFs and possible human failures. These failure mechanisms represent a mid-layer to the qualitative analysis approach.  The foundations of our proposed taxonomy is in the external and internal error “reference points” introduced in the Extended IDAC model and described elsewhere in this dissertation.

This research introduces a comprehensive classification of human error based on the identified error reference points in the underlying models at the individual and team levels, which helps to identify those failure mechanisms. The error categories have been identified based on previously discussed error reference points as well as a complete task decomposition and functional view of the model for the individual and team. We considered not only errors of omission (not executing and missing human action) but also errors of commission such as executing the action on the wrong object or at the wrong time or generally in a wrong way. Such errors have been included to enrich this classification. Errors of commission are usually defined with respect to the direction of actions, the objects of actions, the quality of actions, the sequence and the timing properties of actions. Sasou et al. (1999) recognize the following classification of human error in a team context:

- Individual errors: errors which are made by individuals without participation of any other team member. Examples include most of the errors which happen in executing actions. When all the information available to individual is essential correct, the error is considered to be independent; however, if the information is partially provided or incorrect the error is considered to be dependent.
- Shared errors: errors which are shared by some or all of team members regardless of whether they have been in direct contact. Examples of such errors include errors caused by deficiency in organizational factors such as quality of procedures and interface.
- Team errors: human errors made in group processes. Examples of such errors include mistakes and lapses mostly made during group thinking or planning or other group activities.

In general, the actions associated with the operators and the team can be summarized as:

- Actions performed on the system as a response to a request

- Actions performed as a means to coordinate and communicate activities inside the team (sending, creating and receiving proper messages and message contents in the form of requests and reports for performing other categories of actions)
- Actions performed as a recovery from an unwanted situation

If any mismatch between these actions and the way that they are expected to happen by the plant (hardware system) or other team members occurs, it means that an error has taken place. This error might be a result of error in action execution or a depended error which is a result of errors happening at previous stages or in our case in any team activity. For example, if source information is not available or is miscommunicated it might be due to error in communication, interface or a faulty component. Errors in the context of the operating team need to be defined based on complete task decomposition at the level of team and individual operator so that all the complexities involved with human cognition and team processes can be reflected in the error context. Task decomposition provides a tool to better understand error making process; since we have included the error recovery process in our model, the task decomposition needs to be extended to include error recovery actions.

In order to develop the error model at the level of the team and the individual operator, a comprehensive task study has been conducted. Major task categories have been recognized as:

- System Status Assessment (Operator, Team)
    - Individual: Task of gathering information

    - Team: Task of gathering information via communication and collaboration
    - Individual: Task of understanding the situation
    - Team: Task of understanding the situation via communication and discussion

- Response Planning (Operator, Team)
    - Individual: Task of deciding upon a plan
    - Team: Task of deciding upon a plan via communication and consensus
- Action (Operator, Team)
    - Individual: Task of implementing the decided response
    - Team: Task of distributing the decided action course to be implemented by operators via communication and coordination

In all of the discussed tasks, the “leader” is responsible for coordination activities at the team level and communication plays a major role. Previous research efforts to classify human error have always been classifying errors from an individual operator perspective and despite some efforts to provide error classification for communication such as Kim et al. (2011), most of them have neglected team processes and specially team error management. This research not only includes team processes such as communication and monitoring in task decomposition but also accounts for error management activities as well. Tasks of error management include:

- Detection
    - Individual: Task of reviewing self-actions
    - Team : Task of detecting teammate errors via monitoring their actions to discover mismatches
- Indication
    - Individual: Task of reporting error in self-actions via communication
    - Team: Task of providing report/ feedback on teammate actions via communication
- Correction
    - Individual: Task of correcting error in self-actions by performing a recovery action
    - Team: Task of correcting error in teammate actions by requesting a recovery action

In all the above tasks the "leader" is responsible for coordination of activities at the team level. Table 4 provides list of general categories of error in the control room. This table is focused on error modes (the manifestation of an error in the context).

Table 4: Error categories

| Index | Category | Description |
|---|---|---|
| 1 | Error in source information or message | Critical information or message is missing |
| | | Critical information or message is corrupted or wrong |
| 2 | Error in interface or communication | Critical information or message is not exchanged |
| | | Critical information is incorrectly exchanged |
| | | Critical message is miscommunicated |
| 2 | Error in information or message collection | Critical information or message is not obtained |
| | | Critical information or message is not being attended to |
| | | Critical information or message is dismissed |
| | | Critical information or message is discounted |
| | | Critical information or message is overlooked |
| | | Critical information or message is not responded to |
| | | Critical information or message is incorrectly interpreted |
| | | Inappropriate or wrong information or message is being collected |
| 3 | Error in problem solving or decision making | Diagnosis on system state is not made |
| | | Inappropriate or wrong diagnosis is made on system state or message content |
| | | Decision on strategy or action or reply message is not made |
| | | Inappropriate or wrong decision is made on strategy or action or reply message |
| 4 | Error in action execution or message transferring | Action is not committed |
| | | Incomplete action is committed |
| | | Inappropriate or wrong action is committed |
| | | Action is committed on wrong object |
| | | Action is commited by wrong person |
| | | Action is committed in wrong time |
| | | Message is not sent |
| | | Incomplete message is sent |
| | | Inappropriate or wrong message is sent |
| | | Message is sent to wrong person |
| | | Message is sent in wrong time |

In order to look at the relationship between tasks and error modes, first one needs to assure that the information, the messages, and the individual operators are presented correctly to the operator by the system (control panel) or by the communication channels. Sometimes it is assumed to be true by default; however, we would like to provide a summary of the contributing factors (Table 5). Examples of errors in this category with regards to causal influence of PSFs include: Critical message is not exchanged since the sender (or receiver) was not familiar with using the communication device.

Table 5: Availability of information and message

| Error mode | PSFs |
|---|---|
| Critical information or message is missing | Communication skills of sender & receiver |
| Critical information or message is corrupted or wrong | Communication format of sender and receiver |
| Critical information or message is not exchanged | Familiarity of sender & receiver with using the device |
| Critical information is incorrectly exchanged | Availability of device |
| Critical message is miscommunicated | Accessibility of device |
| | Ease of use of device |
| | Quality of interface |
| | Quality of workspace |
| | External interruptions |
| | Accuracy of device |
| | Team communication |
| | Team cohesion |

Based on the provided task decomposition and the error modes presented in table 4, we suggest the framework proposed in table 6 to be used for activities involving plant status assessment. Note that in team activities such as discussion, the leader has a coordinative role; hence his individual characteristics would contribute to determining the probability of error in such activities. Examples of errors in this category with regards to causal influence of PSFs include team failing in understanding the situation because the critical message was not responded to by the off-site operator since the communication device was unavailable.

Table 6: Error in system status assessment

| Task | Error mode | PSFs |
|---|---|---|
| Gathering information | Critical information or message is not obtained | Experience |
| Understanding the situation | Critical information or message is not being attended to | Training |
| | Critical information or message is dismissed | Stress |
| Gathering information via communication & collaboration | Critical information or message is discounted | Attention |
| Understanding the situation via communication & discussion | Critical information or message is overlooked | Information load |
| | Critical information or message is not responded to | Time load |
| | Critical information or message is incorrectly interpreted | Quality of interface |
| | Inappropriate or wrong information or message is being collected | Team experience |
| | | Team training |
| | Diagnosis on system state is not made | Communication skills of sender & receiver |
| | Inappropriate or wrong diagnosis is made on system state or message content | Communication format of sender & receiver |
| | | Team cohesion |
| | | Team communication |
| | | Accuracy of device |
| | | Ease of use of device |
| | | Familiarity with using the device |
| | | Availability of device |
| | | Accessibility of device |

Based on the task decomposition and the error modes presented in Table 2, we suggest the framework proposed in Table 7 to be used for activities involving response planning. Note that in team activities such as consensus building the leader has a coordinative role; hence, his individual characteristics would contribute to determining the probability of error in such activities. Examples of errors in this category with regards to causal influence of PSFs include: team failing in deciding upon the response because an inexperienced supervisor made an inappropriate diagnosis on system state.

**Table 7: Error in response planning**

| Task | Error mode | PSFs |
|---|---|---|
| Deciding upon a response | Decision on strategy or action or reply message is not made | Experience |
| Deciding upon a response via communication and consensus | Inappropriate or wrong decision is made on strategy or action or reply message | Training |
| | Diagnosis on system state is not made | Fatigue |
| | Inappropriate or wrong diagnosis is made on system state or message content | Stress |
| | Decision on strategy or action or reply message is not made | Attention |
| | Inappropriate or wrong decision is made on strategy or action or reply message | Information load |
| | | Time load |
| | | Quality of procedures |
| | | Training for the role |
| | | Experience for the role |
| | | Commitment to the role |
| | | Motivation for the role |
| | | Concern for safety and quality |
| | | Team cohesion |
| | | Team coordination |
| | | Team communication |
| | | Communication skills of sender & receiver |
| | | Communication format of sender & receiver |
| | | Leadership |
| | | Role awareness |

Based on the provided task decomposition and the error modes presented in table 2, we suggest the framework proposed in Table 8 to be used for activities involving implementing action. Note that in team activities such as distribution of action the leader has a coordinative role hence his individual characteristics would contribute to determining the probability of error in such activities. Examples of errors in this category with regards to causal influence of PSFs include: Action is committed on the wrong object because the operator was stressful and tired; message is sent to the wrong person (message regarding executing an action) because the supervisor was too much engaged in workspace interruptions.

Table 8: Error in implementing action

| Task | Error mode | PSFs |
|---|---|---|
| Implementing the decided response | Action is not committed | Experience |
| Distributing the decided action course to operators via communication and coordination | Incomplete action is committed | Training |
| | Inappropriate or wrong action is committed | Fatigue |
| | Action is committed on wrong object | Stress |
| | Action is commited by the wrong person | Attention |
| | Action is committed in wrong time | Information load |
| | Message is not sent | Time load |
| | Incomplete message is sent | Quality of interface |
| | Inappropriate or wrong message is sent | Quality of workspace |
| | Message is sent to wrong person | Leadership |
| | Message is sent in wrong time | Team coordination |
| | | Team communication |

Table 9 lists the error modes that are a result of committing an error during error management activities with respect to the major task category of detecting, indicating and correcting the error.

Table 9: Error in error management

| Index | Category | Description |
|---|---|---|
| 1 | Error in detecting an error | Error is not detected |
| | | Error is not being attended to |
| | | Error is dismissed |
| | | Error is discounted |
| | | Error is overlooked |
| | | Error is not responded to |
| | | Error is not recognized |
| | | Error is misinterpreted |
| | | Error is being detected incorrectly |
| | | Error is being detected in wrong time |
| 2 | Error in indicating an error | Error is not being reported |
| | | Error is being reported incorrectly |
| | | Error is being reported to the wrong person |
| | | Error is being reported in wrong time |
| 3 | Error in correcting an error | Error is not being corrected |
| | | Inappropriate or wrong recovery action is committed |
| | | Recovery action is committed in wrong time |
| | | No recovery action is possible |

Note that these error modes are considered to be a result of an individual or team error. A mix of these error modes usually occurs since the identification of error by the team is somehow related to the identification of error by the individuals. Examples include: Error is not detected by the team because it was not reported by the individual; inappropriate or wrong action is committed because error is being detected incorrectly by the team.

Table 10: General categories of errors in teams

| Index | Categoy | Description |
|---|---|---|
| 1 | Review, Monitor | Error in reviewing an action by the individual and recognizing the error |
|  |  | Error in monitoring an action by a teammate and recognizing the error |
| 2 | Feedback | Error in transferring the feedback on an action to a teammate |
| 3 | Fix | Error in requesting a corrective action from a teammate to fix the error |
|  |  | Error in performing a corrective action on the system to fix the error |
|  |  | Error in confirming performing of a corrective action to a teammate |

Table 10 lists errors made during common team activities such as monitoring, reviewing and fixing/backing up. This information helps to determine the roots of the error; i.e. the format of the statement (x occurred because of inefficiency of y) which is used in the next table.

Table 11: Failure in error management

| Index | Category | Description |
|---|---|---|
| 1 | Error Detection | Failure to detect the error by individual because action was not reviewed |
|  |  | Failure to detect the error by team because error was not indicated by individual |
|  |  | failure to detect the error by team because of error in monitoring |
| 2 | Error Indication | Failure to indicate the error by individual because error was not detected by individual |
|  |  | Failure to indicate the error by team because of error was not detected by team |
|  |  | Failure to indicate the error by team because of error in feed back |
| 3 | Error Correction | Failure to correct the error by the individual because it was not recognized by the individual |
|  |  | Failure to correct the error by the individual because it was falsely corrected by the individual |
|  |  | Failure to correct the error by the team because it was not indicated to the team by the individual |
|  |  | Failure to correct the error by the team because it was indicated but not recognized by the team |
|  |  | Failure to correct the error by the team because it was falsely corrected by the individual and not recognized by the team |
|  |  | Failure to correct the error by the team because it was falsely corrected by the team |

Table 12 lists the contributing factors to Error detection activities by the individual and the team. Examples of errors in this category with regards to causal influence of PSFs include: Error is not recognized during the task of self-review because operator was not sufficiently trained for the specific role.

Table 12: Error in error detection

| Task | Error mode | PSFs |
|---|---|---|
| Reviewing self-actions | Error is not detected | Experience |
| Detecting teammate errors via monitoring their actions | Error is not being attended to | Training |
| | Error is dismissed | Fatigue |
| | Error is discounted | Attention |
| | Error is overlooked | Information load |
| | Error is not responded to | Time load |
| | Error is not recognized | Quality of procedures |
| | Error is misinterpreted | Quality of workspace |
| | Error is being detected incorrectly | Leader training |
| | Error is being detected in wrong time | Leader participation |
| | | Enforcement and supervision |
| | | Authority inside team |
| | | Training for the role |
| | | Experience for the role |
| | | Commitment to the role |
| | | Motivation for the role |
| | | Concern for safety and quality |
| | | Team cohesion |
| | | Role awareness |
| | | Team communication |
| | | Team coordination |
| | | Leadership |

Table 13 lists the contributing factors to Error indication (report) activities by the individual and the team. Examples of errors in this category with regards to causal influence of PSFs include: Error is not being reported to the team after being recognized in self-review because the operator does not care about quality.

Table 13: Error in error indication

| Task | Error mode | PSFs |
|---|---|---|
| Reporting error in self-actions via communication | Error is not being reported | Experience |
| Providing report/ feedback on teammate actions via communication | Error is being reported incorrectly | Training |
| | Error is being reported to the wrong person | Fatigue |
| | Error is being reported in wrong time | Attention |
| | | Information load |
| | | Time load |
| | | Stress |
| | | Quality of procedures |
| | | Quality of workspace |
| | | Leader training |
| | | Leader participation |
| | | Enforcement and supervision |
| | | Authority inside team |
| | | Training for the role |
| | | Experience for the role |
| | | Commitment to the role |
| | | Motivation for the role |
| | | Concern for safety and quality |
| | | Team cohesion |
| | | Role awareness |
| | | Team communication |
| | | Team coordination |
| | | Leadership |

And finally the next Table 14 lists the contributing factors to Error correction activities by the individual and the team. Examples of errors in this category with regards to causal influence of PSFs include: inappropriate recovery action is requested in the process of correcting the error by the team, because the leader is considered inexperienced for the role.

Table 14: Error in error correction

| Task | Error mode | PSFs |
|---|---|---|
| Correcting error in self-actions by performing a recovery action | Error is not being corrected | Experience |
| Correcting error in teammate actions by requesting a recovery action | Inappropriate or wrong recovery action is committed | Training |
| | Recovery action is committed in wrong time | Fatigue |
| | No recovery action is possible | Attention |
| | | Information load |
| | | Time load |
| | | Stress |
| | | Quality of procedures |
| | | Quality of workspace |
| | | Leader training |
| | | Leader participation |
| | | Enforcement and supervision |
| | | Authority inside team |
| | | Training for the role |
| | | Experience for the role |
| | | Commitment to the role |
| | | Motivation for the role |
| | | Concern for safety and quality |
| | | Team cohesion |
| | | Role awareness |
| | | Team communication |
| | | Team coordination |
| | | Leadership |

## 4.3 A Team Oriented Taxonomy and Causal Model of PSFs

### 4.3.1 Introduction

To develop a quantitative estimate of the Human Error Probability (HEP), most HRA methods utilize PSFs, which characterize the roots and facets of human error and provide a numerical basis for calculating the error probability (Boring, 2006). Modeling these PSFs along with the system response allows simulation-based assignment of their levels, and helps to obtain a more realistic model of relation between context and performance. However, identifying and quantifying the PSFs is a relatively subjective task. Most of the research such as the works of Boring (2006), Kim (2003), Gibson et al. (2008) and Patrick et al. (2006) are focused on classifying the factors rather than developing assessment methods and casual explanation.

Depending on the specific scenarios being simulated and the nature of the system, a subset of PSFs have been modeled and applied.

Team-related PSFs (TPSFs) are those factors that affect the performance and arise from the fact that a group of people is working together in the team on a common task. A complete taxonomy of Individual PSFs is defined and categorized by Groth (2009), which lists the most important TPSFS as communication, team coordination, team cohesion, role awareness and direct supervision (See section 3.5.1); however, no further categories are provided on this group of PSFs. The objectives of this part of the study are:

1) To identify context factors that directly or indirectly affect team performance and for use as parameters of the crew model

2) To develop a detailed causal model for TPSFs to be used for quantification of probability of various crew cognitive and physical actions

In Extended IDAC the basis of the PSFs model have been extracted from the PSFs list provided by Groth (2009) and Kim (2003). We took the following steps to further study the major categories of TPSFs introduced by Groth (2009).

1) Conducted a full study on the existing research on Individual and Team PSFs. The result of this study is described in this section and section 3.5.1 of the dissertation.

2) Classified the contributing PSFs and provided detailed causal maps for each major category of Team PSFs introduced by Groth (2009).

### Table 15: Team PSFs model & suppoting literature

| Performance Shaping Factors | | | |
|---|---|---|---|
| Category | Sub category | Factor | Supporting Research |
| Role awareness | Role | Clear goals | Kim 2003, Bust 2008, Smit 2007, Paris 2000, Stantoni 2000, Kim 2003 |
| | | Clear roles | Kim 2003, Bust 2008, Smith 2007, Paris 2000, Kim 2003 |
| | | Clear norms | Kim 2003, Bust 2008, Smith 2007, Paris 2000, kim 2003 |
| | | Training for the role | Blackman 2008,Bust 2008, Boring 2006, Mengzho 1997, Paris 2000, Kim 2003 |
| | | Experience for the role | Blackman 2008,Bust 2008, Boring 2006, Mengzho 1997, paris 2000, Kim 2003 |
| | | Commitment to the role | Bust 2008, Smith 2007, Boring 2006 |
| | | Motivation for role | Bust 2008, Boring 2006, Kim 2003 |
| | Consequence | Clear responsibilities | Bust 2008, Smith 2007 |
| | | Quality of reference documents | Bust 2008, Boring 2006, Kim 2003 |
| | | Protocols/ Standards | Bust 2008, Paris 2000 |
| | | Concern for quality | Bust 2008, Paris 2000, Stantoni 2000, Kim 2003 |
| | | Concern for safety | Bust 2008, Paris 2000, kim 2003 |
| | | Commitment to the role* | Bust 2008, Smith 2007, Boring 2006 |
| | | Motivation for role* | Bust 2008, Boring 2006, Kim 2003 |
| Team Cohesiveness | Task | Shared goals | Bust 2008, Paris 2000, Stantoni 2000, Kim 2003 |
| | | Compliance to procedures | Blackman 2008, carvalho 2006, Paris 2000 |
| | | Authority gradient | Bust 2008, Bocante 2007 |
| | | Training as a team | Blackman 2008, Sasangohar 2010, Boring 2006 |
| | | Experience as a team | Blackman 2008, Sasangohar 2010, Boring 2006 |
| | Social | Diversity | Mengzho 1997, Kim 2003 |
| | | Mutual trust | Bust 2008, Paris 2000 |
| | | Training as a team* | Blackman 2008, Sasangohar 2010, Boring 2006 |
| | | Experience as a team* | Blackman 2008, Sasangohar 2010, Boring 2006 |
| Team Coordination | N/A | Following leader | Bust 2008, Paris 2000, Kim 2003 |
| | | Following protocols | Bust 2008, Paris 2000 |
| | | Members assertiveness | Paris 2000, Kim 2003 |
| | | Effective communication | Bust 2008, Sasangohar 2010, Stantoni 2000, Kim 2003, Groth 2009 |
| | | Role awareness | Bust 2008, Smith 2007,Paris 2000, Groth 2009 |
| | | Effective leadership | Paris 2000, Stantoi 2000, Petkov 2004, Groth 2009 |
| Effective leadership | N/A | Supervision | Bust 2008, Broberg 2008, Harrington 1993, Paris 2000 |
| | | Enforcement of protocols | Bust 2008, Broberg 2008, Paris 2000 |
| | | Organizational autority | Bust 2008, Harington 1993, Kim 2003 |
| | | Leadership training | Bust 2008, Mengzo 1997, Paris 2000, Stantoni 2000, Kim 2003 |
| | | Participation of leader | Broberg 2008, Paris 2000, Petkov 2004 |
| | | Individual factors for leader | Broberg 2008, Harrington 1993, Mengzho 1997, Paris 2000, Stantoni 2000 |
| | | Role awareness | Bust 2008, Paris 2000, Smith 2007 |
| | | Team cohesiveness | Paris 2000, Kim 2003, Groth 2009 |
| Effective communication | Device-based | Familiarity with device | Hirotsu 2001, Kim 2003 |
| | | Accessability | Bust 2008, Hirotsu 2001, Kim 2003 |
| | | Ease of use | Hirotsu 2001, Kim 2003 |
| | | Accuracy | Hirotsu 2001, kim 2003 |
| | | Communication procedures | Blackman 2008, Carvalho 2006, Bust 2008,Hirotsu 2001, Sasangohar 2010 |
| | | Communication skills | Smith 2007, Patrick 2006, Kim 2003 |
| | | Format / complexity | Bust 2008, Smith 2007, Sasangohar 2010, Kim 2003 |
| | | Terms / language | Bust 2008, Smith 2007, Kim 2003 |
| | | Protocols/ Standards | Bust 2008, Hirotsu 2001, Kim 2003 |
| | | Comfort | Hirotsu 2001, Sasangohar 2010, Paris 2000, Kim 2003 |
| | | External interruptions | Hirotsu 2001, Sasangohar 2010, Paris 200, Kim 2003 |
| | | Team cohesiveness | Paris 2000, Kim 2003, Groth 2009 |
| | Face to Face | Communication procedures* | Blackman 2008, Carvalho 2006, Bust 2008,Hirotsu 2001, Sasangohar 2010 |
| | | Comunication skills* | Smith 2007, Patrick 2006, Kim 2003 |
| | | Format / complexity* | Bust 2008, Smith 2007, Sasangohar 2010, Kim 2003 |
| | | Terms / language* | Bust 2008, Smith 2007, Kim 2003 |
| | | Protocols/ Standards* | Bust 2008, Hirotsu 2001, Kim 2003 |
| | | Comfort* | Hirotsu 2001, Sasangohar 2010, Paris 2000, Kim 2003 |
| | | External interruptions* | Hirotsu 2001, Sasangohar 2010, Paris 200, Kim 2003 |
| | | Team Cohesiveness* | Paris 2000, Kim 2003, Groth 2009 |

### 4.3.2 PSFs Causal Model

This research carefully considered the literature on both individual and on team performance shaping factors, as discussed in the previous chapter. A set of team factors associated with accident management selected out of many that were addressed by literature, are listed in Table 15. The detailed internal model for team PSFs and corresponding causal maps and the mechanism of their effect are shown in Figures 27, 28, 29, 30 and 31.

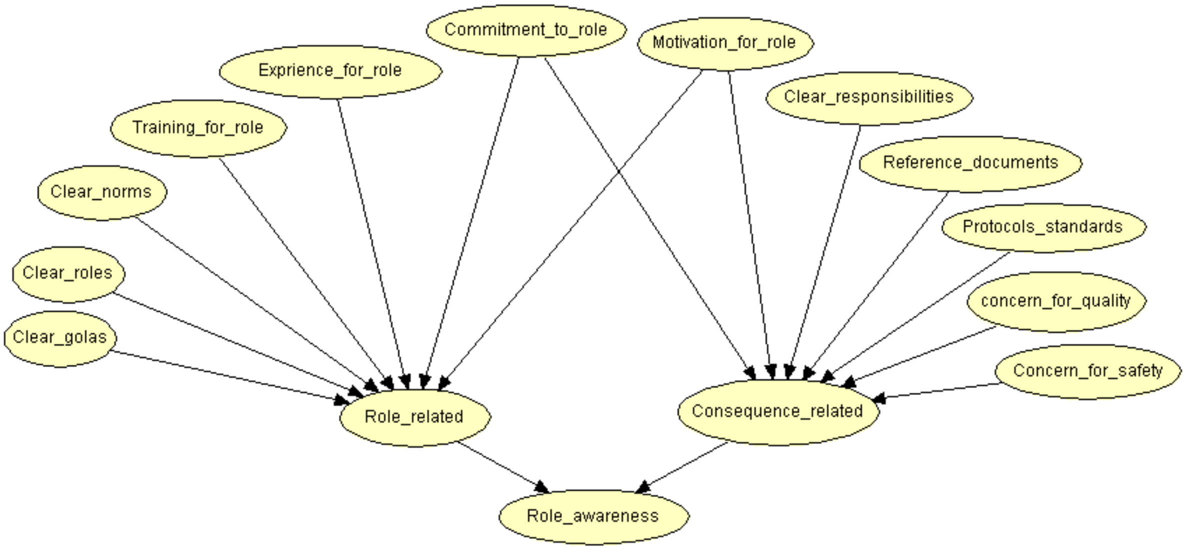


Figure 27: PSF model, Role awareness

Role Awareness is related to how each of the team members perceives their duties, responsibilities, and roles within the team. It is related to how tasks are divided in the team and how team members are expected to interact with each other to accomplish them. We considered two different aspects (Figure 27) of role awareness; 1) Role awareness requires operators to be aware of their place in the team and to act according to the expectations of the role; 2) It requires operators to be aware of the outcomes and consequences of the actions they choose as part of accomplishing the tasks associated with their roles.

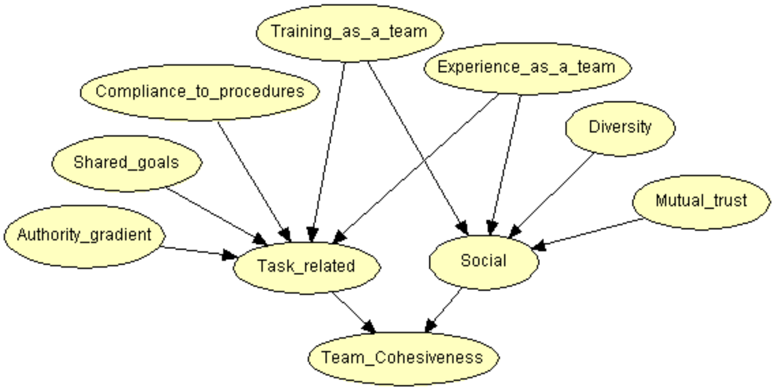


Figure 28: PSF model, Team cohesion

Team Cohesion refers to the way that team members interact with each other and the individual's desire to be involved in the group's activities. We considered team cohesion from two perspectives, shown in Figure 28; 1) Task cohesion refers to the degree to which members of a group work together to achieve common goals. 2) Social cohesion refers to the degree to which members of a team like to work with each other as a team.

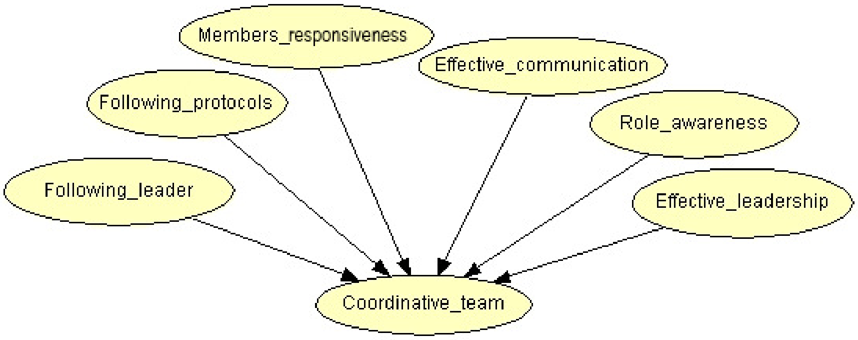


Figure 29: PSF model, Team coordination

Team Coordination (Figure 29) refers to the overall interactions of the team, including division of responsibilities and ability to work as a unit (teamwork). It considers additional factors that contribute to overall team performance such as planning and scheduling on the team level and team decision making. Effective leadership and effective communication contribute to effective coordination in team activities.

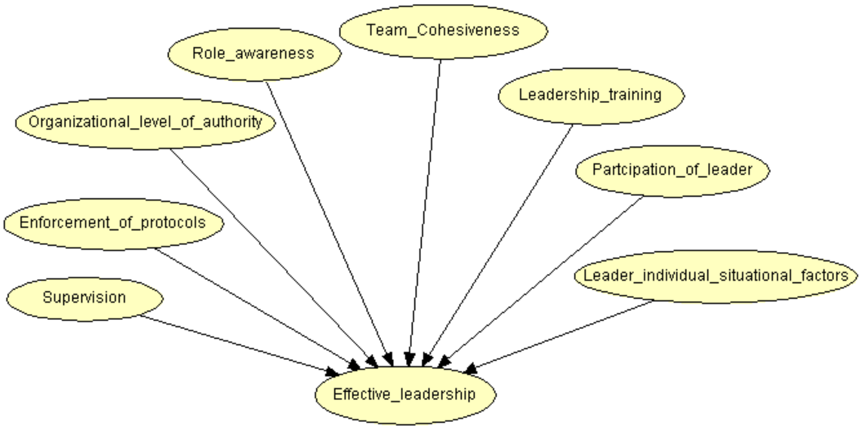


Figure 30: PSF model, Team leadership

Leaders (supervisors) work with and assign tasks to personnel. The leader can be seen as a member of the team, albeit a member with additional authority and responsibility (Groth 2009). The supervisor sets a direction for the team and influences the attitudes of the team members. The supervisor has the dual responsibility of setting goals for the group and also working with group members to accomplish these goals. The individual PSFs related to the leader (Figure 30) also contribute to effective leadership inside the team.

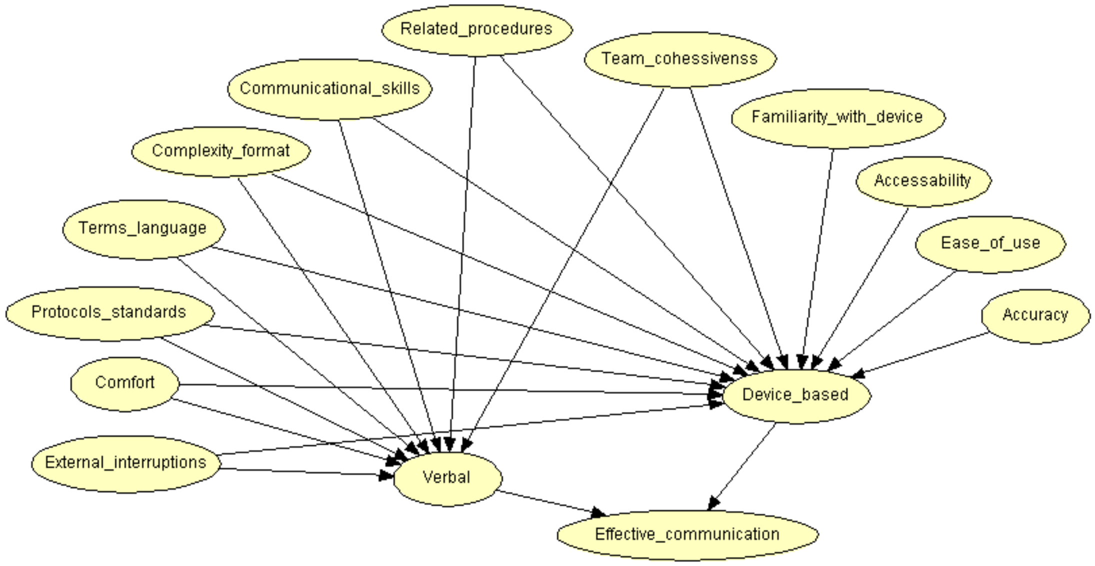


Figure 31: PSF model, Communication

Communication refers to the ability of team members to pass information and transfer messages to each other. Communication can be verbal and face-to-face or device-based (Figure 31). While team cohesiveness contributes to both types of communication, the quality of the communication device as well as the familiarity with using the device are other important contributing factors to effective communication.

The discussed categories of Team PSFs affect all team members. The only exception is that communication is considered to be between two people at a time, hence the quality of communication can be viewed as the quality of channel/ device (applied to the specific communication link), the quality of context of communication (applied to the team), the quality of communication link that senders and receiver establish and the content they exchange (based on communication skills and format the use, this is applied to the communication link). Hence there are team related aspects of communication such as existence and the quality of procedures and protocols for communication, and there are individual aspects of communication such as the format that the sender uses or the communication skills of the receiver. Based on this categorization and in order to we introduced the concept of “Team Factors”.

### 4.3.3 Team Factors

Major categories of Team PSFs have been introduced earlier (e.g., Team cohesion, Team coordination). We also presented a PSF causal model to that shows the influence and contributions of a set of lower level context factors to their group. These context factors are either measurable (such as “training as a team” or “experience in the same control room”) or assessed on a qualitative basis by expert judgment (example would be the “Mutual Trust”).

One objective of this part of the research was to study, extract and list such context factors and classify them as team, individual, organizational, and task-related factors in order to use them as the adjustable parameters (attributes) of the operator’s object model (discussed in Chap 5). Based on this classification, “Team Factors” are context factors which affect the performance of the entire team (all team members) and along with other individual or even task related context factors, contribute to Team PSFs. Table 16 lists team factors that have been defined in this research. A complete list of all factors and their definitions is provided in Table 19.

Table 16: Team factors

| Team Factors | | | |
|---|---|---|---|
| Factor | Levels | Factor | Levels |
| Training as a team | Low | Team responsibilities | Not clear |
| | Average | | Average |
| | High | | Clear |
| Experience as a team | Low | Reference documents | Poor quality |
| | Average | | Normal quality |
| | High | | Good quality |
| Compliance to procedures | Not at all | Standards & Regulations | Less than adequate |
| | Normal | | Adequate |
| | Commited | | More than adequate |
| Team diversity | Not diverse | Following leader | Not at all |
| | Average | | Average |
| | Diverse | | Totally |
| Shared goals | Few | Following protocols | Not at all |
| | Average | | Average |
| | A lot | | Totally |
| Authority gradient | Unfair | Responsiveness | Low |
| | Average | | Normal |
| | Fair | | Good |
| Mutual trust | Low | External interruptions | High |
| | Normal | | Average |
| | High | | Low |
| Team goals | Not clear | Level of Comfort | Uncomfortable |
| | Average | | Normal |
| | Clear | | Comfortable |
| Team roles | Not clear | Protocols for communication | Low quality |
| | Average | | Normal |
| | Clear | | High quality |
| Team norms | Not clear | Procedures for communication | Low quality |
| | Average | | Normal |
| | Clear | | High quality |

Another categorization of context factors defines internal and external factors. Internal factors include situational and task related factors such as cognitive load, individual technical skills, individual social skills, team operational skills, team general skills, team soft skills, team structure, and team roles. External context factors include environmental, workspace, and organizational factors.

### 4.3.4 Individual vs. Individual Team-related Factors

An individual operator can be viewed from the point of view of technical skills, cognitive limitations or characteristics, and social skills; hence the perspective from which we are determining our context factors is important. For an individual there are characteristics such as “general experience in NPPs” that are important in characterizing that individual’s knowledge and skills level and ultimately behavior.

However these do not consider the fact that the individual is part of a team. These factors in this research are referred to as individual PSFs. In addition, there are context factors that are about the individual operator but relate to the fact that he is a part of a team. For instance, “training for the role” or “commitment to the role” are such factors.

These two categories of context factors along with the operator’s cognitive characteristics such as level of stress and task related factors such as information and workload shape the way the operator acts inside the team. Table 17 lists the individual factors used for this purpose and their associated levels. Note that “quality of workspace” refers to the perception of comfort that the operator has inside the control room.

Table 17: Individual factors

| Individual Factors: General | | | |
|---|---|---|---|
| OAT/OCT/ODM | | OAT/OCT/ODM | |
| **Factor** | **Levels** | **Factor** | **Levels** |
| Experience | Less than adequate | Quality of workspace | Uncomforatble |
| | Good | | Normal |
| | Professional | | Comfortable |
| Training | Less than adequate | Training for the role | Less than adequate |
| | Special training | | Special training |
| | Normal training | | Normal training |
| Level of fatigue | High | Experience for the role | Less than adequate |
| | Average | | Good |
| | Low | | Professional |
| Level of stress | High | commitment to the role | Low |
| | Average | | Average |
| | Low | | High |
| Level of attention | Low | Motivation for the role | Low |
| | Average | | Average |
| | Good | | High |
| Quality of procedures | Low | Concern for quality | Low |
| | Average | | Average |
| | Good | | High |
| Quality of interface | Low | Concern for safety | Low |
| | Average | | Average |
| | Good | | High |

There are other role-related context factors that are important in case of the team leader. These factors include: "Leader participation" and "level of enforcement" and so on. Hence there are additional factors that characterize the supervisor behavior; these factors are listed in Table 18.

Table 18: Individual factors (Leader)

| Individual Factors: Team Leader | |
|---|---|
| ODM | |
| Factor | Levels |
| Leadership knowledge | Less than adequate |
| | Average |
| | Adequate |
| Leader's participateion | Less than adequate |
| | Special training |
| | Normal training |
| Enforcement of procedures | Low |
| | Average |
| | High |
| Supervision | Low |
| | Average |
| | High |
| Organizational autority | Low |
| | Average |
| | High |
| Quality of procedures | Low |
| | Average |
| | High |

PSFs are modeled using causal maps, which are directed graphs reflecting the influence path from a behavior metric into the error context via PSFs, and the "intervening variables" and their interdependencies. The development of a causal map offers a way of highlighting both the complexity within and the interconnection between the TPSFs.

We reviewed the existing literature on PSFs in section 3.5.1 of Chapter 3. The quality of verbal communications, clearly defined roles and duties, standard communication structure and protocols, and the quality of procedures and leadership are among factors that have been identified as affecting knowledge sharing, problem solving, negotiation of goals and action selection processes inside the team, by Patrick et al.

(2006), Gibson et al. (2008) and Groth (2009). Team cohesion, team coordination and communication quality have been addressed as potentially dominant team-related PSFs by Kim et al. (2003), Patrick et al. (2006), Boring (2006) and Groth (2009). Among individual PSFs, stress, attention, task complexity, experience/training, and time constraint have been mentioned as important PSFs in the studies by Gibson et al. (2008), and Boring (2006).

**Table 19: List of PSFs**

| Category | PSF | Definition |
|---|---|---|
| Individual | Experience | Familiarity with the task based on operational experience in a similar task |
| | Training | Familiarity with the task based on training for the same task |
| | Level of fatigue | Level of undesirable physical condition which lowers the productivity |
| | Level of stress | Level of cognitive and emotional pressure that impedes the operator from easily completing a task |
| | Level of attention | Cognitive resources directed to the task |
| | Quality of procedures | Existence and use of formal operating procedures |
| | Quality of interface | Human factor and ergonomics considered in the design of interface with system |
| | Quality of workspace | Human factors and ergonomics considered in the design of workspace |
| | Training for the role | Familiarity with the role within the team based on training for the same role |
| | Experience for the role | Familiarity with the role within the role based on experience in a similar role |
| | commitment to the role | commitment to the objectives of the role and team |
| | Motivation for the role | Enthusiasm and interest in the role |
| | Concern for quality | Personal preferences on issues related to quality |
| | Concern for safety | Personal preferences on issues related to safety |
| | Leadership knowledge | Familiarity with the leadership role and its responsibilities based on knowledge |
| | Leader's participation | Willingness of team leader to participate in the task |
| | adherence to procedures | Encouraging team members to follow procedures |
| | Supervision | level of monitoring and feedback by team leader |
| | Organizational authority | Level of authority provided by the organization for the individual |
| Team | Training as a team | Extent and length of time this team has been receiving training together |
| | Experience as a team | Extent and length of time this team has been working together |
| | Compliance to procedures | Commitment to follow procedures |
| | Team diversity | Diverse team members regarding their qualifications and skills |
| | Shared goals | The extent to which team members share the objectives of the team |
| | Authority gradient | Shared authority inside the team |
| | Mutual trust | Level of trust and respect inside the team |
| | Team goals | The extent to which team goals are well defined |
| | Team roles | The extent to which team roles are well defined |
| | Team norms | clarity of team accepted behavioral tendencies |
| | Team responsibilities | The extent to which team members responsibilities are defined |
| | Reference documents | Existence and quality of additional supportive documents for the team's tasks |
| | Standards & Regulations | Existence and quality of regulations for team team's tasks |
| | Following leader | Willingness of team to follow the leader |
| | Following protocols | Willingness of team to follow protocols and standards |
| | Responsiveness | Speed and extent of team's response to change in system state |
| | External disruptions | Team's ability to work in an environment with disruptive characteristics such as non-task related noise and presence of non team members |
| | Level of Comfort | Quality of workspace with respect to level of comfort |
| Communication (Link) | Protocols for communication | Existence and adherence to format and standards of communication |
| | Procedures for communication | Existence and use of formal procedures dedicated to communication |
| | Communication skills | Sender and receiver's skills with respect to various modes of communication |
| | Format | Clarity of message with respect to format and use of language |
| | Familiarity with device | The degree of sender's and receiver's familiarity with use of communicational device |
| | Availability of device | whether the device is installed and functional |
| | Accessibility of device | whether the device is accessible to operators |
| | Ease of use of device | Ease or complexity of using the communicational device |
| | Accuracy of device | Quality of device in transferring message from sender to receiver |

The discussed model of context factors determines the operator's profile which is the adjustable part of operator's object model (See Chapt. 5) . Table 20 lists the operator's functional model. This model along with the operator's profile forms the operator object model.

**Table 20: Operator functions**

| Operator Main Functions |
|---|
| Receiving input information/Receivig input Message |
| Processing Input Information/Processing Input Message |
| Making Decision/Creating Output Message |
| Executing Action / Sending Output Message |
| Detecting Error |
| Indicating Error |
| Correctiong Error |

Table 21 summarizes the human operator functions and team functions of Extended IDAC framework and lists how PSF categories have been assigned to failures of such functions. The PSFs model is used to quantify the probability of error for each of operator's basic tasks discussed in the error model.

**Table 21: Context factors and operator's functions**

| Function | Performance Shaping Factors |
|---|---|
| Availability (individual) | Fatigue, stress, attention, quality of workspace |
| Availability (information) | Since the plant is responsible for providing information, it is assumed that information is always available unless there is a failure in plant that would be detected based on the other information sources providing data |
| Availability (message) | Device-based Communication: communication skills of sender & receiver, communication format that sender and receiver, familiarity of sender & receiver with using the device, availability of device, Accessibility of device, ease of use of device and accuracy of device, team communication and team cohesion |
| | Verbal Communication: communication skills of sender & receiver, communication format that sender and receiver use, team communication and team cohesion |
| Information/ Message Processing (individual) | Experience, training, stress, attention, information load, time load, quality of interface |
| Decision making (message) | Experience, training, fatigue, stress, attention, information load, time load, quality of procedures, training for the role, experience for the role, commitment to the role, motivation for the role, concern for safety and quality, team cohesion, team coordination and team communication |
| Action execution/ message handling (individual) | Experience, training, fatigue, stress, attention, information load, time load, quality of interface and quality of workspace |
| Error detection (individual) | Experience, training, fatigue, attention, information load, time load, quality of procedures, quality of workspace, training for the role, experience for the role, commitment to the role, motivation for the role, concern for safety and quality, team cohesion, team coordination and team communication |
| Error indication (individual) | Experience, training, fatigue, stress, attention, information load, time load, quality of procedures, quality of workspace, training for the role, experience for the role, commitment to the role, motivation for the role, concern for safety and quality, team cohesion, team coordination and team communication |
| Error correction (individual) | Experience, training, fatigue, stress, attention, information load, time load, quality of interface, quality of workspace, training for the role, experience for the role, commitment to the role, motivation for the role, concern for safety and quality, team cohesion, team coordination and team communication |
| Information/ Message Processing (team) | Experience, training, information load, time load, quality of interface |
| Decision making (team) | Experience, training, stress, attention, information load, time load, quality of procedures, training for the role, experience for the role, commitment to the role, motivation for the role, concern for safety and quality, team cohesion, role awareness and leadership |
| Action execution/ Message handling (team) | Experience, training, fatigue, stress, attention, information load, time load, quality of procedures, quality of workspace |
| Error detection (team) | Experience, training, fatigue, attention, information load, time load, quality of procedures, quality of workspace, leader training, leader participation, enforcement and supervision, authority inside team, training for the role, experience for the role, commitment to the role, motivation for the role, concern for safety and quality, team cohesion, role awareness and leadership |
| Error indication (team) | Experience, training, fatigue, stress, attention, information load, time load, quality of procedures, quality of workspace, leader training, leader participation, enforcement and supervision, authority inside team, training for the role, experience for the role, commitment to the role, motivation for the role, concern for safety and quality, team cohesion, role awareness and leadership |
| Error correction (team) | Experience, training, fatigue, stress, attention, information load, time load, quality of procedures, quality of interface, quality of workspace, leader training, leader participation, enforcement and supervision, authority inside team, training for the role, experience for the role, commitment to the role, motivation for the role, concern for safety and quality, team cohesion, role awareness and leadership |

### 4.3.5 Dynamic PSFs

This research also models a two dynamic PSFs associated with the dynamics of the system and change during the course of the scenario. The two Dynamic PSFs considered are:

1) Information load
2) Time load

The load on team members increases when abnormal signals are detected. The effects of Information load on cognitive and nontechnical skills have been studied by researchers in different high-risk environments (McGrath et al., 1994), (Flin et al., 2004) and (Flin et al., 1998). Overload comes in two forms: the tasks themselves are time-urgent and must be done within a certain limited time window or not at all. In such cases, task overload translates into a matter of speed of response. In the other form, overload simply refers to having too many things to do at one time, or too many stimuli to attend to at once, even though the tasks themselves do not have a critical time component. This kind of overload can be translated into a matter of priority and sequence of tasks.

In this research the information load relates to the number of active alarms at each time step. Having too many alarms being on at the same time increases the probability of failure of human cognitive functions. The information load is automatically calculated by having access to the number of activated alarms (and indicators) vs. total number of alarms and indicators. The levels of Information load are defined in the same fashion as other PSFs. For instance if the total number of alarms is 8 and just 2 of them are activated, the information load is considered to be low. Similarly, high information load means having more than 6 active alarms at the same time.

In order to calculate the Time pressure load, we used a fixed value as the critical time; the critical time refers to the average time needed for the system to reach the undesired state, if the operators do not interfere and perform the necessary control actions. This value is different for each setting and need to be adjusted before the simulation. Time pressure load is defined as the ratio between the perceived required time to perform the task and the perceived available time. Hence time load increases while team is approaching the end of the scenario.

### 4 .3.6 HEP Quantification Approach

Once the set of performance shaping factors associated with each functionality block is determined, the SLIM[10] method (Embrey, 1984) is applied to calculate the probability of failure for each operator function. SLIM is a systematic method for positioning the likelihood of success of a task on a scale as a function of the differing conditions influencing successful completion of tasks. The probability is calculated based on the following equation:

$$Pr = Pr_0 \times e^{-a \times SLI}$$

"$Pr_0$" is a basic value for probability of failure of the function, "a" is an adjusting constant and SLI is defines as:

---

[10] Success Likelihood Index Method

$$SLI = \sum_{i=1}^{N} w_i \times PSF_i$$

Where "$w_i$" is the weight associated with each performance shaping factor and "$PSF_i$" is the value assigned to that factor. The probability of success for tasks based on this scale can be determined by calibrating the scale with reference tasks as assessed by the same judge or team of judges. The SLIM approach relies upon expert judgment to determine the weight (importance) of each PSF with regard to its effect on the reliability of the task. The experts assign a numerical rating for each PSF under consideration. Once the weights and ratings have been assessed by the judges, they are multiplied together for each PSF and then summed across PSFs to arrive at the Success Likelihood Index (SLI). Once the SLI is determined, HEP or in this case Pr can be calculated as discussed above.

## 4.4 Communication Model

Under high workload conditions communication inside a team becomes very important since the team attempts to create a shared understanding of the situation. Communication is a dynamic process involving the exchange of information and meanings between senders and receivers, both knowingly and unknowingly. Team members are simultaneously sending and receiving messages and communicate internally.

The communication model used in this research considers a number of roles and contributing factors:

- The Sender (speaker) is the source of the message that is being transferred.

- The message is the information that is being transferred.
- The Receiver (listener) is the destination of the message, where the message is directed.
- The channel which connects the sender and the receiver; usually different channels are available and the number of channels may vary. In Extended IDAC communication is explicit (verbal), and is either face-to-face or device-based.
- The feedback can be in the form of a nod, return message, or any kind of confirmation or acknowledgement for receiving the message. Since all communications in Extended IDAC are explicit, all feedbacks are in the form of verbal messages.
- The distractions in communication serve as barriers, blocks, and create problems in communication. Distractions can be relative to time, external factors, internal factors, or semantics. In Extended IDAC distractions are captured and modeled via PSFs, e.g. “external interruptions” under team factors category.
- The communication environment may be relaxing or stressful; the context of the situation or personal moods can impact the environment.

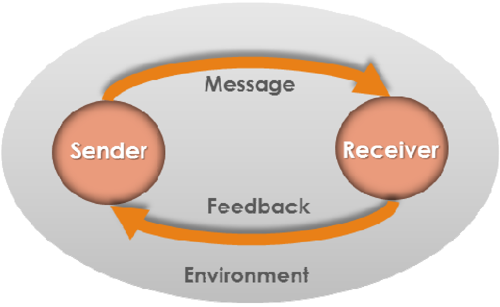


Figure 32: A typical closed loop communication link

Any communication link in a control room has three important elements: Sender, Receiver and the Message (Figure 32). Characteristic of the sender, receiver and the message are the foundations to a successful communication. The figure shows essential parts of communication, whereas the arrows represent the communication channels. The most important sender characteristics are the credibility and attractiveness. The creditability of the sender is defined as the perceived expertise and trustworthiness of the communicator. The personality characteristics of the receiver, such as intelligence, level of language skills, and self-esteem are also important. The relationship of the receiver to the message is another factor since people are more open to arguments that are within their range of acceptability.

The sophistication, level of emotion, and aesthetics of the message are considered among critical factors (Levi 2007). There are a few other issues about the team composition that are important for teams during operation such as unhealthy vs. healthy conflict, and distribution of power and diversity among team members. However, the study of these topics is out of the scope of this research.

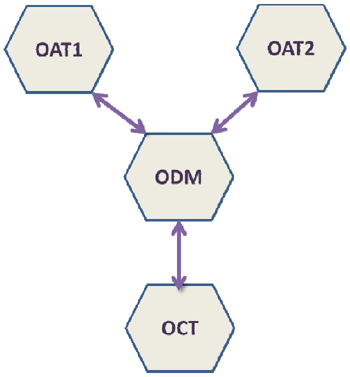


Figure 33: Wheel (Star) communication network

There are a number of ways to organize communications networks, each with different advantages. Networks of communications may be:

- Centralized - where a leader directs the flow of communication
- Decentralized - each member of the group has access to the ideas of all other members

Communication in control rooms usually follows the structure of wheel networks. The wheel (star) communication network (Figure 33) is a centralized network around the supervisor. To communicate appropriately, the ODM acts as a 'hub', distributing information to the rest of the team. There is little or no connection among the rest of the team. In this structure the leader controls lines of communication and ensures that messages are passed efficiently.

Collaboration is an important concept in the context of a complex system. Collaborative work entails cognitive aspects of communication (Levi 2007). Group members send, receive and store different kinds of information within the group as well as outside sources. Collaborative work also entails emotional and motivational aspects of communication. Human conversations are considered as a series of interlocked communication cycles. Each cycle involves a series of operations on a message: composition, editing, transmission, reception, feedback (acknowledgment of receipt), and reply. Since nuclear power plant operators work usually in small groups having face-to-face and synchronous conversations, these cycles become extremely important in studying their communicative interactions. In face-to-face communications, each member can communicate to all others via a wide spectrum of communication modalities: verbal, Para-verbal (e.g. voice inflections), and Nonverbal (e.g. smiles and gazes) (Levi 2007).

In communications with outside the control room, the reliability of the communication device and the environmental conditions should be taken into account as well. Communication analysis methods often involve using transcriptions of communication for in-depth examination. A post processing routine can be used to derive a number of different communication measures that reflect the quantity, directionality, timing and type of communications that occur. Most measures are calculated per unit time, and can be captured at the individual level or at the team level.

## *4.5 Object-Based Modeling and Simulation Approach*

Model-based evaluation through simulation is an alternative to the use of control room simulators for human performance assessment and is mentioned here because of the large amount of ongoing research on this approach. Analytic simulation is a quantitative process that has been used to study systems early in the design process and to imitate the behavior of very complex systems. This method is useful in situations where it may not be possible to get large numbers of subjects or where it is difficult to reproduce environmental conditions, and where the cost to develop systems for a complete simulator may be prohibitive.

While model-based simulation techniques are becoming popular in system risk analysis, different representation languages for model development have emerged, each with strengths but also limitations in scope and application. An ideal technique should be straightforward, easy to manage, and capable of handling operator cognitive activities and interactions, as well as system dynamics and feedback loops. Object-based methodologies are the most preferred methods for real time and event driven system simulation. They are extensively used in knowledge representation applications. By applying this methodology, the behavior is managed automatically and inside the component (object) which facilitates the modification of individual object properties with or without affecting other parts of the system.

Also the response to any change in the system is obtained intelligently. In object-based modeling methodologies the main idea is to simply replace every piece of the system with an "intelligent" entity that represents its properties and mimics its behavior. The complex system is broken down into a number of domains whereas large domains are partitioned into subsystems.

An object is defined as an entity that is uniquely identifiable and has attributes, states and operations that collectively determine its behavior (Sully, 1993) and (Rumbaugh et al., 1991). Objects collaborate by responding to requests from other objects to carry out specified operations.

In order to identify objects, systems are broken down into a number of cooperating subsystems which are reasonably independent and self-contained. Figure 34 illustrates this process. First the domains of elements are identified. These domains are a number of distinctly different subject matters. Then, large domains are partitioned into subsystems (Shlaer et al., 1992). Objects are identified in the context of the associated subsystems.

A main advantage of using object based modeling is the fact that individual objects may be modified with or without affecting the other parts of the system. Objects having similar meaning and purpose are grouped together to form a class. Association links define the relationships among classes. Once the objects are constructed and submitted to the system, the associated blocks (simulation models) can be customized. The system is defined with a detailed infrastructure as a network of connected abstract block diagrams; and just the simple question, "connected or not?” identifies the links. A complex system is a collection of many of objects with different natures cooperating together toward the realization of its fundamental objectives.

After objects in each group are identified, their behavior needs to be modeled; hence, the next step is knowledge acquisition for scenario generation, which is basically to acquire additional information about the system and its environment. This knowledge is used to automatically generate risk scenarios. In the case of object based models, this step includes translating the success logic into failure logic, assigning the probabilities of failure for objects or functionalities at each time step, and to identify a primary set of failure modes for the system. The level of details for failure logic is driven by the analysis objectives and the availability of data. Having the states of components and events, the failure logic of the system and enough rules and conditions, the final state of the system can be determined for any given condition.

In order to replace a piece of system with its representative model for simulation goals, the properties such as time-to-failure distributions, as well as the probabilities of failures per demand are included in the model.

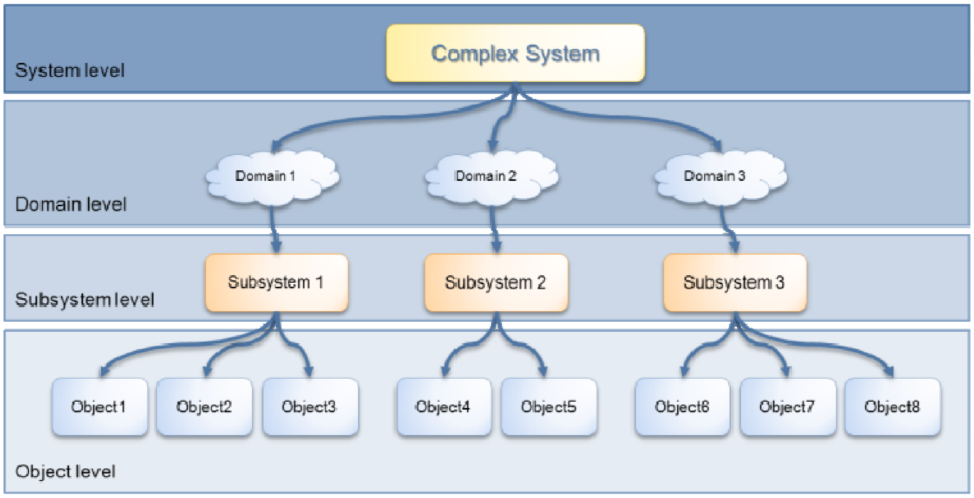


Figure 34: Objects in the context of a complex system

After development of object-based models for the operating crew and their interactions, simulation is conducted to generate operating scenarios and ultimately a set of failure modes. High-level behavioral models and predefined sets of simple rules are used to model the interactions among functional entities and are considered the basis of simulation autonomy and scenario generation.

Hence, the representative probabilistic simulation models for system elements are developed through the following steps:

(1) The Model Development stage including using a Top-Down approach for identifying object classes with attributes and behaviors, and a Bottom-up approach for identifying object class association links and development of integrated simulation model.

(2) The Model Interpretation stage including knowledge acquisition for scenario generation and developing model of system dynamics.

### 4.5.1 Application in Investigating Crew Behavior

The structure of a complex system permits delivery of desired functionality through specific component interactions or behavior. The modeling paradigm should be capable of representing the desired functionality of the individual components, their structure, as well as their interactions. The components in such model do not act in isolation but instead interact with each other. A common source of error or system vulnerability is a mismatch at the interface of the blocks/components where data is interchanged that can lead to system failure in the form of an incident/accident. The complete communication model of the system elements needs to be developed as well to address the variety of interactions. The objective is to capture the operational knowledge of the complex multi-dimensional system, and to apply this knowledge for obtaining representative models for its elements.

In modeling a NPPs control room, there are three different categories of objects that need to be constructed: the hardware system is composed of hardware elements such as pumps and valves; the operating crew composed of individual human operators; and the control panel composed of alarms and indicators. “Active objects”, such as the equipment operator, have different ways of acting on “passive objects”, such as informative messages. For the operating team, these ways include: create, send, or receive a message.

Our methodology highly depends on the transformation of “functional block diagrams” into object diagrams to represent the structure of subsystems. By transformation of “reliability block diagrams” into object diagrams, the complex system is defined with a detailed infrastructure as a network of connected abstract block diagrams. High level behavioral models and predefined sets of simple rules are used to model the interactions among functional entities and are the basis of simulation autonomy and scenario generation. Since the simulation model needs to be defined by the user in the model editor, the application of custom-defined libraries facilitates the process of defining the simulation model.

A framework is developed inside MATLAB Simulink to accomplish the above tasks that includes a customized library of pre-defined blocks. Since the target application domain for this research is the control room of a complex environment such as a NPP, the simulation library is a collection of pre-defined models of human operators, and different hardware components.

While the general characteristics are encapsulated in the form of object class attributes and operations, there is a capability to add or remove to the set of embedded characteristics to account for personal differences in terms of basic attributes and PSFs. Once the objects are constructed and submitted to the model editor as a simulation library, the associated blocks are customized to facilitate defining the model. The system is defined with a detailed infrastructure as a network of connected abstract block diagrams. The operators differ in their personal characteristics and cognitive capabilities, accounted for in the model by using different quantities for basic attributes and PSFs. These models are then incorporated together to form the integrated simulation model. The dynamics of behavior are captured by using an inside controller for each object structure. The controller is responsible for branch generation.

The approach involves the development of object-based simulation model for individual operators, the plant, and the operating crew based on the conceptual framework for team processes: “collaborative information-processing”, “shared decision-making”, and “distributed action-execution.” It also involves the development and integration of an “error management module”, and team PSFs.

Finally, team behavior under a specific scenario is studied and explained using simulation results. By representing the complexity of the system using modular decomposition, various attributes and methods are introduced for each module which combined together form the integrated behavior of the entire system (Mao et al., 2008).

After the development of the simulation model is complete, a simulator module (code) is used to assign control parameters and simulation variables for each run; the simulator module is developed to cover a wide range of possibilities in order to provide a complete and consistent system profile. The simulation controller is responsible for actuating accident initiating events and plant hardware failures as well as setting up sequence termination criteria. The Simulator is responsible to generate the detailed behavior of the system based on the multilevel simulation model. Each transition for system state is conditioned on its duration, time, state of another component and other parameters. The branching points in the model are designed such that not only the failure of system elements and their functionalities but also the team-related errors such as miscommunication and misunderstandings generate different paths and scenarios in the system risk profile. During the simulation the states of various subsystems and operator responses dynamically change and time dependent scenarios are generated.

### 4.5.2 Object-based Crew Model

In object-based methodology, actors are active real world objects that produce and consume values during simulation (Chang et al., 2007). Actor's attributes are periodically updated. This research considers each member of the team to be a modified version of an abstract class called "operator". In this model, ODM, OAT1, OAT2 and OCT are actors which have been defined by customizing the same set of general attributes and functions by enabling or disabling some default features. Passive objects are data objects which are used for storing data or transition of data.

Since the communication among team members is modeled through using messages, a message would be an example of a passive object. Active objects have methods to be used on passive objects. For the operating team, these methods include: to create, send or receive a message. The model of a single operator communicates to the other operators via sending and receiving messages and interacts with the system via receiving information and performing action (Figure 35).

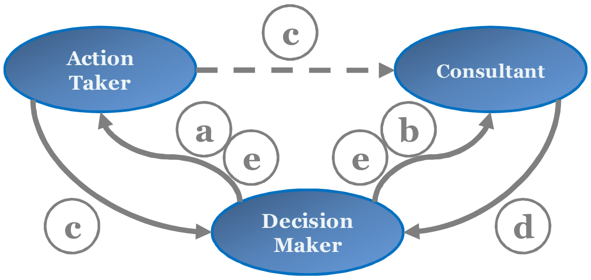


Figure 35: Communication links

The types of messages transferred in communication loops shown in figure 26 are:

a) Request for information /action

b) Request for advice on diagnosis

c) Report of status information/acknowledgement

d) Report of advice on diagnosis

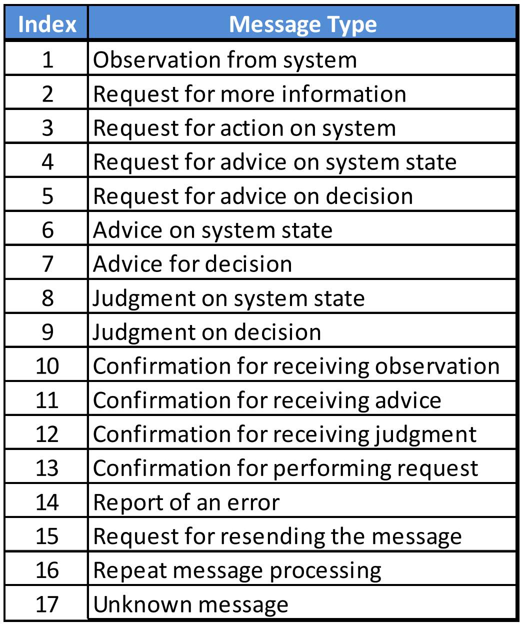
e) Report of judgment on diagnosis

The operating teams are connected to each other via message transmission and responding activities. This model implements all interaction links via: 1) "create message", 2) "send message", 3) "receive message" functions. The perceived message is an input to the decision making module as well the perceived system state and the new message is created as an outcome of an action planning block; however, once the message is created it is being sent by the action execution module. The message is the center of any communication link.

In object-based approaches, there is a separate class for the elements that make interactions possible. There are abstract protocol ports defined to accomplish interfacing. These ports implement communications to guarantee "handshaking" between blocks. It is important to separate interface from internal behavior so that the communication and synchronization can be implemented.

In the context of this system the message is either a request or a reply to a request or an acknowledgement / confirmation and is distinguished based on its sender, its receiver and the type of data that is transferred by the message (message content). Since the message is either a report on observation or error, a judgment on diagnosis and strategy, advice on diagnosis or strategy or a request for action or message (including repeating an action) or simply just the confirmation, the message content would be information or a recognized error, a diagnosis, strategy, or action or simply nothing. The message is considered a passive object, which means it is the subject of manipulation for a group of active objects or actors. Table 22 represents the kind of messages used in this methodology.

**Table 22: Message categories**



| Index | Message Type |
|---|---|
| 1 | Observation from system |
| 2 | Request for more information |
| 3 | Request for action on system |
| 4 | Request for advice on system state |
| 5 | Request for advice on decision |
| 6 | Advice on system state |
| 7 | Advice for decision |
| 8 | Judgment on system state |
| 9 | Judgment on decision |
| 10 | Confirmation for receiving observation |
| 11 | Confirmation for receiving advice |
| 12 | Confirmation for receiving judgment |
| 13 | Confirmation for performing request |
| 14 | Report of an error |
| 15 | Request for resending the message |
| 16 | Repeat message processing |
| 17 | Unknown message |

ODM is the person who is connected to the rest of the group both ways; hence, the communication network is centralized around the decision maker. The advantage of such communication layout is that the team communication is clear and facilitated; this also gives higher level of coordination inside the group. The disadvantage would be the fact that the team focuses on ODM judgments and beliefs rather than discussion. OAT, ODM, OCT can take the active roles of the communication loops (as Sender or Receiver) interchangeably. OAT is a licensed operator who is responsible for interacting with the equipment. He/she is responsible to receive ODM's command to check an indicator or change a component state. Without ODM's command OAT is not supposed to have any physical interaction with the control panel (e.g., change a component state). OCT is an operator who has professional knowledge of the operating system. In NPPs OCT (e.g., technical advisor) is not a licensed reactor operator, so he/she is not supposed to have any physical interaction with the control panel. The responsibility of OCT is to give advice to ODM. In order to develop object-based model of the operating crew, the main object classes (active and passive objects) should be identified, as well as the associations among classes. Extended IDAC introduces another role (OAT2) who is an operator action taker but is located outside the control room.

### 4.5.3 MATLAB Simulink & CREWSIM

MATLAB Simulink provides a wide range of capabilities for simulation modeling by supporting block diagram style object modeling and embedded MATLAB functions for modeling the behavior. A custom-defined library (CREWSIM) is developed to facilitate the process of defining the simulation model and includes a collection of pre-defined models of human operator, communication links, initiator blocks and different hardware components. Such pre-defined classes of components can be desirably instantiated and customized to mimic the requested behavior in the specific domain. These component classes include some general characteristics encapsulated in the form of attributes and operations and as well as the blank states and the ability to add to or remove from the set of embedded characteristics. By assigning states and manipulating the set of attributes and operations for these classes, the user is able to obtain system model. The individual operator's model structure is based on IDAC methodology. IDAC decomposes the operator's cognitive flow into: Information-processing (I), Decision-making (D), and Action-execution (A). General characteristics are encapsulated as object class attributes and operations, with the flexibility of being edited to account for personal differences and performance shaping factors (PSFs).

The Simulation controller is a code that is responsible for data manipulation, information dissemination, inference, calls to external routines and command implementation and need to be modified for each application. The dynamics of behavior is captured by using a local controller inside each object structure, responsible for branch generation. The simulation algorithm generates a dynamic event tree based on branch points associated with the internal and external error reference points and the lowest level functionalities of each simulated module. Each branch represents distinct combinations of system and operator states. Once a system end-state is reached, the scenario ends.

# Chapter 5: Case Study

The approach is demonstrated through a case study for the operating crew of a four-steam generator feed-water system under a postulated accident scenario (pipe-break). A configuration of four operators is being studied as a reasonable approximation of an NPP operating crew while interacting with the feed-water subsystem of the plant. The crew module consists of the Decision Maker, the Action Taker, and the Consultant roles as well as face-to-face & device-based communication channels among them. The integrated simulation model represents the complex system and consists of the plant model (hardware system) as well as the crew model. Five major subsystems for the hardware system are characterized and included. These subsystems are the following: main subsystem, intermediate subsystem, emergency subsystem, steam generating subsystem and output subsystem. The major system components are: boiler feed-pumps or main feed-pumps, emergency feed-pumps, control valves, pipes, steam generators, and heaters. The governing equations are mass balance equations, which generate system dynamics. The platform for developing the feed-water simulation model is MATLAB Simulink. The operating team consists of the equipment operator (OAT2), located in the plant, the equipment operator (OAT1), the shift supervisor (ODM) and the shift technical-advisor (OCT), located in the control room. Each operator is responsible for a variety of tasks, all following the general cognitive steps of IDAC, with different associated individual characteristics as well as responsibilities. The communication network is centralized around the decision-maker. All operators take active roles in communication loops (as sender or receiver) interchangeably. The crew model has been also developed in

MATLAB Simulink platform and has been added into the plat model to form the integrated simulation model for the complex system.

## 5.1 Plant Model

In a typical steam generator power plant (Figure 36), the steam is produced, transferred to the turbine, and used for energy generation; the condensed water is then returned to the boilers to be used again in the cycle. A four steam generator plant has four identical steam generators with integral pre-heaters which transfer the heat from the heavy water reactor of the primary heat transfer system side to the light water on the secondary side. The feed water system supplies normal feed water to the steam generators which transfer the heat from the heavy water reactor of the primary heat transfer system side to the light water on the secondary side. The temperature of the incoming feed water is increased to the boiling point and subsequently evaporated. The feed water system comprises the main feed water pumps power and auxiliary feed water pumps. The auxiliary feed water system supplies feed water to the steam generators at full operating pressure in the event that the main feed water system is unavailable.

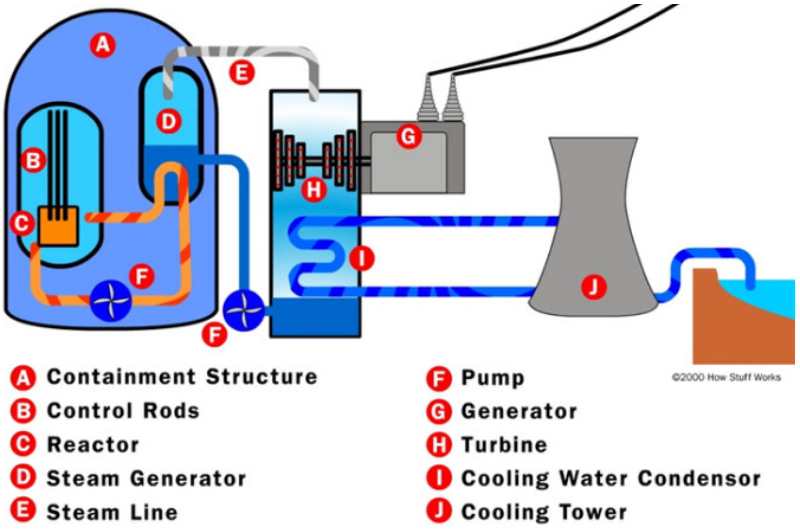


Figure 36: Steam generator plant

One of the main functionalities of the control room of any NPP is to maintain the steam generators’ water level at a desired value by regulating the feed water flow rate. Ineffective feed water control has been the root cause of many of reactor shutdowns, which leads to severe economic loss (Zhao et al., 2000). Therefore it is important to study the water level regulation process, through developing a technical model and application of simulation methods. The structure of this model need to be established based on the physical understanding of the process. Since this research is investigating the dynamic behavior of the NPP operating crew, to obtain a more realistic representation of the entire system, the crew model is designed to be operating on the feed water system model. The simulation model is the integration of the so called hardware and human models. The hardware model of interest is the model of a simplified representation for a feed water system in a four steam generator plant (Figure 37 and Figure 38). This model includes five subsystems, thirty four valves, six boiler feed pumps, four heaters and four steam generators. The control panel designed for such a system includes many alarm indicators, component indicators and physical parameter indicators. The major system components are: Boiler Feed Pumps (BFP) or Main feed pumps (MFP), Emergency feed pumps (EFP), Control Valves (V), Pipes (J), Steam generators (SG), and Heaters (HTR). Table 23 lists system major components.

The steam generator level control system balances feed water to steam flow for all operating conditions. Control is performed by the distributed computer control system; the operators control the flow rate in pipes and the water level in steam generators by using the different control valves. Pumps, Valves and Heaters can fail on-demand during the system operation; such events are the basis of branch generation in the simulation. Once a component fails it is assumed unrecoverable.

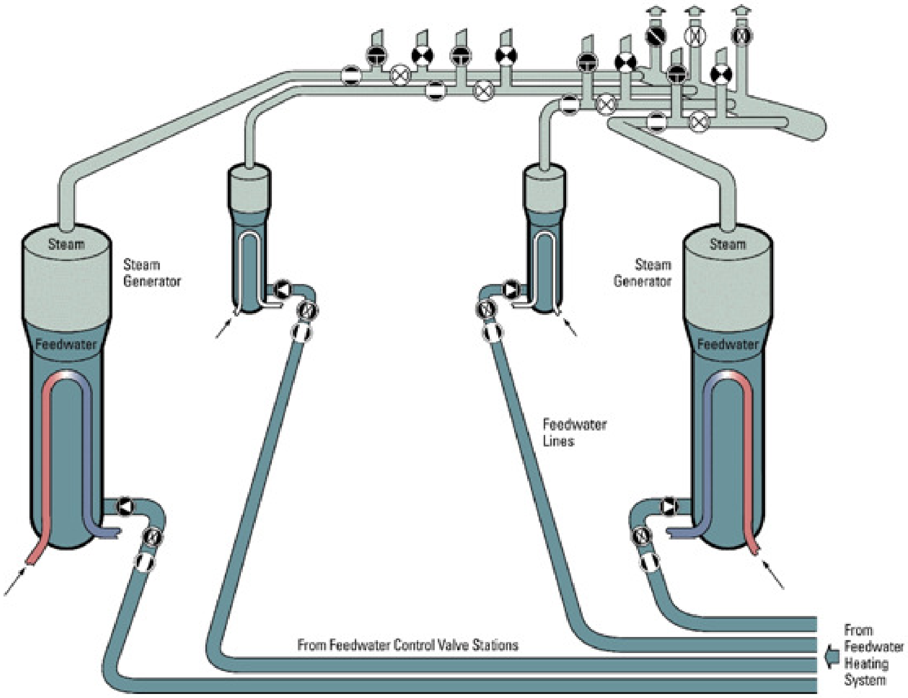


Figure 37: Four steam generator plant and feed water system

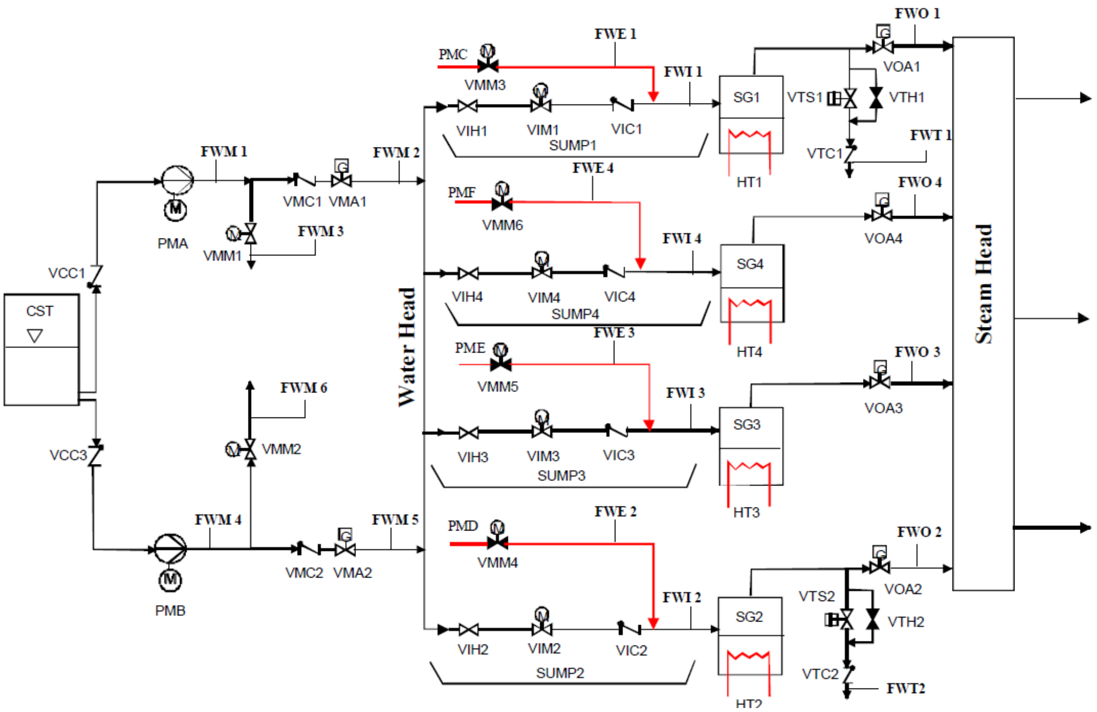
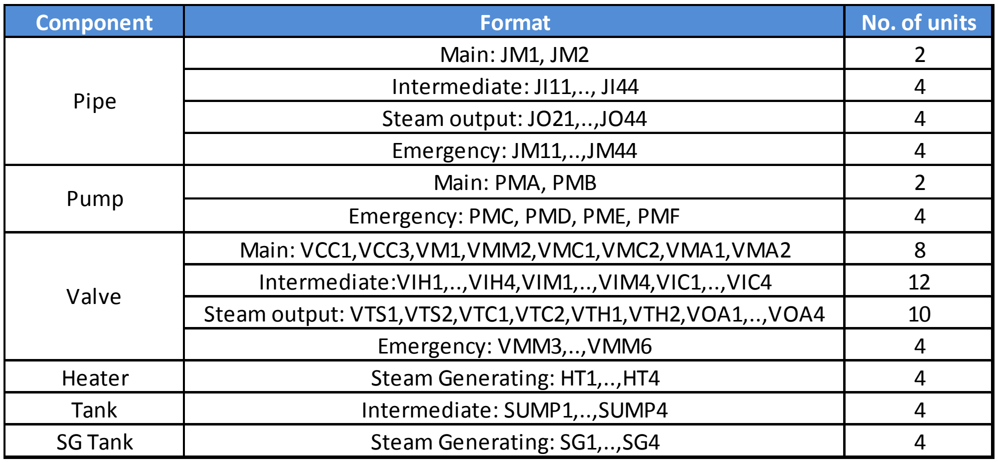


Figure 38: A simplified version of the feed water system

The Main Sub-system is composed of two main feed water paths which carry the water to the water head. The Intermediate Sub-system includes four paths each of which leads to a steam generator. The Steam-Generating Sub-system includes four steam generators and their heaters. The Steam-Output Sub-system includes all the output paths from the steam generators to outside of the plant. The Emergency Feed water Sub-system includes four emergency feed pumps and their injection paths. Since the goal is to develop an object based model, identified active objects in this system are: Main and Emergency Feed Pumps, Heaters, Steam Generators, Valves, Pipes. This simple model is a good representation of plant operations (Chang, 1999). Components are modeled as objects to reflect their different nature and characteristics of elements and to improve model reuse. The governing equations are mass balance equations which generate faster simulation runs. This model has been designed and developed using the object based modeling methodology. The platform for implementing this model is MATLAB Simulink. Simulink works well for multi-domain simulation purposes and provides customizable sets of block libraries for representing a variety of different concepts. The application of embedded MATLAB functions is allowed inside a simulation block which makes it a good choice for practicing the concepts of encapsulation and information hiding.

Table 23: Hardware system major components



| Component | Format | No. of units |
|---|---|---|
| Pipe | Main: JM1, JM2 | 2 |
| | Intermediate: JI11,.., JI44 | 4 |
| | Steam output: JO21,..,JO44 | 4 |
| | Emergency: JM11,..,JM44 | 4 |
| Pump | Main: PMA, PMB | 2 |
| | Emergency: PMC, PMD, PME, PMF | 4 |
| Valve | Main: VCC1,VCC3,VM1,VMM2,VMC1,VMC2,VMA1,VMA2 | 8 |
| | Intermediate:VIH1,..,VIH4,VIM1,..,VIM4,VIC1,..,VIC4 | 12 |
| | Steam output: VTS1,VTS2,VTC1,VTC2,VTH1,VTH2,VOA1,..,VOA4 | 10 |
| | Emergency: VMM3,..,VMM6 | 4 |
| Heater | Steam Generating: HT1,..,HT4 | 4 |
| Tank | Intermediate: SUMP1,..,SUMP4 | 4 |
| SG Tank | Steam Generating: SG1,..,SG4 | 4 |

There are four emergency boiler feed pumps (PMC, PMD, PME, and PMF) which provide emergency water injection into the SGs to prevent them from getting dried out in special cases. The water source for these four emergency pumps is also the CST. The electric power for heaters in the system can be cut off immediately in case of emergency. Each SG water input flow rate could be controlled by the valves located in the Intermediate Sub-system paths. If a pipe break occurs at time zero, certain flow mismatch alarms are activated; once the operator perceives the activation of alarm, the cognitive processes are initiated to recognize the event and perform mitigation activities. All the steam generators' water levels decrease due to the reduced input after such an initiating event. When any SG water level is low (low-level) the emergency pumps automatically start and become ready. If the SG water level continues to decrease and reaches the low-low-level, the corresponding safety injection control valve opens and the safety injection coolant injects into the SG (Chang, 1999).

The major components, Boiler Feed Pumps or Main Feed Pumps (BFP or MFP) and Emergency Feed Pumps (EFP), Control Valves (V), and Heaters (HTR) are instances of a class named "Plant Component" (Table 24). Such components inherit a set of attributes (name, state, status, probability of failure) from their parent class; however there are certain specific attributes associated with each specialized child class; for instance, head and flow value are specific to pump class. These components are connected together with Pipes. The Pipe break incident, which is considered the initiating event for the accident scenario, has been modeled as an event with an associated probability of occurrence which is preset as a simulation parameter. The scenario of interest is initiated by a pipe break event occurring in either main or intermediate subsystems. The operating crew needs to perform the accident mitigation steps correctly and in time, otherwise the steam generators would become either solid or dried out.

### 5.1.1 Normal Operation

In the steam generation system, the coolant storage tank (CST) provides water for the steam generators. Its capacity is assumed to be infinite in the simulation cases. Two motor-driven main feed pumps (PMA and PMB) provide the water flow through two main loops into a water head. The water is then distributed into four intermediate loops. The water flows into the steam generators, heated by the provided heating source and becomes steam. The steam flows through FWO1, FWO2, FWO3, and FWO4 to a steam head and then is distributed to the turbine and outside. FWi stands for flow meters which are located on different paths to provide the control crew with the flow value of water in each path.

### 5.1.2 Emergency Situation

There are four emergency boiler feed pumps (PMC, PMD, PME, and PMF) which provide emergency water injection into the SGs to prevent them from getting dried out in special cases. The water source for these four emergency pumps is also the CST. The electric power for heaters in the system can be cut off immediately in case of emergency. Each SG water input flow rate could be controlled by the valves located in the Intermediate Sub-system paths.

If a pipe break occurs at time zero, certain flow mismatch alarms are activated; once the operator perceives the activation of alarm, the cognitive processes are initiated to recognize the event and perform mitigation activities. All of the steam generators' water levels decrease due to the reduced input after such initiating event. When any SG water level is low (low-level) the emergency pumps automatically start and become ready. If the SG water level continues to decrease and reaches the low-low-level, the corresponding safety injection control valve opens and the safety injection coolant injects into the SG (Chang, 1999).

The main steps of the approach to develop the simulation model are:

1) Identify system major components

2) Identify process control parameters

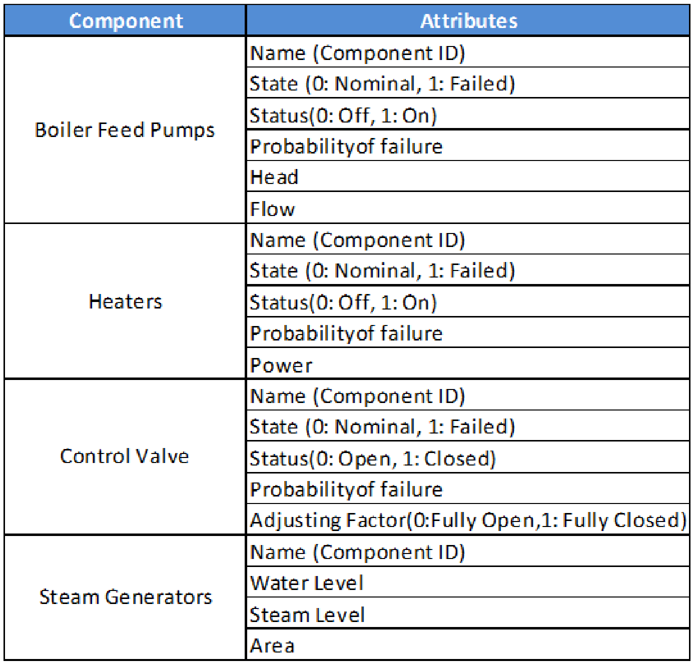
3) Develop process control equations

4) Define inputs and outputs of the simulation model

5) Develop object models for individual components and their relationships

6) Develop integrated system model.

Table 24: Object models for major components



| Component | Attributes |
|---|---|
| Boiler Feed Pumps | Name (Component ID) |
| | State (0: Nominal, 1: Failed) |
| | Status(0: Off, 1: On) |
| | Probabilityof failure |
| | Head |
| | Flow |
| Heaters | Name (Component ID) |
| | State (0: Nominal, 1: Failed) |
| | Status(0: Off, 1: On) |
| | Probabilityof failure |
| | Power |
| Control Valve | Name (Component ID) |
| | State (0: Nominal, 1: Failed) |
| | Status(0: Open, 1: Closed) |
| | Probabilityof failure |
| | Adjusting Factor(0:Fully Open,1: Fully Closed) |
| Steam Generators | Name (Component ID) |
| | Water Level |
| | Steam Level |
| | Area |

Figure 39 represents the block used in CREWSIM, which is the simulation model for the simplified feed water system. The input to the developed MATLAB Simulink block for the simplified feed water system is the action code that is transferred to the system via the equipment operators and the outputs of the block are a set of alarms which together determine the system state. These alarms include: Steam generator water level alarm, Flow mismatch alarm, Main loop integrity alarm, Intermediate loop integrity alarm, Output loop integrity alarm, Main pumps alarm, Emergency pumps Alarm, and Heaters alarm. There is also a trigger that is being activated once the system reaches its end state which is when the water level in steam generator falls below the threshold. The water level of steam generators in fact is not the only output value of the simulated system; the flow for each path at any time step is calculated and is available inside the model; The initial parameters for model set up include: initial water and steam level for steam generators, the water temperature and the boiling temperature, the head and flow values each pump provides, the water latent heat value, and the pressure under which system operates.

### 5.1.3 Dynamics of the Hardware System

This part provides details on how the dynamics of the hardware system has been modeled and lists the governing equations. In order to achieve the governing equations for water level regulation process, the first step is to recognize the critical system parameters. For a complete list of parameters used in this calculation please see table 25. Since the objective of the control system is to maintain the steam generator water level at a desired value by regulating the feed water flow rate, the governing equations for the variation in the water level need to be addressed. The equivalent adjusting factor for main path 1 and main path 2 is:

$$R_{M1} = R_{VMC1} + R_{VMA1}$$
$$R_{M2} = R_{VMC2} + R_{VMA2}$$

Table 25: List of parameters

| Parameter | Index |
|---|---|
| Boiler Feed Pump Head<br>(PMA,..,PMF) | $H_A$ , $H_B$ |
| Emergency Feed Pump Feed<br>(PMC,.., PMF) | $H_C$ , .., $H_F$ |
| Boiler Feed Pump Flow<br>(PMA,PMB) | $D_A$ , $D_B$ |
| Emergency Feed Pump Flow<br>(PMC,.., PMF) | $D_C$ , .., $D_F$ |
| Valve Adjusting Factor<br>(VMM1,..,VMM6,VIM1,..,VIM4) | $R_{VMM1}$ , .. |
| Adjusting Factor for path | $R_{I1}$ , $R_{M1}$ , .. |
| Temperature of Feed Water | $T_w$ |
| Boiling Temperature | $T_B$ |
| Latent Heat | L |
| Pressure | P |
| Density of Water | $\rho_W$ |
| Water Level in Steam Generators | $H_{W1}$, .., $H_{W4}$ |
| Steam Level in Steam Generators | $H_{S1}$, .., $H_{S4}$ |
| Heater Power | $\dot{Q}_i$ |

Please note that the factor R is just an adjustment to reflect what percentage of the flow is passing through the path; hence. By applying this factor, the flow value for path i from point X to Point Y which normally has a resistance of $r_i$ would be:

$$D_i = (1 - R_i) \times \frac{H_X - H_Y}{r_i}$$

Considering the water head as point X and the steam head as point Y, the equivalent values for head and flow at point X would be:

$$H_X = H_A - R_{M1} \times D_A = H_B - R_{M2} \times D_B$$
$$D_X = D_A + D_B$$

The equivalent resistances for Intermediate paths are:

$$
\begin{aligned}
R_{I1} &= R_{VIH1} + R_{VIM1} + R_{VIC1} \\
R_{I2} &= R_{VIH2} + R_{VIM2} + R_{VIC2} \\
R_{I3} &= R_{VIH3} + R_{VIM3} + R_{VIC3} \\
R_{I4} &= R_{VIH4} + R_{VIM4} + R_{VIC4}
\end{aligned}
$$

The head values for steam generators are sum of the value of steam head and the value of water head.

$$
\begin{aligned}
H_{SG1} &= H_{W1} + H_{S1} \\
H_{SG2} &= H_{W2} + H_{S2} \\
H_{SG3} &= H_{W3} + H_{S3} \\
H_{SG4} &= H_{W4} + H_{S4}
\end{aligned}
$$

However,

$$
\begin{aligned}
H_{SG1} &= H_C - R_{VMM3} \times D_C + H_X - R_{I1} \times D_{I1} \\
H_{SG2} &= H_D - R_{VMM4} \times D_D + H_X - R_{I2} \times D_{I2} \\
H_{SG3} &= H_E - R_{VMM5} \times D_E + H_X - R_{I3} \times D_{I3} \\
H_{SG4} &= H_F - R_{VMM6} \times D_F + H_X - R_{I4} \times D_{I4}
\end{aligned}
$$

The heater power is used to increase the water temperature to the boiling temperature.

$$
\begin{aligned}
\dot{Q}_1 &= (L + (T_B - T_W) \times \rho_W) \times D_{O1} \\
\dot{Q}_2 &= (L + (T_B - T_W) \times \rho_W) \times D_{O2} \\
\dot{Q}_3 &= (L + (T_B - T_W) \times \rho_W) \times D_{O3} \\
\dot{Q}_4 &= (L + (T_B - T_W) \times \rho_W) \times D_{O4}
\end{aligned}
$$

Hence, the change in water level for steam generators is calculated by:

$$
\begin{aligned}
(D_{I1} - D_{O1}) \times t &= A \times \Delta H_{W1} \\
(D_{I2} - D_{O2}) \times t &= A \times \Delta H_{W2} \\
(D_{I3} - D_{O3}) \times t &= A \times \Delta H_{W3} \\
(D_{I4} - D_{O4}) \times t &= A \times \Delta H_{W4}
\end{aligned}
$$

The water level of steam generators is not the only output value of the simulated system: the flow for each path at any time step needs to be calculated and available to check from the control panel; the signals for alarm activation are among other outputs for hardware system. The simulation parameters that need to be set before starting the simulation include: initial water and steam level for steam generators, the water temperature and the boiling temperature, the head and flow values each pump provides, the water latent heat value, the pressure under which system works and the density of water.

### 5.1.4 Simulink Model for the Hardware System

Figure 40 and Figure 41 describe the model in more detail; the associations among different classes of objects are clear in the model layout. The calculations are accomplished in a separate block which represents the dynamics of the system and generates the outputs. All parameters are accessible by clicking on the blocks (to change or to observe).

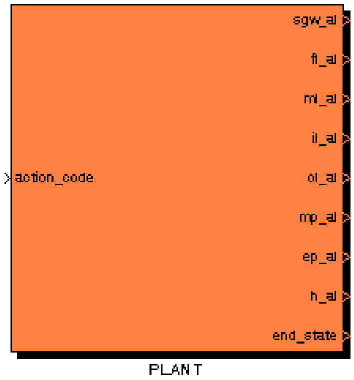


Figure 39: Simulink block for hardware system in CREWSIM

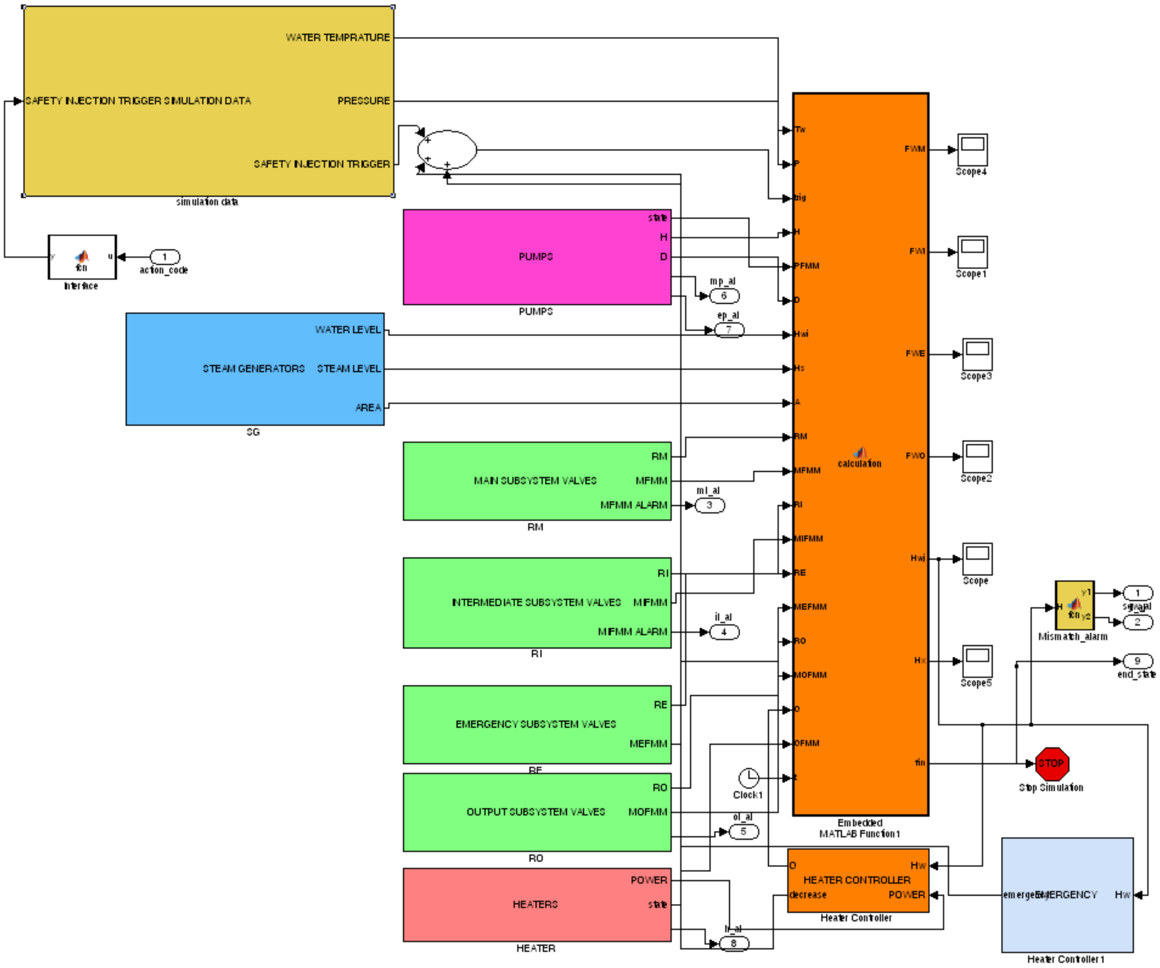


Figure 40: Details of Simulink model for hardware system

Figure 42 describes identified system states and undesired end states for the hardware system. See appendix B for a complete list of identified system states, decisions, authorized actions, authorized messages and possible errors in the context of the simplified feed water system. Different system states and associated parameters and events are summarized below. The undesired end states are considered as steam generators being dried out or solid.

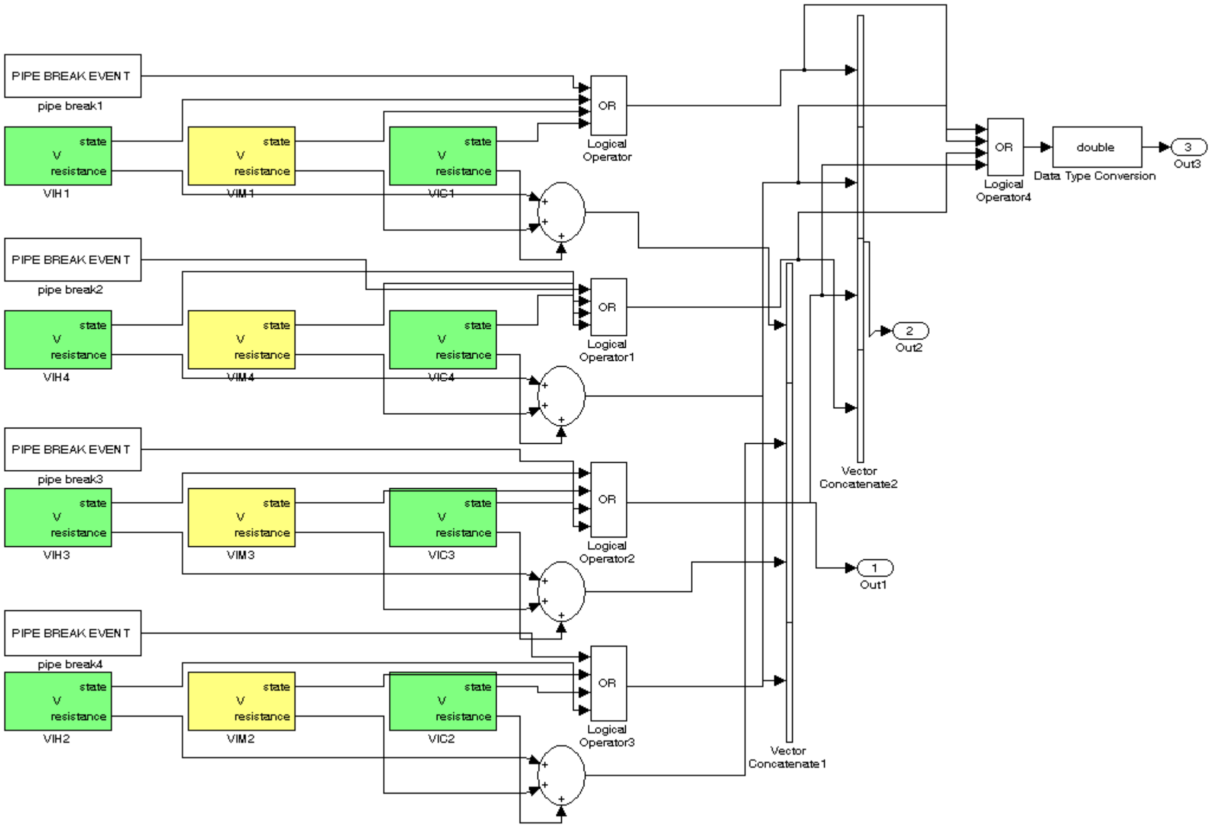


Figure 41: Details of Simulink model for Intermediate subsystem

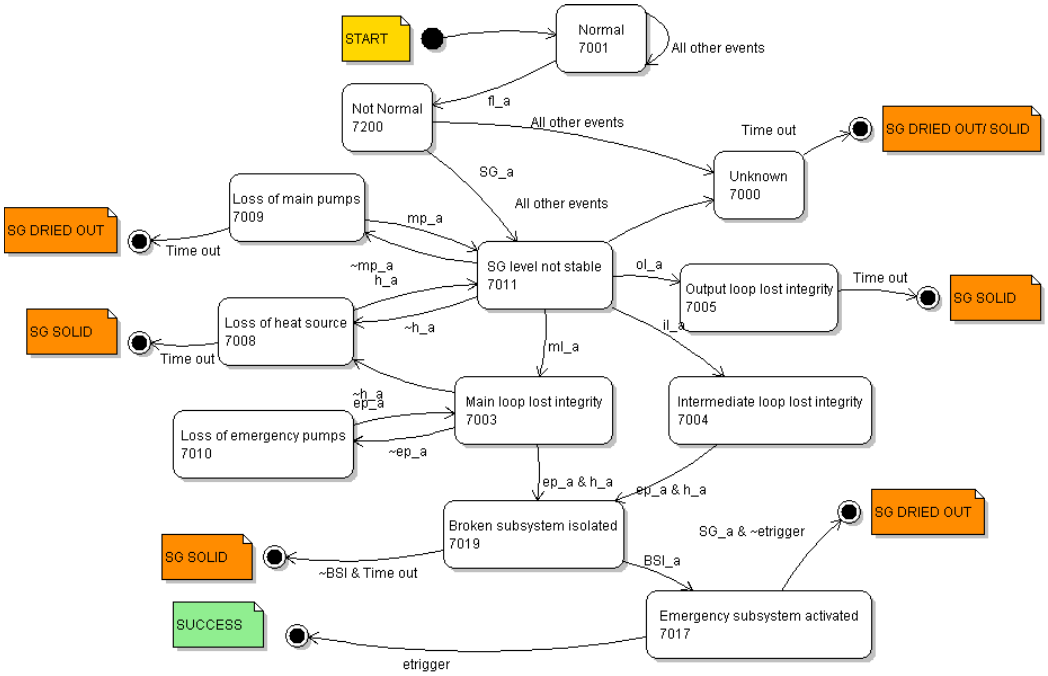


Figure 42: State transition diagram for hardware system

## *5.2 Crew Model*

A configuration of four operators is being studied as a reasonable approximation of an NPP operating crew while interacting with the feed-water subsystem. The team consists of the equipment operator (OAT2), located in the plant, the equipment operator (OAT1), the shift supervisor (ODM) and the shift technical-advisor (OCT), located in the control room. (Figure 43)

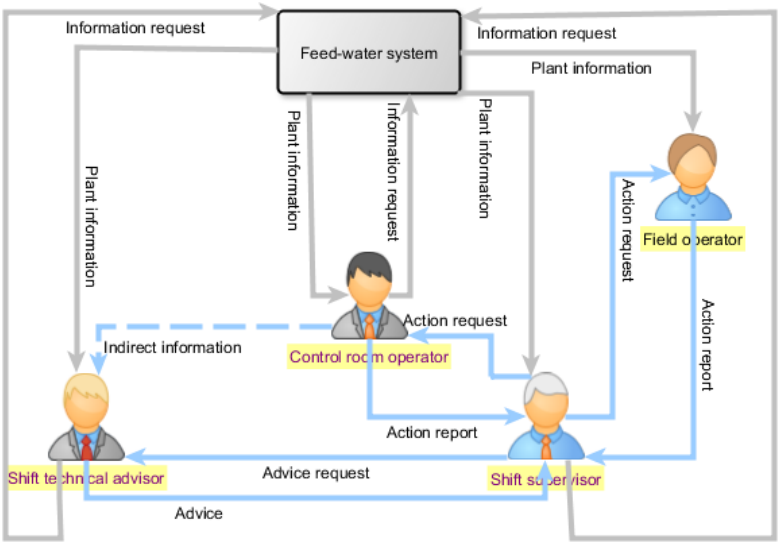


Figure 43: Different roles for operating crew of the proposed hardware system

Each operator is responsible for a variety of tasks, all following the general cognitive steps of IDAC, with different associated individual characteristics as well as responsibilities. The communication network is centralized around the decision-maker. All operators take active roles in communication loops (as sender or receiver) interchangeably. The major tasks in a team context based on the IDAC framework are categorized as: plant status assessment including the task of collaborative information collection and the task of understanding the situation; response planning, which includes the task of deciding upon a response, and action execution which includes the task of implementing the decided response. There is also the major task of error management, which includes monitoring, review, feedback and back up. The process involves requesting or transferring observation, judgment, advice and confirmation on decision or action via proper messaging as well as acknowledgement. Cognitive modules are modeled in MATLAB Simulink via use of sequential function blocks. These functions operate on system information and/or messages from other crew members and ultimately produce new messages and/or control actions in a sequential manner. Figure 44 illustrates how team members communicate using messages. Each communication link carries the message and the message content. The message is in the form of an observation, a judgment, advice, a request or a report and an acknowledgment. The message content might be a piece of information, a system state, a decision or an action; it can also be advice on system state, advice on decision or advice on action.

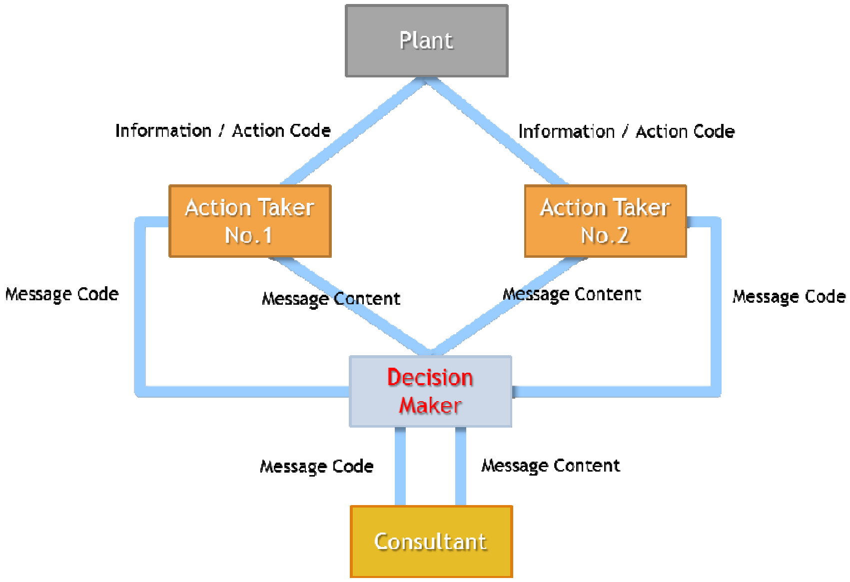


Figure 44: Implementation of the communication inside the operating team

Based on IDA Infrastructure for individual operators, the basic cognitive activities of the operator have been developed as three sequential modules: Information processing module, Decision making module, Action execution module. The probability of failure of each cognitive function as well as the availability of the operator and plant information are characterized by a set of individual PSFs which have been introduced earlier. The probability of failure of communication (as a major team process) as well as the availability of the operator and the communication channel as well as the message are characterized by a set of communication (team-related) PSFs. In addition to cognitive blocks, each operator has an embedded Error management module which in turn consists of Error detection module, Error Indication module, Error correction module. Similarly there is a probability of failure on demand associated with each module that is characterized by contributing performance shaping factors. The main system functions for each operator are listed in table 26.

**Table 26: Operator functions on the hardware system**

| Operator Functions |
|---|
| Verify the status of system components or alarms |
| Change the status of system components |
| Turn on/ off heaters |
| Turn on/off main or emergency pumps |
| Close/Open valves |
| Activate emergency trigger |
| Create a message |
| Send a message |
| Receive a message |

In CREWSIM, each operator inside the team is represented by a block (Figure 45). The inputs to this block are: The input message and the input message content which are transferred to the operator via the communication channel, and the input error which is a code that helps the simulator trace errors inside team processes and the outputs of this block are the created message and its content. Output error is similarly a code that helps the simulator to trace errors inside team processes.

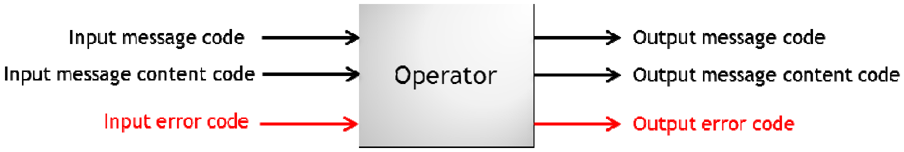


**Figure 45: Individual operator**

In addition to this, there is the input information channel from the plant and the output action channel that carries the performed action to its destination inside the plant. The block is customized by a set of performance shaping factors being set up using the model editor at the time of creating the object, which determine the characteristics of each operator and make the operator and its attributes unique.

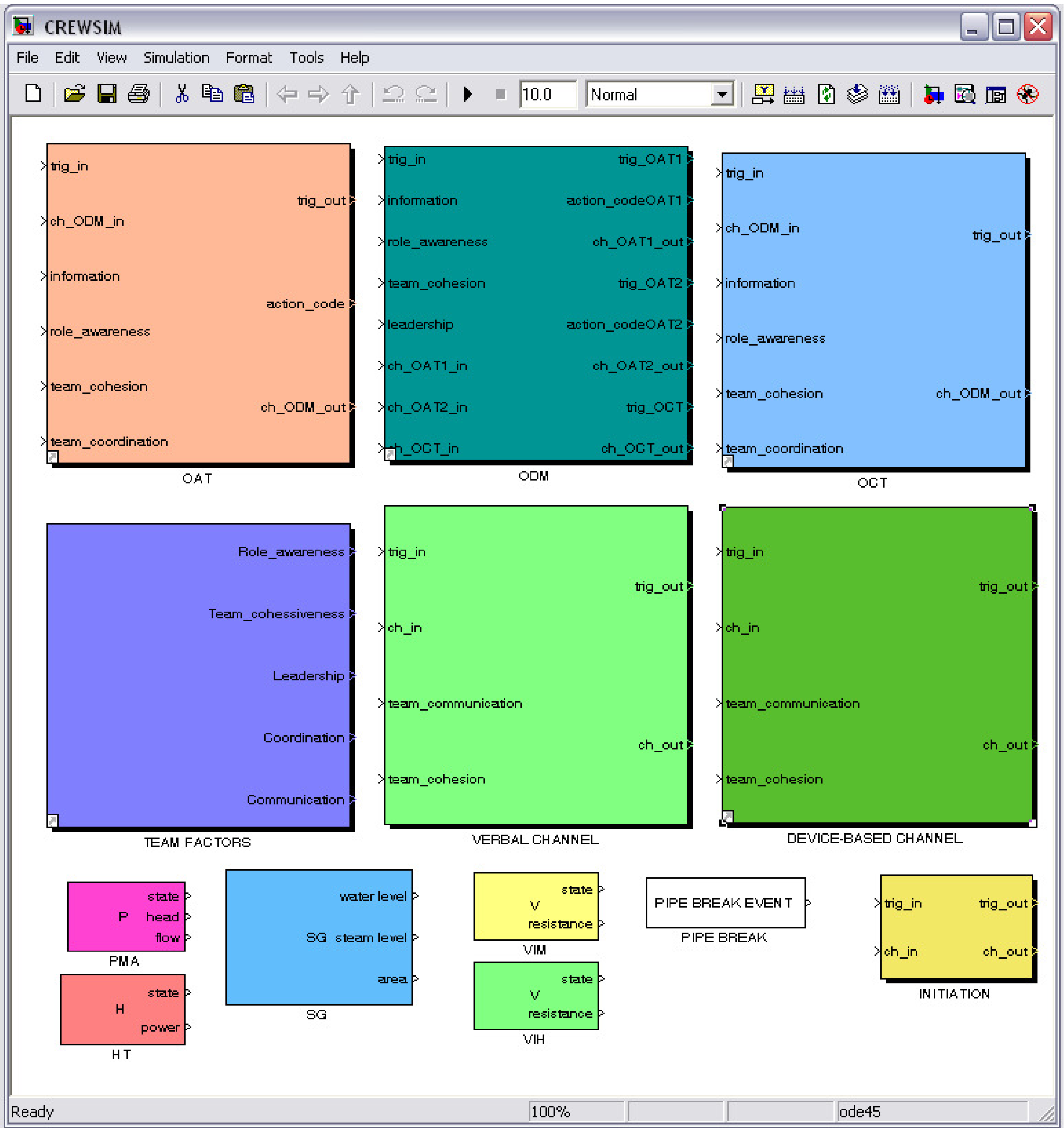


Figure 46: CREWSIM library in Simulink

The developed MATLAB Simulink blocks for operator roles are shown in figure 47 with the rest of the blocks developed in CREWSIM. The decision maker is linked to three other persons, hence there are three different communication channels associated with each team member and they have their own characteristics and parameters. The communication channels are in the form of face-to-face and verbal (inside the control room) and device based (outside the control room); basically, having a device based communication channel, the reliability of the device and the familiarity of operator to the application of device are important factors. These channels are used to exchange the message and message content between operators; the input and output errors to these channels are codes that help the simulator keep track of the errors. The developed MATLAB Simulink blocks for communication channels are listed in figure 46 as well. Figure 47 provides details on the simulation model for the operating crew of the proposed feed water system. For more information please see appendix A: CREWSIM User's guide.

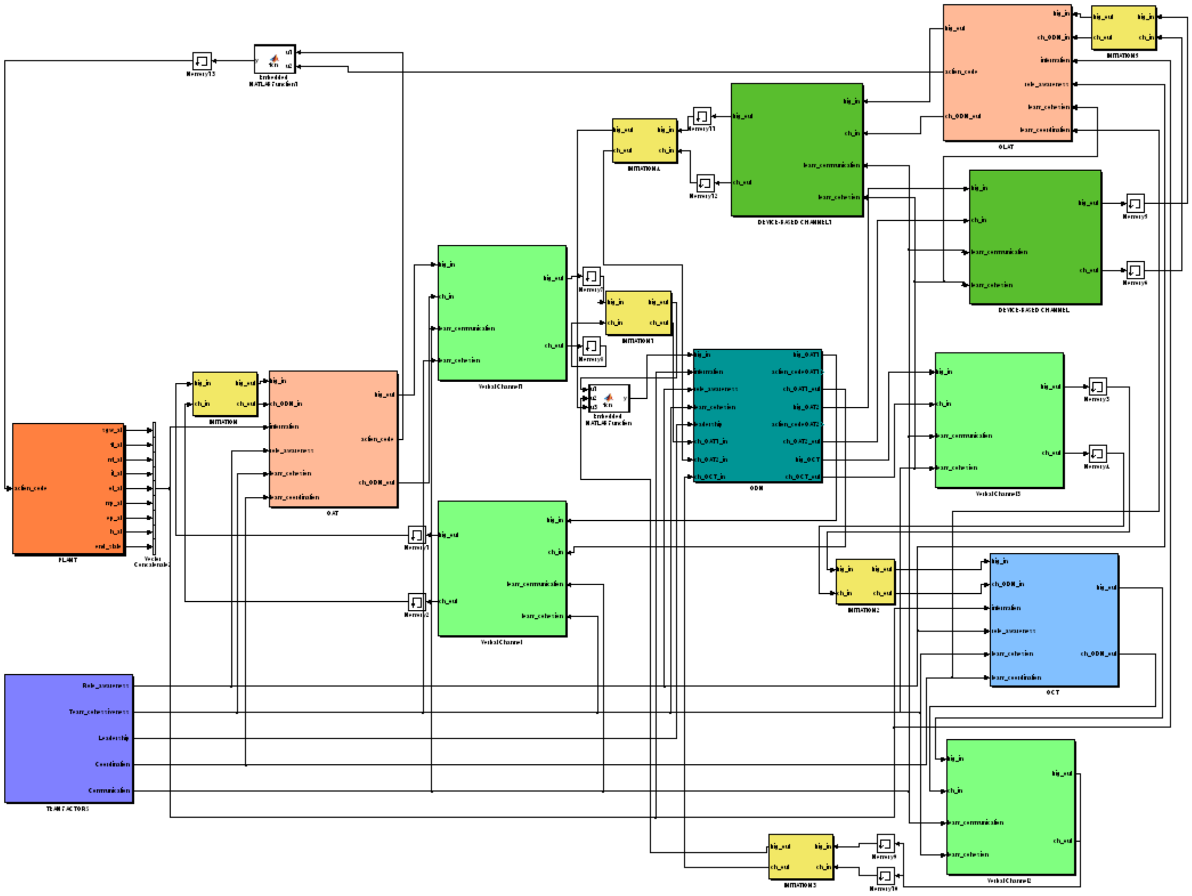


Figure 47: Details of the Simulink model for the operating crew

## 5.3 Scenario

The investigated accident scenario to practice the proposed methodology of this research is initiated by a pipe break. The model is designed in a way that this event can occur at any of the paths during any time step. However, since the emphasis of this research is on the operating crew, the pipe break event occurs in one of the intermediate subsystem paths. The operators are required to detect the problem, activate the emergency subsystem to correct the problem, and as a result the heaters are turned off and the broken path is isolated; otherwise the steam generator would be dried out or solid. Failure in accomplishing any of these functionalities is caused by one or more human function failure at a lower level. The different steps are of the scenario are illustrated in figure 48.

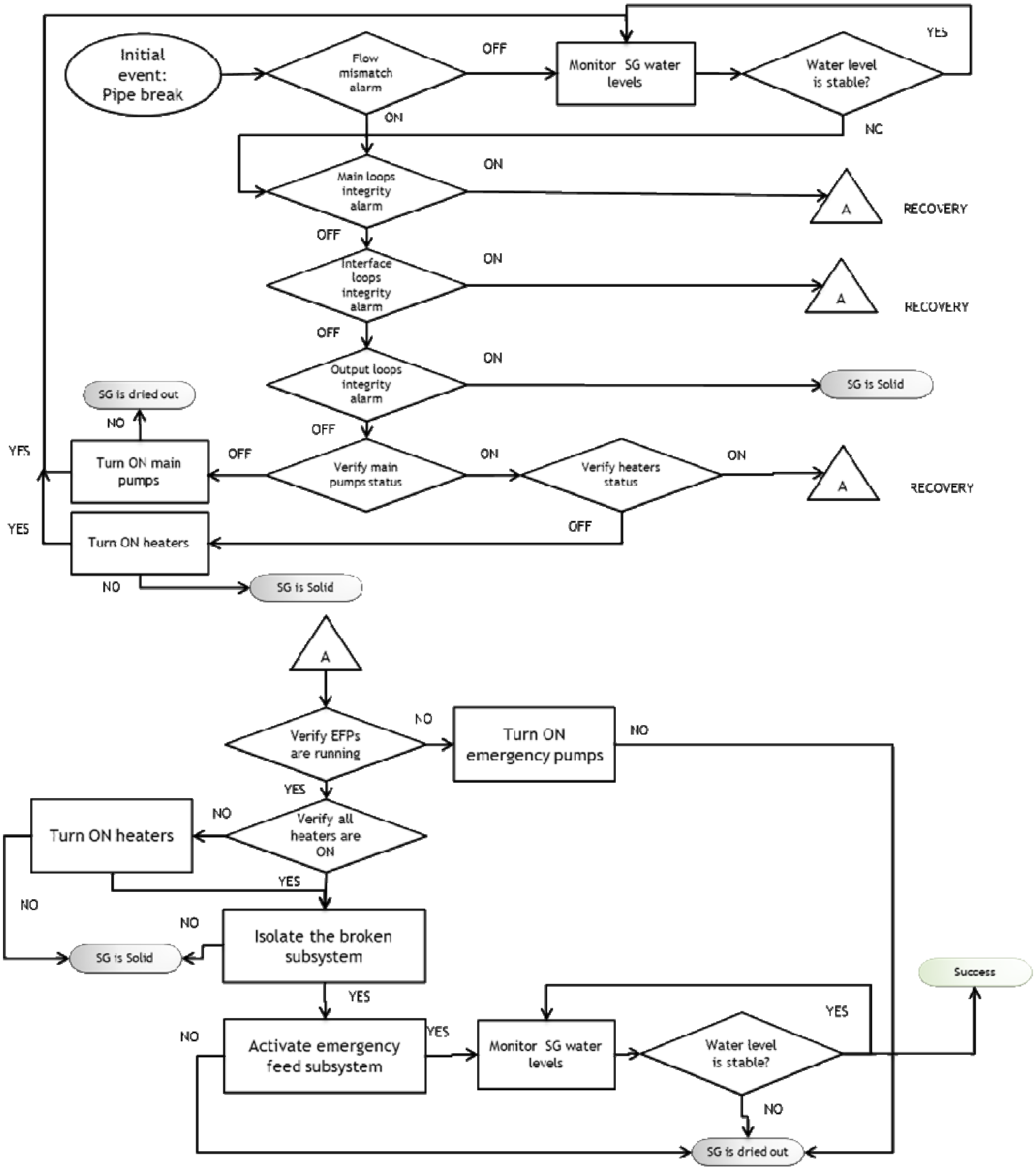


Figure 48: Accident scenario

## 5.4 Simulation

Dynamic event-based systems are modeled using discrete events that cause the system to change from one state to another. The idea is to dynamically change the states of various subsystems, components and operators' responses within the system and generate possible time dependent scenarios. In our method, a simulation controller is responsible for assigning control parameters and simulation variables for each run. It is also responsible for actuating initiating events as well as recognizing that the end state is reached and the simulation needs to be stopped. The dynamics of behavior are captured by using a local controller inside each object structure that is responsible for branch generation.

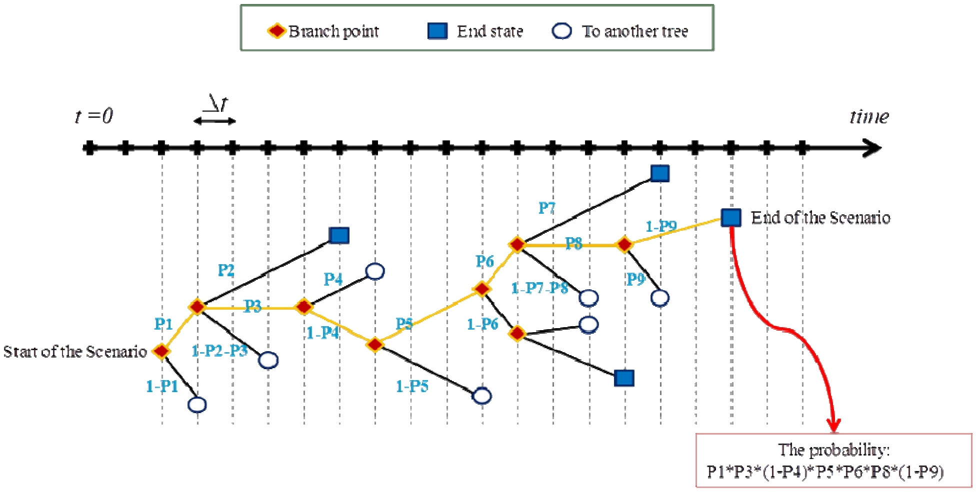


Figure 49: DDET and branch generation

The simulation algorithm generates a dynamic event tree based on branch points associated with the internal and external error reference points and the lowest level functionalities of each simulated module. Each branch represents distinct combinations of system and operator states. Once a system end-state is reached, the scenario ends. The accident scenarios are created once certain conditions are met and associated branching points are activated. The unique path through the Dynamic Discrete Event Tree (DDET) branching points from the initiating event to an end state defines a specific accident sequence (Figure 49).

Simulation aims to walk through different scenarios to achieve possible end states of the system and calculate their associated probabilities by repeating this process. Each operator is involved in such scenarios by performing a chain of functions in a backward and forward manner. Each of these functions needs a couple of time steps to be accomplished by the operator, so there is a duration parameter associated to each function. The steps of scenarios recorded by the simulation reveal the mechanism that leads to each of the possible end states. The branching points in the model are designed such that the failure of system elements and their functionalities as well as the team-related errors as part of a team process generate different paths and scenarios in the system risk profile. During the simulation, the states of various subsystems and operator responses dynamically change and generate time-dependent scenarios. The overall observed performance of the operating team is investigated using a post-processing routine on documented simulation log files from two different perspectives; the accuracy of team actions with respect to timing, sequence, and taking inappropriate or unnecessary actions is evaluated via a reference target list, with the focus being on the pre-defined timeline for action completion. Also, based on the designed study that was discussed in the previous chapter, the performance of teams with different characteristics is compared.

The simulation model provides branching rules and sequence termination criteria needed to construct the dynamic event tree. Such branching points are associated with accident initiating events, and active hardware failures as well as individual and team related issues. Individual human errors have been recognized within the context by identifying mismatches based on internal and external reference points and using emergency procedures as authorized actions. The developed classification of human error in this context covers both omission and commission errors. Commission errors consider different aspects of information processing activities such as observing the wrong object, different dimensions of the decision making process such as delayed interpretation, as well as different aspects of action execution such as direction, timing, and sequence of actions. In the case of communication error, an omission error occurs when the message is not there, is missed or unavailable; while a commission error would result in an unknown message being transferred. Both situations would cause the receiver to create a recovery message requesting for resending of the previous message. Taking inappropriate or unnecessary actions or taking actions on the wrong object are classified as commission errors as well. Error Management Module is responsible for representing how individual errors are treated inside the team and how recovery messages and actions are created. For a complete list of errors and recovery actions, please see appendix B.

# Chapter 6: Experiment & Results

The research effort has been focused on conducting the simulation and analysis of simulation runs in order to develop a more comprehensive understanding of the complexities of team related issues and how they affect the entire system risk. To this end, a study was designed to simulate a number of team characteristics and their consequences and to compare the results with several theoretical models and empirical studies. The simulation example model was also used to demonstrate face validity and additional capabilities of the methodology that can be used in extended studies on team behavior. This chapter describes the conducted simulations and provides an analysis of the results. A sensitivity study on the SLIM method is included as well to justify the PSF quantification method used in this research.

## *6.1 Design of the Study*

### 6.1.1 Objectives

This research focuses on operator team members' characteristics as well as team and organizational factors and how such factors impact a team's performance. In order to relate observed performance to PSFs, for a selection of PSFs, the investigation attempts to realize whether the systematic differences in PSF manifestations can account for differences in performance among teams of operators. The objectives of this experiment are:

- To demonstrate face validity of the modeling approach
- To explore sources of variability among the operating crew
- To compare the crew and crew members' roles in successful and unsuccessful scenarios

- To determine the most important factors among PSF categories (Individual, Team and Organization) and communication means and to study and compare the mechanisms of their effect on team performance.
- To compare finding of this research to existing theories and observations about NPPs operating crew behavior derived from literature

### 6.1.2 Subject of the Study

The basic configuration considered for the team consists of four people; two equipment operators, one located in the control room and the other located in the plant. The rest of the team includes the shift supervisor who is the main decision maker and the technical advisor who provides consultation and advice. These characteristics considered include individual, team, environmental and situational factors. The following major categories have been considered as controllable variables in the simulation:

- Individual characteristics: Personal and Role related
- Team characteristics: Team related, Environment and Organizational
- Team process characteristics: Communication, characteristics of sender, receiver, the communication link, and communication environment

In addition, the initial probabilities of failure for plant components, initial states, and system process parameters such as temperature and pressure in the plant as well as initial probabilities of failure for basic human functions are among controllable variables. Dynamic performance shaping factors (time-based) are among uncontrollable variables. Situational and task characteristics are handled automatically and via team dynamics. Examples of PSFs related to situation and task characteristics are time load and information load which are calculated dynamically at each time step and are considered known variables to the simulation controller.

In order to restrict the number of cases generated by simulation, except for the first pipe in intermediate subsystem, all the other components in the plant model are set to “working normally”. (The simulation model, however, allows any other combinations of failure and success component failures).

### 6.1.3 Method

Since a total number of four operators have been defined in the CREWSIM model described in previous chapter, four sets of individual characteristics (Table 17), are assigned. Also since the crew includes an equipment operator located outside the control room, there are two different kinds of communication channels; device-based and face-to-face (inside the control room) (Table 30). There are 6 blocks for communication inside the team. Team factors include those factors that would impact the team as a unit and hence are applicable to all individuals in the team. Tables 16, 17 and 18 and 30 list the controllable parameters in the crew model that are assigned by the user before each simulation round. The initial state of each of the operators is also set up before each simulation round by using an initial set up block in CREWSIM[11]. Each round of simulation was a set of 100 simulation runs. The total number of cases generated was 175, resulting in 17500 simulation runs. Since the models are graphical and in MATLAB Simulink environment, the input parameters were set manually via the model editor and different models were stored prior to

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[11] See CREWSIM users’ guide in appendix section

running the simulation. In the simulation platform, a simulation controller code runs different simulation rounds and stores the log files.

The simulation log files are the outputs of this experiment. A post processing routine was used to quantitatively explore individual, team and ultimately collective performances.

Table 27: Communication Channel

| Communication Channel | | | |
|---|---|---|---|
| With Device / Device Properties | | No Device (Face to Face) / General | |
| Factor | Level | Factor | Level |
| How familiar is the sender with device? | Beginner | Communication skills of sender | Less than adequate |
| | Familiar | | Average |
| | Expert | | Good |
| How familiar is the receiver with device? | Beginner | Format/ language of sender | Complex |
| | Familiar | | Average |
| | Expert | | Easy |
| Availability of device | No | Communication skills of receiver | Less than adequate |
| | Yes | | Average |
| | | | Good |
| Accessability of device | No | Format/ language of receiver | Complex |
| | Yes | | Average |
| | | | Easy |
| Ease of use | Complex | | |
| | Easy | | |
| Accuracy | Bad quality | | |
| | Good quality | | |

## 6.1.4 Scenario

All of the operating teams simulated had to follow the same scenario. In order to minimize the effect of variability associated with failure of components inside the plant, the initiating event was set as “pipe break in the first path of the intermediate subsystem of the proposed feed water system”. However, since all the active objects including key sub-systems and components have been fully modeled, the model is capable of simulating single or combined failure of equipment.

The initial probabilities of failure for most of the components inside the model are assigned subjectively. Since we did not intend to introduce any bias, these failure event probabilities have been set equally for such components. For example, the probabilities of failure for human cognitive functions are initially assigned equal; however, through the mechanism of influence of PSFs inside the model these probabilities are automatically modified to reflect the dynamically changing context and PSF values. The undesired end state is the steam-generator drying out which would happen during the scenario if the emergency subsystem is not activated by the operating crew during a specific period of time after the occurrence of the initiating event. The output of the integrated operating crew model is the action code that triggers the emergency subsystem.

### 6.1.5 Questions of Interest

The study aims to understand why and how flaws in each of the major categories of PSFs, listed in Section 6.1.2, would lead to the undesired state of the system.

- How many times the undesired “end state” (SG Dry Out) is reached during a round of simulation?
- Why and how the undesired end state is reached, with focus being on monitoring the timeline of the scenario including the time of the occurrence of errors, time of execution of wrong actions, time of execution of the recovery actions and time of the occurrence of the end state?
- Which of the input factors have the strongest impact on the output and why, (measured by number of occurrence of undesired sate in a round of simulation)?

- How does the model results compare with findings documented in the literature based on similar situations involving real control crew via observational methods?

## 6.2 Scenario Generation

Using different combinations and arrangements of the three major categories of simulation parameters discussed earlier, different configurations of teams can be represented. We had to generate all possible cases and investigate them. The model allows the user to select three different levels of qualitative rating for input factors; however, with teams composed of 4 operators (each subject to 14-20 parameters) and 6 communication channels (each subject to 4-10 parameters) and one set of team factors (subject to 20 parameters) and each of parameters having 2 or 3 levels, a sub set of variables and variations had to be selected to keep the number of required simulation runs under control. A screening test of 20 cases was set up and run initially. We considered an "average team" (in terms of PSFs and other characteristics) and at each round we set only one factor at low (bad) level (Table 31).

Table 28: Initial screening

| Index | Crew | | | | Communication | | Team | Results |
|---|---|---|---|---|---|---|---|---|
| | OAT1 | OAT2 | ODM | OCT | No Device | With Device | Team Factors | No. of Dried Outs |
| 1 | Average | Average | Average | Average | Average | Average | Average | 0 |
| 2 | Average | Average | Average | Average | Average | Average | Bad | 0 |
| 3 | Average | Average | Average | Average | Average | Average | Good | 0 |
| 4 | Average | Average | Bad | Average | Average | Average | Average | 48 |
| 5 | Average | Average | Good | Average | Average | Average | Average | 0 |
| 6 | Average | Average | Average | Average | Average | Bad | Average | 0 |
| 7 | Average | Average | Average | Average | Average | Good | Average | 0 |
| 8 | Bad | Good | Average | Average | Average | Average | Average | 0 |
| 9 | Good | Bad | Average | Average | Average | Average | Average | 0 |
| 10 | Bad | Bad | Average | Average | Average | Average | Average | 0 |
| 11 | Good | Good | Average | Average | Average | Average | Average | 0 |

The number of Dry out situations was the key index to judge (at a high level) the net impact of the factor that was set to low value. The last column shows the number of Dry outs out of 100 simulation runs. Based on the generated 2000 simulation runs, we noticed that we are unable to observe the dried out situation in most of the cases. Such end states were only observed when the supervisor (ODM-decision maker) individual characteristics were set to lowest level. Therefore we decided to not to run cases for ODM characteristics set at high level, because of low chance that such cases would provide insightful data on Dry out situations.

Additionally, it made sense to only look at the cases that the supervisor and/or the rest of team members are set to average or weak. We used the following criteria to limit our input variations:

- Instead of randomly selecting different levels for each parameter for each block, we changed the parameters in a group setting. For example, having a bad action taker means all his individual characteristics are set at worst levels. Communication factors were also treated the same way; instead of looking at each link, we looked at two groups: verbal (face-to-face) communication inside team and device-based communication to outside the control room. This way, a bad communication means all communication factors that are associated with a specific link and similar links have been set up at their worst level. A sensitivity analysis was performed on the PSFs (within the SLIM method) to justify for this assumption.
- Of the three levels for qualitative rating of model parameters, we used only two levels: “average” and “poor/bad”, meaning that we considered all cases

that had an average or bad supervisor (ODM) and overlooked the rest of cases which we assumed would not provide important insights. In order to justify this assumption, we used Taguchi method for the design of the experiment and generated 27 representative cases and included good levels for parameters as well. We repeated the simulation and analysis for this set of cases and compared the results.

### 6.2.1 Taguchi Method

Factorial design intends to test all possible combinations of inputs, which is not practical when the dimensions of the problem are as big as they are in our case. Genichi Taguchi has proposed several approaches to manage experimental designs (Antony et al., 2004). He combined statistics and engineering to achieve rapid improvements in product designs and manufacturing processes. His efforts led to a subset of screening experiments commonly referred to the Taguchi Techniques or the Taguchi Methods. These methods utilize two-level, three-level, and mixed-level fractional factorial designs. We used JMP software to perform Taguchi method that produced 27 representative cases (Table 36).

### 6.2.2 Sensitivity Analysis on PSFs Model

In order to perform sensitivity and importance analysis on the contributing factors of the probability function (based on SLIM method), one may look at the partial derivatives with respect to each variable. In this case it is assumed that the base probability of failure ($Pr_0$) is completely independent from the SLI, therefore the importance of these components can be accurately scaled by partial derivatives. If factor a, assumed to be constant we get:

$$Pr = Pr_0 \times e^{-a \times SLI}$$

$$\left.\begin{array}{l} \dfrac{\partial Pr}{\partial Pr_0} = e^{-a \times SLI} \\ \dfrac{\partial Pr}{\partial SLI} = -Pr_0 \times a \times e^{-a \times SLI} \end{array}\right\} \Rightarrow \left| \dfrac{\partial Pr / \partial Pr_0}{\partial Pr / \partial SLI} \right| = \dfrac{1}{Pr_0 \times a} \geq 1$$

The base probability is in the interval zero to one, and SLI can be as low as 0 for all "bad" PSFs, 5 for "average" PSFs and 10 for all "good" PSFs as mentioned earlier. As shown above, the rate of change in probability due to changes in base probability is larger than the rate of change due to changes in SLI. This relative importance, however, depends on the base probability itself. For example if factor a is considered to be "1", as evident in this equation the importance of the two will be in the same order of magnitude when base probability of failure is very high (i.e. close to one). At a more typical base probability of 0.1 (considered in the case study) the change in base probability is almost 10 times more important than the changes in SLI. As explained earlier the SLI is calculated based on performance shape factors as follows:

$$SLI = \sum_{i=1}^{N} w_i \times PSF_i$$

If the same weights are considered for all shape factors, the SLI will be simply the average of contributing PSFs. Let us further assume that PSF is a random number, uniformly distributed between 0 and 10. In this case, according to central limit theorem, the standard deviation of the average of N samples (i.e. SLI) is proportional to the inverse of square root of number of samples N. This means that the variation of SLI is expected to reduce as more PSFs are included into the problem. This simply means SLI basically converges to 5 (i.e. the average of PSF range) when the number of PSFs increases. In other words, the probability of failure will no longer be sensitive to individual PSFs and may be only influenced when group changes in PSFs are observed.

Monte Carlo simulation within possible ranges of the variables, including values of PSFs, number of PSFs, SLI, and base probability of failure confirms the above conclusions. For example assuming uniform distributions for base probability of failure and PSFs with three possible choices of 0, 5, and 10 as mentioned earlier reveals the same trends in final calculated probability of failure.

Figure 50 shows the contour plot of the probability for different cases of base probability and SLI. As illustrated in this figure, the probability remains practically insensitive to SLI unless all PSFs indicate a very poor performance. The base probability, however, remains an important player in the full range.

Figure 51 illustrates the central limit theorem concept. As shown in this figure, the standard deviation of SLI shrinks when more PSFs are influencing the performance. The mean PSF which is basically the SLI value converges to average of the range considered for PSFs as evident in this figure.

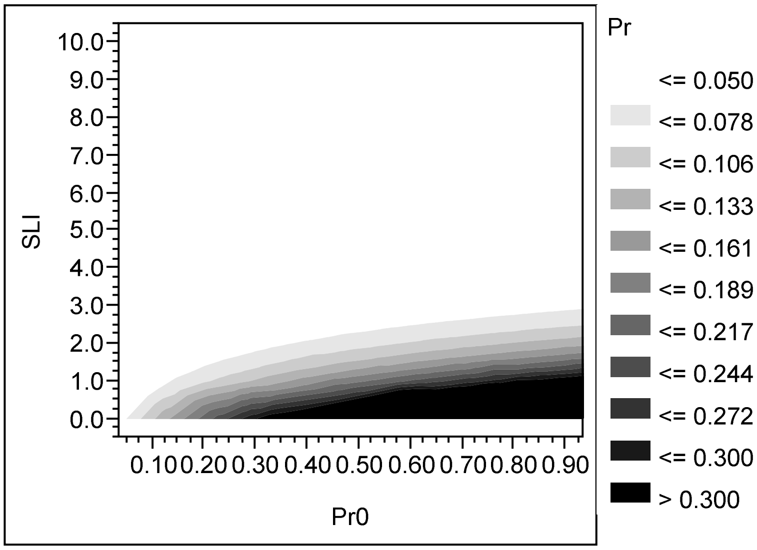


Figure 50: Contour plot of probability of failure vs. base probability & SLI

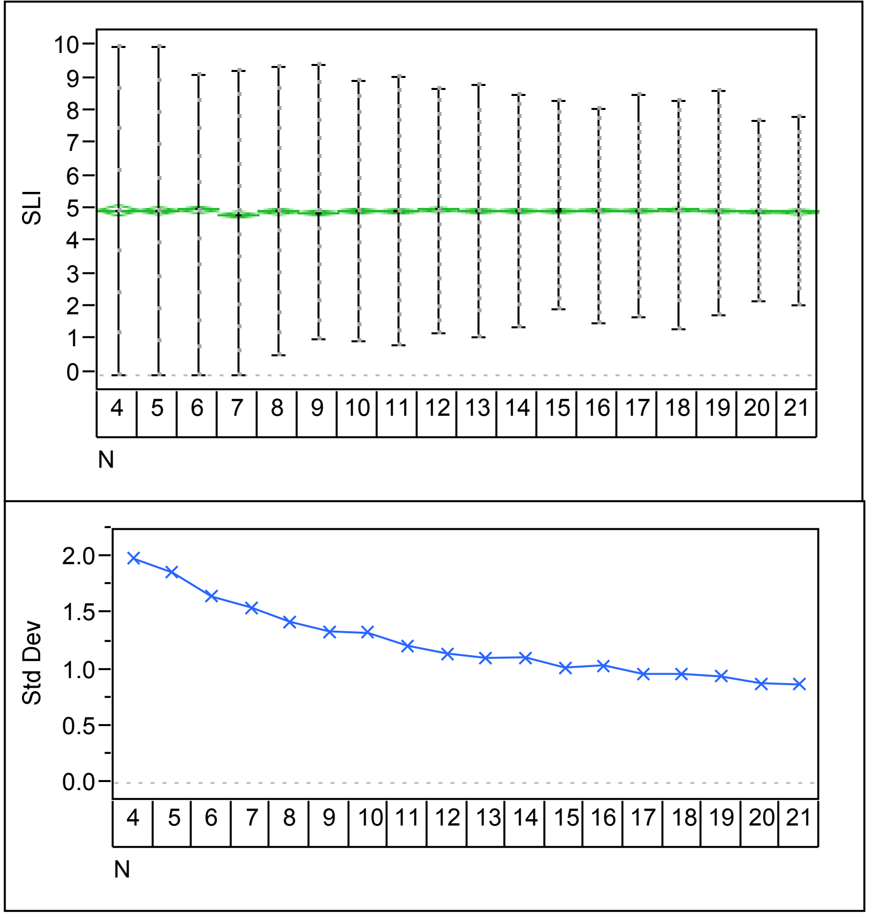


Figure 51: Variability chart for SLI vs. No. of influential PSFs

## 6.3 Simulation Results

Beside the 20 cases that we initially used for screening and derived 2000 runs, we added 128 cases of different combinations of factors and assumptions made, resulting in 12800 simulation runs (since each of the cases includes 100 runs). Details of each run are recorded in simulation log files. The simulation log files are huge text files which record everything that happens in the system (crew, hardware and physical process variables) at each time step.

The simulation log files were processed and the number of Dry out situations was derived from the text. As an example of the generated scenario, a part of the simulation log file associated with case No.4 in Table 32 is being provided in appendix C (From time step 1.8 to time step 2.2). In this scenario the communication between inside and outside the control room has failed due to device inefficiency and hence operator no.2 (OAT2) has not received the message from operator no.4 (ODM) correctly. The error recognition, indication and correction steps in the team (performed by the supervisor) are successfully accomplished by Operator no.4 (ODM) and the supervisor asks the operator to resend the message (request for a recovery action). However, since the communication is ineffective, the field operator (operator no.2, OAT2) is not able to receive this message correctly either. In the next steps, ODM asks the control room operator (operator no.1, OAT1) to correct the situation by performing the required action on the system. Operator no.3 (the consultant) doesn’t have an active role in this part of scenario.

Table 32 and Table 33 provide detailed data on the first 64 cases with the supervisor being set to “average” and by considering all possible combinations of other factors. By looking at the data it is clear that not all the cases result in SG Dry Out situations. As a supporting study we used the 27 cases generated by Taguchi method and repeated the study (2700 simulation runs). Hence, we have processed a total of 17500 simulation runs on this layout of the team.

**Table 29: Average Supervisor (Part 1)**

| Index | Crew | | | | Communication | | Team | Results |
|---|---|---|---|---|---|---|---|---|
| | OAT1 | OAT2 | ODM | OCT | No Device | With Device | Team Factors | No. of Dried Outs |
| 1 | Bad | Bad | Average | Bad | Bad | Bad | Bad | 68 |
| 2 | Bad | Bad | Average | Average | Bad | Bad | Bad | 0 |
| 3 | Bad | Average | Average | Bad | Bad | Bad | Bad | 75 |
| 4 | Bad | Average | Average | Average | Bad | Bad | Bad | 0 |
| 5 | Average | Bad | Average | Bad | Bad | Bad | Bad | 0 |
| 6 | Average | Bad | Average | Average | Bad | Bad | Bad | 0 |
| 7 | Average | Average | Average | Bad | Bad | Bad | Bad | 0 |
| 8 | Average | Average | Average | Average | Bad | Bad | Bad | 0 |
| 9 | Bad | Bad | Average | Bad | Average | Average | Average | 74 |
| 10 | Bad | Bad | Average | Average | Average | Average | Average | 0 |
| 11 | Bad | Average | Average | Bad | Average | Average | Average | 0 |
| 12 | Bad | Average | Average | Average | Average | Average | Average | 0 |
| 13 | Average | Bad | Average | Bad | Average | Average | Average | 0 |
| 14 | Average | Bad | Average | Average | Average | Average | Average | 0 |
| 15 | Average | Average | Average | Bad | Average | Average | Average | 0 |
| 16 | Average | Average | Average | Average | Average | Average | Average | 0 |
| 17 | Bad | Bad | Average | Bad | Average | Average | Bad | 68 |
| 18 | Bad | Bad | Average | Average | Average | Average | Bad | 0 |
| 19 | Bad | Average | Average | Bad | Average | Average | Bad | 0 |
| 20 | Bad | Average | Average | Average | Average | Average | Bad | 0 |
| 21 | Average | Bad | Average | Bad | Average | Average | Bad | 0 |
| 22 | Average | Bad | Average | Average | Average | Average | Bad | 0 |
| 23 | Average | Average | Average | Bad | Average | Average | Bad | 0 |
| 24 | Average | Average | Average | Average | Average | Average | Bad | 0 |
| 25 | Bad | Bad | Average | Bad | Bad | Bad | Average | 78 |
| 26 | Bad | Bad | Average | Average | Bad | Bad | Average | 0 |
| 27 | Bad | Average | Average | Bad | Bad | Bad | Average | 64 |
| 28 | Bad | Average | Average | Average | Bad | Bad | Average | 0 |
| 29 | Average | Bad | Average | Bad | Bad | Bad | Average | 0 |
| 30 | Average | Bad | Average | Average | Bad | Bad | Average | 0 |
| 31 | Average | Average | Average | Bad | Bad | Bad | Average | 0 |
| 32 | Average | Average | Average | Average | Bad | Bad | Average | 0 |

Table 30: Average Supervisor (Part 2)

| Index | Crew | | | | Communication | | Team | Results |
|---|---|---|---|---|---|---|---|---|
| | OAT1 | OAT2 | ODM | OCT | No Device | With Device | Team Factors | No. of Dried Outs |
| 33 | Bad | Bad | Average | Bad | Bad | Average | Average | 68 |
| 34 | Bad | Bad | Average | Average | Bad | Average | Average | 0 |
| 35 | Bad | Average | Average | Bad | Bad | Average | Average | 0 |
| 36 | Bad | Average | Average | Average | Bad | Average | Average | 0 |
| 37 | Average | Bad | Average | Bad | Bad | Average | Average | 0 |
| 38 | Average | Bad | Average | Average | Bad | Average | Average | 0 |
| 39 | Average | Average | Average | Bad | Bad | Average | Average | 0 |
| 40 | Average | Average | Average | Average | Bad | Average | Average | 0 |
| 41 | Bad | Bad | Average | Bad | Average | Bad | Average | 78 |
| 42 | Bad | Bad | Average | Average | Average | Bad | Average | 0 |
| 43 | Bad | Average | Average | Bad | Average | Bad | Average | 64 |
| 44 | Bad | Average | Average | Average | Average | Bad | Average | 0 |
| 45 | Average | Bad | Average | Bad | Average | Bad | Average | 0 |
| 46 | Average | Bad | Average | Average | Average | Bad | Average | 0 |
| 47 | Average | Average | Average | Bad | Average | Bad | Average | 0 |
| 48 | Average | Average | Average | Average | Average | Bad | Average | 0 |
| 49 | Bad | Bad | Average | Bad | Bad | Average | Bad | 71 |
| 50 | Bad | Bad | Average | Average | Bad | Average | Bad | 0 |
| 51 | Bad | Average | Average | Bad | Bad | Average | Bad | 0 |
| 52 | Bad | Average | Average | Average | Bad | Average | Bad | 0 |
| 53 | Average | Bad | Average | Bad | Bad | Average | Bad | 0 |
| 54 | Average | Bad | Average | Average | Bad | Average | Bad | 0 |
| 55 | Average | Average | Average | Bad | Bad | Average | Bad | 0 |
| 56 | Average | Average | Average | Average | Bad | Average | Bad | 0 |
| 57 | Bad | Bad | Average | Bad | Average | Bad | Bad | 70 |
| 58 | Bad | Bad | Average | Average | Average | Bad | Bad | 0 |
| 59 | Bad | Average | Average | Bad | Average | Bad | Bad | 66 |
| 60 | Bad | Average | Average | Average | Average | Bad | Bad | 0 |
| 61 | Average | Bad | Average | Bad | Average | Bad | Bad | 0 |
| 62 | Average | Bad | Average | Average | Average | Bad | Bad | 0 |
| 63 | Average | Average | Average | Bad | Average | Bad | Bad | 0 |
| 64 | Average | Average | Average | Average | Average | Bad | Bad | 0 |

Table 34 and table 35 list the rest of the cases in which the supervisor characteristics are all set to be “bad”. By looking at the data it is clear that there is a sudden increase in the number of SG Dry Out cases and in every case Dry out occurs.

Table 31: Bad Supervisor (Part 1)

| Index | Crew | | | | Communication | | Team | Results |
|---|---|---|---|---|---|---|---|---|
| | OAT1 | OAT2 | ODM | OCT | No Device | With Device | Team Factors | No. of Dried Outs |
| 65 | Bad | Bad | Bad | Bad | Bad | Bad | Bad | 82 |
| 66 | Bad | Bad | Bad | Average | Bad | Bad | Bad | 81 |
| 67 | Bad | Average | Bad | Bad | Bad | Bad | Bad | 85 |
| 68 | Bad | Average | Bad | Average | Bad | Bad | Bad | 85 |
| 69 | Average | Bad | Bad | Bad | Bad | Bad | Bad | 72 |
| 70 | Average | Bad | Bad | Average | Bad | Bad | Bad | 85 |
| 71 | Average | Average | Bad | Bad | Bad | Bad | Bad | 71 |
| 72 | Average | Average | Bad | Average | Bad | Bad | Bad | 74 |
| 73 | Bad | Bad | Bad | Bad | Average | Average | Average | 73 |
| 74 | Bad | Bad | Bad | Average | Average | Average | Average | 76 |
| 75 | Bad | Average | Bad | Bad | Average | Average | Average | 84 |
| 76 | Bad | Average | Bad | Average | Average | Average | Average | 82 |
| 77 | Average | Bad | Bad | Bad | Average | Average | Average | 81 |
| 78 | Average | Bad | Bad | Average | Average | Average | Average | 76 |
| 79 | Average | Average | Bad | Bad | Average | Average | Average | 79 |
| 80 | Average | Average | Bad | Average | Average | Average | Average | 81 |
| 81 | Bad | Bad | Bad | Bad | Average | Average | Bad | 84 |
| 82 | Bad | Bad | Bad | Average | Average | Average | Bad | 86 |
| 83 | Bad | Average | Bad | Bad | Average | Average | Bad | 84 |
| 84 | Bad | Average | Bad | Average | Average | Average | Bad | 85 |
| 85 | Average | Bad | Bad | Bad | Average | Average | Bad | 82 |
| 86 | Average | Bad | Bad | Average | Average | Average | Bad | 74 |
| 87 | Average | Average | Bad | Bad | Average | Average | Bad | 74 |
| 88 | Average | Average | Bad | Average | Average | Average | Bad | 75 |
| 89 | Bad | Bad | Bad | Bad | Bad | Bad | Average | 86 |
| 90 | Bad | Bad | Bad | Average | Bad | Bad | Average | 81 |
| 91 | Bad | Average | Bad | Bad | Bad | Bad | Average | 77 |
| 92 | Bad | Average | Bad | Average | Bad | Bad | Average | 84 |
| 93 | Average | Bad | Bad | Bad | Bad | Bad | Average | 76 |
| 94 | Average | Bad | Bad | Average | Bad | Bad | Average | 81 |
| 95 | Average | Average | Bad | Bad | Bad | Bad | Average | 82 |
| 96 | Average | Average | Bad | Average | Bad | Bad | Average | 68 |

Table 32: Bad Supervisor (Part 2)

| Index | Crew | | | | Communication | | Team | Results |
|---|---|---|---|---|---|---|---|---|
| | OAT1 | OAT2 | ODM | OCT | No Device | With Device | Team Factors | No. of Dried Outs |
| 97 | Bad | Bad | Bad | Bad | Bad | Average | Average | 78 |
| 98 | Bad | Bad | Bad | Average | Bad | Average | Average | 83 |
| 99 | Bad | Average | Bad | Bad | Bad | Average | Average | 81 |
| 100 | Bad | Average | Bad | Average | Bad | Average | Average | 81 |
| 101 | Average | Bad | Bad | Bad | Bad | Average | Average | 74 |
| 102 | Average | Bad | Bad | Average | Bad | Average | Average | 78 |
| 103 | Average | Average | Bad | Bad | Bad | Average | Average | 77 |
| 104 | Average | Average | Bad | Average | Bad | Average | Average | 71 |
| 105 | Bad | Bad | Bad | Bad | Average | Bad | Average | 81 |
| 106 | Bad | Bad | Bad | Average | Average | Bad | Average | 87 |
| 107 | Bad | Average | Bad | Bad | Average | Bad | Average | 83 |
| 108 | Bad | Average | Bad | Average | Average | Bad | Average | 81 |
| 109 | Average | Bad | Bad | Bad | Average | Bad | Average | 86 |
| 110 | Average | Bad | Bad | Average | Average | Bad | Average | 81 |
| 111 | Average | Average | Bad | Bad | Average | Bad | Average | 73 |
| 112 | Average | Average | Bad | Average | Average | Bad | Average | 80 |
| 113 | Bad | Bad | Bad | Bad | Bad | Average | Bad | 85 |
| 114 | Bad | Bad | Bad | Average | Bad | Average | Bad | 89 |
| 115 | Bad | Average | Bad | Bad | Bad | Average | Bad | 79 |
| 116 | Bad | Average | Bad | Average | Bad | Average | Bad | 83 |
| 117 | Average | Bad | Bad | Bad | Bad | Average | Bad | 71 |
| 118 | Average | Bad | Bad | Average | Bad | Average | Bad | 72 |
| 119 | Average | Average | Bad | Bad | Bad | Average | Bad | 82 |
| 120 | Average | Average | Bad | Average | Bad | Average | Bad | 73 |
| 121 | Bad | Bad | Bad | Bad | Average | Bad | Bad | 81 |
| 122 | Bad | Bad | Bad | Average | Average | Bad | Bad | 81 |
| 123 | Bad | Average | Bad | Bad | Average | Bad | Bad | 82 |
| 124 | Bad | Average | Bad | Average | Average | Bad | Bad | 88 |
| 125 | Average | Bad | Bad | Bad | Average | Bad | Bad | 73 |
| 126 | Average | Bad | Bad | Average | Average | Bad | Bad | 71 |
| 127 | Average | Average | Bad | Bad | Average | Bad | Bad | 87 |
| 128 | Average | Average | Bad | Average | Average | Bad | Bad | 78 |

Similarly, Taguchi cases were simulated and the log files have been processed; Table 36 lists the results.

Table 33: Representative cases identified by Taguchi method

| Index | Pattern | Crew | | | | Communication | | Team | Results |
|---|---|---|---|---|---|---|---|---|---|
| | | OAT1 | OAT2 | ODM | OCT | No Device | With Device | Team Factors | No. of Dried Outs |
| 1 | ––––––– | Bad | Bad | Bad | Bad | Bad | Bad | Bad | 82 |
| 2 | ––––000 | Bad | Bad | Bad | Bad | Average | Average | Average | 81 |
| 3 | ––––+++ | Bad | Bad | Bad | Bad | Good | Good | Good | 85 |
| 4 | –000––– | Bad | Average | Average | Average | Bad | Bad | Bad | 0 |
| 5 | –000000 | Bad | Average | Average | Average | Average | Average | Average | 0 |
| 6 | –000+++ | Bad | Average | Average | Average | Good | Good | Good | 0 |
| 7 | –+++––– | Bad | Good | Good | Good | Bad | Bad | Bad | 0 |
| 8 | –+++000 | Bad | Good | Good | Good | Average | Average | Average | 0 |
| 9 | –++++++ | Bad | Good | Good | Good | Good | Good | Good | 0 |
| 10 | 0–0+–0+ | Average | Bad | Average | Good | Bad | Average | Good | 0 |
| 11 | 0–0+0+– | Average | Bad | Average | Good | Average | Good | Bad | 0 |
| 12 | 0–0++–0 | Average | Bad | Average | Good | Good | Bad | Average | 0 |
| 13 | 00+––0+ | Average | Average | Good | Bad | Bad | Average | Good | 0 |
| 14 | 00+–0+– | Average | Average | Good | Bad | Average | Good | Bad | 0 |
| 15 | 00+–+–0 | Average | Average | Good | Bad | Good | Bad | Average | 0 |
| 16 | 0+–0–0+ | Average | Good | Bad | Average | Bad | Average | Good | 73 |
| 17 | 0+–00+– | Average | Good | Bad | Average | Average | Good | Bad | 79 |
| 18 | 0+–0+–0 | Average | Good | Bad | Average | Good | Bad | Average | 76 |
| 19 | +–+0–+0 | Good | Bad | Good | Average | Bad | Good | Average | 0 |
| 20 | +–+00–+ | Good | Bad | Good | Average | Average | Bad | Good | 0 |
| 21 | +–+0+0– | Good | Bad | Good | Average | Good | Average | Bad | 0 |
| 22 | +0–+–+0 | Good | Average | Bad | Good | Bad | Good | Average | 86 |
| 23 | +0–+0–+ | Good | Average | Bad | Good | Average | Bad | Good | 82 |
| 24 | +0–++0– | Good | Average | Bad | Good | Good | Average | Bad | 74 |
| 25 | ++0––+0 | Good | Good | Average | Bad | Bad | Good | Average | 0 |
| 26 | ++0–0–+ | Good | Good | Average | Bad | Average | Bad | Good | 0 |
| 27 | ++0–+0– | Good | Good | Average | Bad | Good | Average | Bad | 0 |

## *6.4 Analysis & Comparison*

### 6.4.1 Examples of the Generated Scenarios

In this section a number of representative and interesting scenarios generated through simulation of the case study have been selected, and have been portrayed with more details to demonstrate various types of information on timing, type of errors, causal factors and contextual characteristics produced by the proposed team behavior model and dynamic simulation methodology. These scenarios provide more detailed information about the complexities of human actions in interaction loops and how they contribute to the system risk. These examples demonstrate the usefulness of the simulation log files in understanding the team dynamics and how each person inside the team contributes to the evolution of an accident scenario from the moment that the initiating event occurs (or even before that) to the point that end state is reached.

In studying these scenarios, note that these are scenarios that have been picked randomly to provide a better understanding of how team activities are modeled and are reflected in these scenarios. The tables list the highlights of the scenarios. The total time for the simulation of each model has been set to t=25. Since we are generating a discrete dynamic event tree, this time is being divided by MATLAB Simulink to a set of time steps (each =0.1) to provide a discrete concept of time. Hence by saying t= 1.1 we mean we are at the 11th time step. Our model of error management by design allows for just two attempts to be made to recover from errors in a sequence because otherwise operators would have been engaged in loops. If the error situation is not recovered from after two attempts, the situation is declared unrecoverable and team fails in recovering from that error situation.

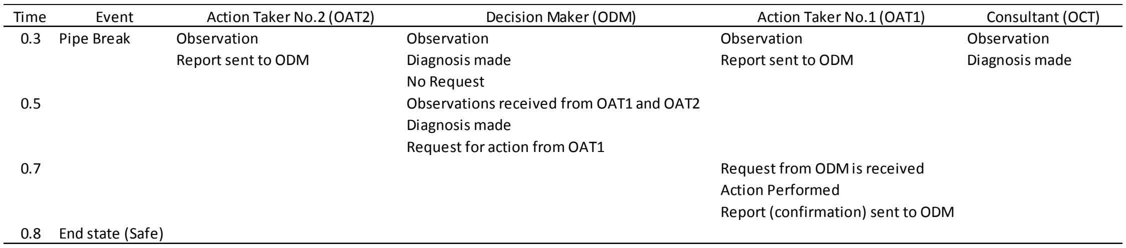
## 1) Table 32, Simulation Case No.16

**Successful Case**

**Summary:** Extreme case: All operators and all factors are average

This is one of the extreme cases in which all the operators and all of the factors have been set to be in nominal condition. There was no error observed in the operating crew.

From t=0 to t=0.3 the system is at nominal state. The initiating event (a pipe break) happens at t=0.3, and is detected observations are made by OAT1 and OAT2 who inform and sent to ODM at this time step. OCT also recognize the situation but is not being asked for any advice. At t=0.5 ODM receives both observations and issues instruction requests the right action from OAT1 to perform the required action. At t=0.7 OAT1 receives the command to activate emergency subsystem, executes the required action and sends the confirmation message back to ODM. At t=0.8 end state is declared to be reached and a dry out accident is successfully avoided. Scenario highlights are listed in figure 52.



| Time | Event | Action Taker No.2 (OAT2) | Decision Maker (ODM) | Action Taker No.1 (OAT1) | Consultant (OCT) |
|---|---|---|---|---|---|
| 0.3 | Pipe Break | Observation | Observation | Observation | Observation |
| | | Report sent to ODM | Diagnosis made | Report sent to ODM | Diagnosis made |
| | | | No Request | | |
| 0.5 | | | Observations received from OAT1 and OAT2 | | |
| | | | Diagnosis made | | |
| | | | Request for action from OAT1 | | |
| 0.7 | | | | Request from ODM is received | |
| | | | | Action Performed | |
| | | | | Report (confirmation) sent to ODM | |
| 0.8 | End state (Safe) | | | | |

Figure 52: Scenario highlights, Simulation case No.16

## 2) Table 32, Simulation Case No.8

### Successful Case

All operators are average, all communication and team factors are bad

**Summary:** In this case all the operators are being set to be average (nominal), and all communication and team factors are set to be bad.

In this case, immediately after starting the scenario, communication with outside the control room fails because of deficiency in device, and OAT2 is almost isolated. In this case the device used for communication to outside of the control room is faulty and the situation is considered to be unrecoverable. OAT2 tries to report this problem with communication to ODM; however, since the device is not working correctly, ODM keeps receiving unrecognizable messages from OAT2. ODM is successful in recognizing the error (unrecognizable message received) and as a recovery action he asks OAT2 to resend the message at t=0.1. But since the communication device is not working properly, OAT2 receives an unrecognizable message from ODM and is unsuccessful in recovering from situation at t=0.2. Since the system is in normal condition, this doesn't have any impact on system state but this loop of OAT2 sending unrecognizable message and ODM asking for message resending is being repeated. At t=6.9 a pipe break event occurs in the plant and the associated alarm is activated. OAT1 is successful in observing the event and reporting it to ODM. ODM has access to plant information, observes the event, diagnoses the system state to be "not normal" and recognizes the system state as "Intermediate loop lost integrity". He plans to activate emergency trigger, but waits until he receives observation from OAT1. ODM keeps receiving unrecognizable messages from OAT2 but is successful in recognizing, indicating and correcting this error by asking OAT2 to resend the message. However, the problem with the device still exists. At t=7, OAT2 still sends unrecognizable messages. ODM requests for resending the message. OAT1 sends his observation on system state to ODM. At t=7.1 OAT2 is in the same situation. ODM declares that no recovery action is possible for OAT2. The team continues to operate without OAT2. At this time, ODM receives observation on system state from OAT1 and asks him to activate the emergency system. At t=7.3, OAT1 receives request and performs the action on the system and sends a confirmation message to ODM. At t=7.4 end state is reached and Dry Out is successfully avoided. Scenario highlights are listed in figure 53.

| Time | Event | Action Taker No.2 (OAT2) | Decision Maker (ODM) | Action Taker No.1 (OAT1) | Consultant (OCT) |
|---|---|---|---|---|---|
| 0 | D-B Comm fails | Report sent to ODM | | | |
| 0.1 | | | Receives unknown message from OAT2<br>Starts error recovery<br>Requests for resending the message | | |
| 0.2 | | Receives unknown message<br>Report sent to ODM | | | |
| 6.9 | Pipe Break | Observation<br>Report sent to ODM | Observation<br>Diagnosis made<br>Receives unknown message from OAT2<br>Starts error recovery<br>Requests for resending the message | Observation<br>Report sent to ODM | Observation<br>Diagnosis made |
| 7 | | Receives unknown message<br>Report sent to ODM | | | |
| 7.1 | | | Receives unknown message from OAT2<br>Starts error recovery<br>No recovery possible<br>Observations received from OAT1<br>Diagnosis made<br>Request for action from OAT1 | | |
| 7.3 | | | | Request from ODM is received<br>Action Performed<br>Report (confirmation) sent to ODM | |
| 7.4 | End state (Safe) | | | | |

Figure 53: Scenario highlights, Simulation case No.8

## 3) Taguchi Set, Simulation Case No.1

### Unsuccessful Case

Extreme Case, All Operator PSFs are set to Bad

**Summary:** This case is another extreme Case; all operators and factors are set to be bad.
At t=0 device-based communication fails in team due to device failure, and there is no possible recovery from this situation since the device is not repairable. OAT2 reports the problem to ODM; however, since the device is not working correctly, ODM receives unrecognizable message from OAT2. ODM is successful in recognizing the problem (unknown message received) and as a recovery action he asks the message to be repeated. But since the device is not working properly, OAT2 keeps receiving unknown message from ODM and is unsuccessful in recovering from situation. However, the system is in normal condition and this doesn't have any impact on system state.

A pipe break initiating event happens at t=0.7 and ODM receives the observation made by OAT1 and at the same time realizes that there is no recovery action possible for the device-based communication error, hence the team fails in recovering from this situation. The team needs to continue operation with just one equipment operator. ODM sends a request for activating emergency subsystem to OAT1. At t=0.8 OAT1 does not attend to the input so he doesn't receive the request from ODM, and misses the message. Without guidance from ODM and not noting the input from the system, OAT1 also fails to recognize the situation and hence he is not able to make a decision and waits undecided. ODM and OCT do not attend to input either and hence cannot follow the situation. In this situation a *shared error* has happened inside the team. At this time none of the team members are aware of the system state, and they all declare an unknown system state. (In a situation such as this case where a shared error happens, it is possible that an external interruption just distracted all operators at the same time.) The situation worsens since communication error happens inside control room among ODM, OCT and OAT1 and they unable to send and receive messages correctly, and keep receiving unknown messages from each other. ODM not only fails in recognizing the situation but all error management activities fail as well. Because the operators failed in diagnosing the situation and there is no guidance from ODM, OAT1 is unable to perform any actions on the system. Error recovery is not an option anymore since it failed at the individual and team level. In this case, all activities fail. The situation remains the same till t=20.1 when the steam generator water level reaches its lowest allowable value and the steam generators are declared "Dried out". Scenario highlights are listed in Figure 54.

| Time | Event | Action Taker No.2 (OAT2) | Decision Maker (ODM) | Action Taker No.1 (OAT1) | Consultant (OCT) |
|---|---|---|---|---|---|
| 0 | D-B Comm fails | Report sent to ODM | | | |
| 0.1 | | | Receives unknown message from OAT2 | | |
| | | | Starts error recovery | | |
| | | | Requests for resending the message | | |
| 0.2 | | Receives unknown message | | | |
| | | Report sent to ODM | | | |
| 0.7 | Pipe Break | Observation | Observation | Observation | Observation |
| | | Report sent to ODM | Diagnosis made | Report sent to ODM | Diagnosis made |
| | | | Receives unknown message from OAT2 | | |
| | | | Starts error recovery | | |
| | | | No recovery possible | | |
| | | | Observations received from OAT1 | | |
| | | | Diagnosis made | | |
| | | | Request for action from OAT1 | | |
| 0.8 | | | Fails to attend to reports | Fails to attend to request | Fails to attend to inputs |
| | | | Unknown system state is diagnosed | | |
| | | | Error recovery fails | | |
| | | Receives unknown message | | Unknown system state | Unknown system state |
| | | Report sent to ODM | | Error recovery fails | Error recovery fails |
| 20.1 | End state (Dry out) | No action | | No action | |

Figure 54: Scenario highlights, Taguchi set, Simulation case No.1 (a)

## Successful Case:

**Summary:** Device-based communication fails at t=0 and the initiating event (pipe break) happens at t=0; Since OAT2 keeps sending unrecognizable messages to ODM, ODM is engaged in error recovery and sends a request to OAT2 to resend the message. At t=0.2, ODM asks OAT2 to resend the message, but the problem with communication still exists. At this time, OAT1 sends the message about his observation on system state to ODM. At t=0.4 ODM receives the observation and asks OAT1 to perform the corrective action. He also declares that the problem with communication is not solvable and the situation is not recoverable. At t=0.6 OAT1 performs the action and sends a confirmation message to ODM, and at t=0.7 the accident is successfully terminated. In this case, since the component failure occurred at the beginning of the scenario, the time load of the task was at a low level and operators were able to catch the course of events. In investigating a couple of other cases, we recognized that if the component failure event is combined with any of the operators being unavailable, the dry out situation cannot be avoided. Scenario highlights are listed in Figure 55.

| Time | Event | Action Taker No.2 (OAT2) | Decision Maker (ODM) | Action Taker No.1 (OAT1) | Consultant (OCT) |
|---|---|---|---|---|---|
| 0 | D-B Comm fails | | | | |
| | Pipe Break | Observation | Observation | Observation | Observation |
| | | Report sent to ODM | Diagnosis made | Starts error recovery | Diagnosis made |
| | | | Receives unknown message from OAT2 | No report | |
| | | | Starts error recovery | | |
| | | | Requests for resending the message | | |
| 0.2 | | Receives unknown message | | Observation | |
| | | Report sent to ODM | | Report sent to ODM | |
| 0.4 | | | Receives unknown message from OAT2 | | |
| | | | Starts error recovery | | |
| | | | No recovery possible | | |
| | | | Observations received from OAT1 | | |
| | | | Diagnosis made | | |
| | | | Request for action from OAT1 | | |
| 0.6 | | | | Request from ODM is received | |
| | | | | Action Performed | |
| | | | | Report (confirmation) sent to ODM | |
| 0.7 | End state (Safe) | | | | |

Figure 55: Scenario highlights, Taguchi set, Simulation case No.1 (b)

## 4) Taguchi Set, Simulation Case No.10

### Successful Case

**Summary:** This is a case when the off-site operator OAT2, is set to be poor, and face to face communication is less than adequate.

At t=1.2 OAT2 fails to attend to the input and system state is incorrectly reported as unknown state to ODM. At t=1.3 ODM receives the wrong observation and since he has access to system information, as a recovery action asks OAT2 to resend the message. At t= 1.4, ODM receives the wrong observation once again but doesn’t perform any action and waits. At t=1.5 OAT2 receives request for resending the message but doesn’t perform action and waits. At t=1.6 Errors are all removed. OAT2 attends to input from the system and recognizes a normal situation. At t=5.5 a pipe break event occurs, and observations made by OAT1 and OAT2 are sent to ODM. At t=5.7 ODM receives both observations and asks OAT1 to perform the corrective action (activation of the emergency subsystem). At t=5.9 OAT1 receives the command and executes the required action on the system and sends the confirmation message to ODM. This terminates the accident scenario successfully (at t=6). Scearo highlights are listed in Figure 56.

| Time | Event | Action Taker No.2 (OAT2) | Decision Maker (ODM) | Action Taker No.1 (OAT1) | Consultant (OCT) |
|---|---|---|---|---|---|
| 1.2 | | Fails to attend to input<br>Wrong observation<br>Report sent to ODM | | | |
| 1.3 | | Wrong observation<br>Report sent to ODM | Observations received from OAT2<br>Starts error recovery<br>Requests for resending the message | | |
| 1.4 | | | Observations received from OAT2<br>No message | | |
| 1.5 | | Receives request from ODM<br>No message | | | |
| 1.6 | | No Error | No Error | | |
| 5.5 | Pipe Break | Observation<br>Report sent to ODM | Observation<br>Diagnosis made<br>No Request | Observation<br>Report sent to ODM | Observation<br>Diagnosis made |
| 5.7 | | | Observations received from OAT1 and OAT2<br>Diagnosis made<br>Request for action from OAT1 | | |
| 5.9 | | | | Request from ODM is received<br>Action Performed<br>Report (confirmation) sent to ODM | |
| 6 | End state (Safe) | | | | |

Figure 56: Scenario highlights, Taguchi set, simulation Case No.10 (a)

### Another Successful Case:

From t=0 to t=1 the system is in nominal condition. At t=0.8 OAT2 fails in recognizing normal system state and falsely reports an unknown system state observation to ODM. At t=0.9 ODM realizes the error since he has access to the system state and asks OAT2 to resend he message (since he knows the system state is normal). At t=1 the pipe break event (imitating event) occurs and the accident scenario starts. OAT2 attends to the input, observes the event, recognizes the situation (system state is not normal) and reports it to ODM. However ODM is still receiving the false observation he sent in the precious time step and is unable to recognize the situation (he is engaged in team error recovery). As a first order recovery action, he asks OAT2 to resend the message. OAT1 also attends to the input from the system and is able to recognize the situation and reports his observation to ODM. At t=1.1, OAT2 receives a request for resending the message sent from ODM and resends his correct observation this time. OAT1 still sends his observation. At t=1.2, OAT2 fails to recognize the situation since he did not attend to the input (alarm) from the system. He is also unable to recover from this situation at the same time step. ODM receives both observations sent from OAT1 and OAT2 (at previous time step) and collects the information from the system himself and recognizes the situation as "intermediate loop lost integrity" correctly. He asks OAT1 to activate emergency subsystem as called for by the emergency operating procedure. At t=1.3, ODM receives a wrong message from OAT2 since the operator did not attend to the input at the previous time step and was unable to send the right observations. However OAT1 still sends the correct observation from the system. ODM starts team recovery and attempts to recover from situation by indicating the error to the operators and asking for a recovery action. However since this is an *attendance error,* no recovery action is possible at the same time step. At t=1.4 OAT2 is attending to the input once again. He starts to send the right observation on the system. OAT1 performs the requested action and sends the confirmation message to ODM. At t=1.5, OAT2 fails to recognize the situation since he did not attend to the input from the system once again. However, since the safe end state is already reached, the scenario ends at this step and the occurrence of undesired end state (dry out) is being avoided despite the numerous errors committed by team. Scenario highlights are listed in Figure 57.

| Time | Event | Action Taker No.2 (OAT2) | Decision Maker (ODM) | Action Taker No.1 (OAT1) | Consultant (OCT) |
|---|---|---|---|---|---|
| 0.8 | | Fails to recognize system state<br>Wrong observation | | | |
| 0.9 | | | Observations received from OAT2<br>Starts error recovery<br>Requests for resending the message | | |
| 1 | Pipe Break | Observation<br>Report sent to ODM | Observation<br>Diagnosis made<br>Starts error recovery<br>Requests for resending the message | Observation<br>Report sent to ODM | Observation<br>Diagnosis made |
| 1.1 | | Receives request from ODM<br>Observation<br>Report sent to ODM | | Observation<br>Report sent to ODM | |
| 1.2 | | Fails to attend to input<br>Error recover fails | Observations received from OAT1 and OAT2<br>Diagnosis made<br>Request for action from OAT1 | | |
| 1.3 | | | Wrong Observation received from OAT2<br>Observation received from OAT1<br>Starts error recovery<br>No recovery possible | | |
| 1.4 | | Observation<br>Report sent to ODM | | Request from ODM is received<br>Action Performed<br>Report (confirmation) sent to ODM | |
| 1.5 | End state (Safe) | Fails to attend to input | | | |

Figure 57: Scenario highlights, Taguchi set, simulation Case No.10 (b)

## 5) Taguchi Set, Simulation Case No.11

### Successful Case

This is a case when the off-site operator OAT2, is set to be poor, and team factors are less than adequate.

### Summary

This is a case that off-site operator OAT2 is set to be poor, and team factors are poor. From t=0 to t=0.5 system is in nominal condition. At t=0.6 the pipe break event (initiating event) occurs and the accident scenario starts. OAT2 attends to the input, observes the event, recognizes the situation (that the system state is not normal) and reports it to ODM. OAT1 also attends to the input from the system and is able to recognize the situation and reports this observation to ODM. At t=0.7, OAT1 and OAT2 send their observations on the system state to ODM. At t=0.8, OAT2 does not attend the system input (alarm) and error recovery is not successful either. ODM receives both observations sent on previous time steps and recognizes the system state and asks OAT1 for activating emergency subsystem as the right action based on the procedures. OAT1 sends his right observation on the system to ODM. At t=0.9, ODM receives a wrong observation from OAT2 since the operator did not attend to the input in the previous time step and was unable to send the right observations. However OAT1 sends the correct observation from the system. ODM starts team recovery and attempts to recover from the situation by indicating the error to the operators and asking for a recovery action. However since this is a case of attendance error, no recovery action is possible at the time step. At t=1.4 OAT2 is attending the input once again, and starts to send the right observation on system. OAT1 performs the requested action and sends the confirmation message to ODM. At t=1.5, OAT2 fails to recognize the situation since he did not attend to the input from the system once again. However, since the safe end state is already reached, the scenario ends at this step and the occurrence of undesired end state (dry out) is being avoided despite the numerous errors committed by team. Scenario highlights are listed in Figure 58.

| Time | Event | Action Taker No.2 (OAT2) | Decision Maker (ODM) | Action Taker No.1 (OAT1) | Consultant (OCT) |
|---|---|---|---|---|---|
| 0.6 | Pipe Break | Observation<br>Report sent to ODM | Observation<br>Diagnosis made<br>No Request | Observation<br>Report sent to ODM | Observation<br>Diagnosis made |
| 0.8 | | Fails to attend to the input<br>Wrong observation<br>Report sent to ODM | Observations received from OAT1 and OAT2<br>Diagnosis made<br>Request for action from OAT1 | | |
| 0.9 | | | Wrong Observation received from OAT2<br>Observation received from OAT1<br>Starts error recovery<br>No recovery possible | | |
| 1.4 | | Observation<br>Report sent to ODM | | Request from ODM is received<br>Action Performed<br>Report (confirmation) sent to ODM | |
| 1.5 | End state (Safe) | Fails to attend to the input | | | |

Figure 58: Scenario highlights, Taguchi set, simulation Case No.11

## 6) Table 34, Simulation Case No.80

### Unsuccessful Case

ODM PSFs are set to Bad, All other Operators are Set Average and All Other Factors are Average

**Summary**

The shift supervisor ODM factors are set to be poor, all other operators are average and all factors are average. At t=0.9, ODM fails to attend the input from the system and incorrectly diagnoses the normal system state as an unknown (accident) incorrectly. He also fails in recovering from this error. At t=1.1 he receives observations from OAT1 and OAT2 incorrectly and decides to ask for an action on the system. However in reviewing this issue during self-review (error recovery) he recognizes the error and hence does not send any request or action to the rest of the team. The situation remains the same since ODM frequently fails in attending to the input from the system and gives false report on the system state. All team members are engaged in error recovery actions and their diagnosis on the system state jumps back and forth between normal and unknown system states. At t=3.8 component failure (pipe break) occurs. The observations are reported to ODM; however ODM fails in diagnosis of the situation and in planning for action and therefore is not successful in recovering from this situation and does not ask the consultant for advice. ODM fails in recognizing the system state and reports unknown system state to rest of the team. This situation stays the same until undesired end state (dry out) is reached at the end of the scenario. Scenario highlights are listed in Figure 59.

| Time | Event | Action Taker No.2 (OAT2) | Decision Maker (ODM) | Action Taker No.1 (OAT1) | Consultant (OCT) |
|---|---|---|---|---|---|
| 0.9 | | | Fails to attend to the input | | |
| 1.1 | | Observation | Receives wrong Observation | Observation | |
| | | Report sent to ODM | Wrong diagnosis | Report sent to ODM | |
| | | | Starts error recovery | | |
| | | | No request for action | | |
| | | Wrong diagnosis | | Wrong diagnosis | Wrong diagnosis |
| 3.8 | Pipe Break | Observation | | Observation | Observation |
| | | Report sent to ODM | | Report sent to ODM | Diagnosis made |
| | | | Receives wrong Observation | | |
| | | | Wrong diagnosis | | |
| | | | Error Recovery fails | | |
| | | Wrong diagnosis | | Wrong diagnosis | |
| 23.2 | End State (Dry out) | No action | | No action | |

**Figure 59: Scenario highlights, Simulation case No.80**

### 6.4.2 Variability

The result of simulating the main test cases was analyzed from the variability point of view using the mean value and standard deviation for the occurrence of an undesired state as the parameter of interest. The analysis was performed using JMP software tool. We were interested in the source of variability which is basically a factor that if kept constant, would result in a lower standard deviation; meaning that the source of variability is captured. For instance, figure 60 shows the analysis for just the "Team factors". We categorized cases based on this criterion: "Team factors" being "bad" or "average". The large value of standard deviation means this factor is not a source of variability among the team all by itself.

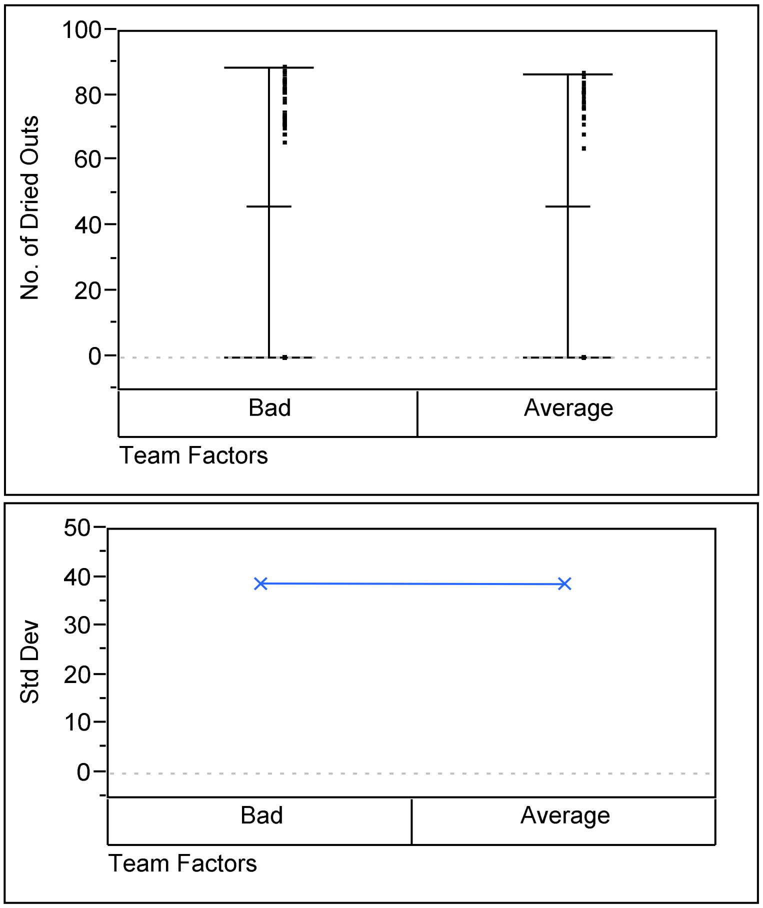


Figure 60: Variability chart for No. of Dry outs- Team factors

Then we included more factors to examine different combinations from the variability perspectives. Figure 61 shows a combination of team and communication factors. Since the standard deviation is still high, none of these factors can be considered major sources of variability in the team.

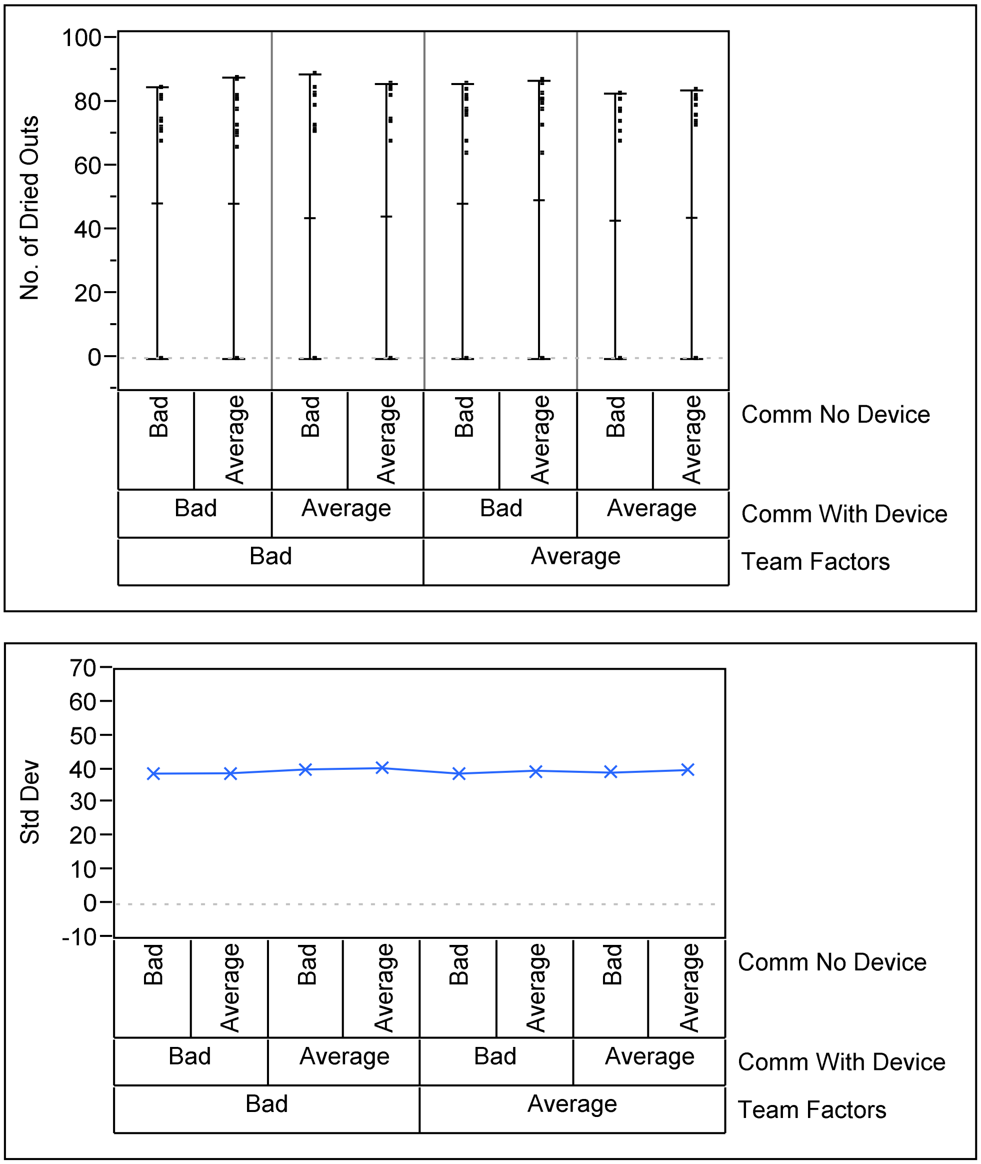


Figure 61: Variability chart for No. of Dry outs- Communication & Team factors

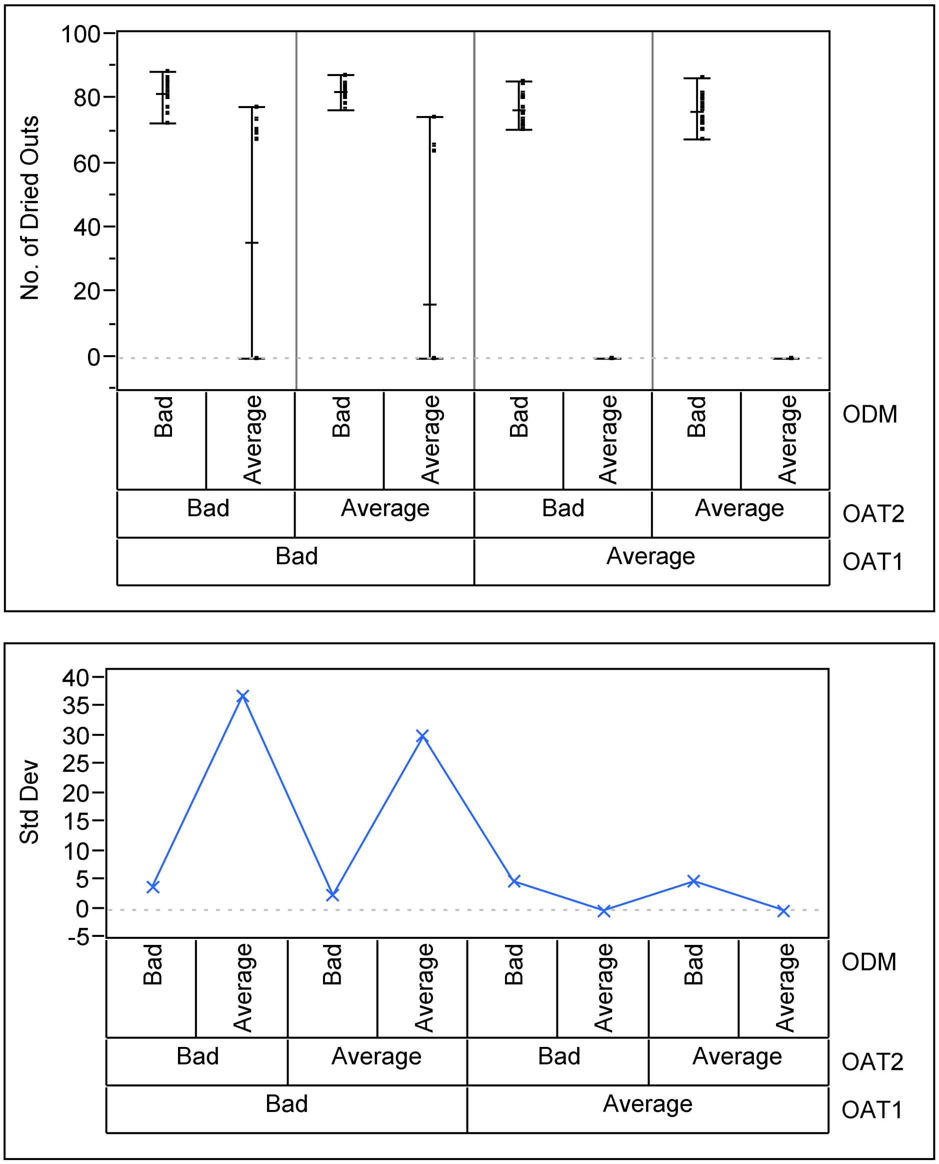


Figure 62: Variability chart for No. of Dry outs - Operators (a)

Figure 62 and 63 show the different configuration of team members and how the number of dry outs is changed by these factors. The standard deviation values are rather small, meaning the team performance is dependent on these factors. The standard deviation is the smallest when the supervisor (ODM) is weak, so this is one of the sources of variability in the team.

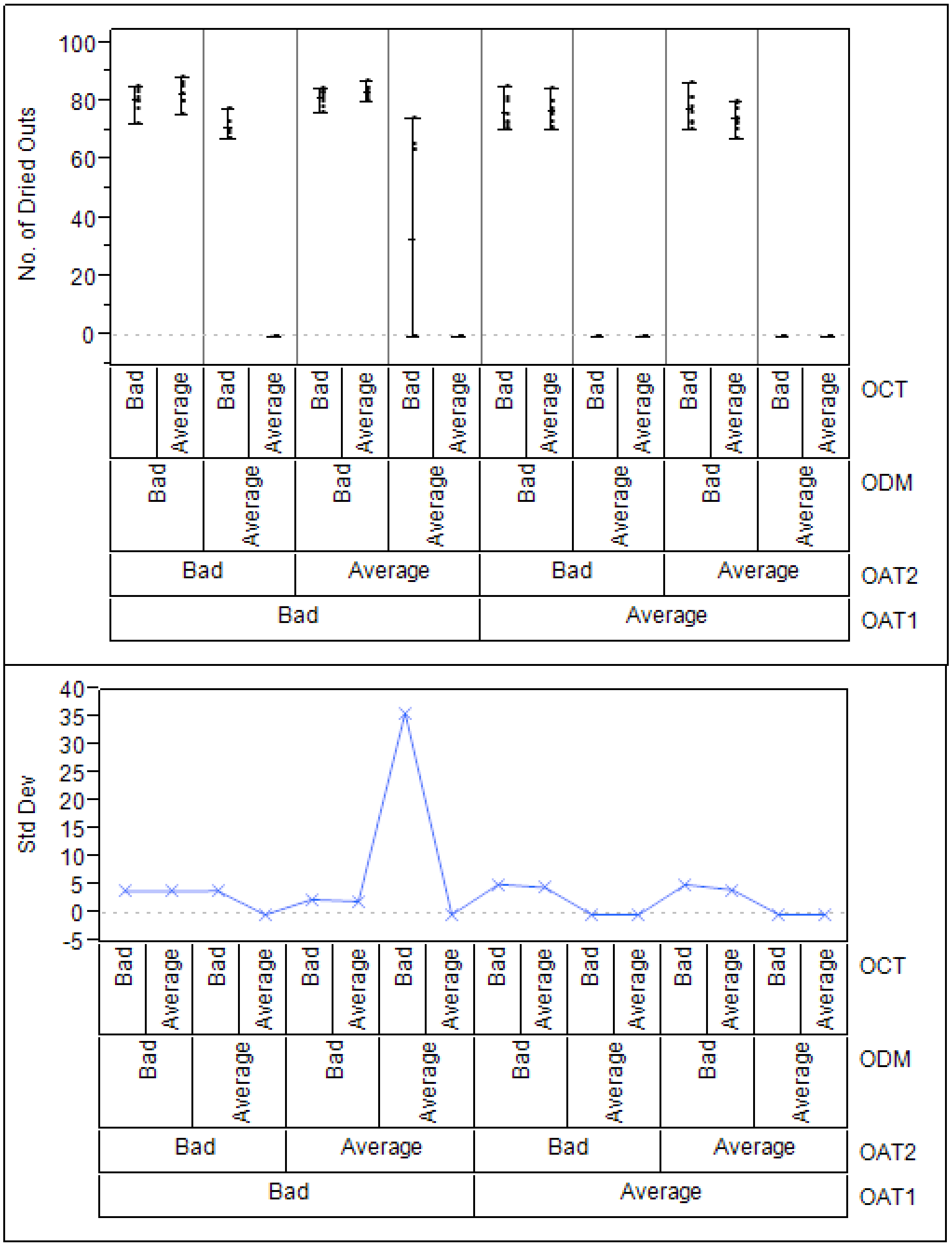


Figure 63: Variability chart for No. of Dry outs- Operators (b)

Figure 64 shows a combination of team factors and operators. It is clear that a weak consultant (OCT) produces a large standard deviation compared to other factors so this factor cannot be considered a source of variability in the team.

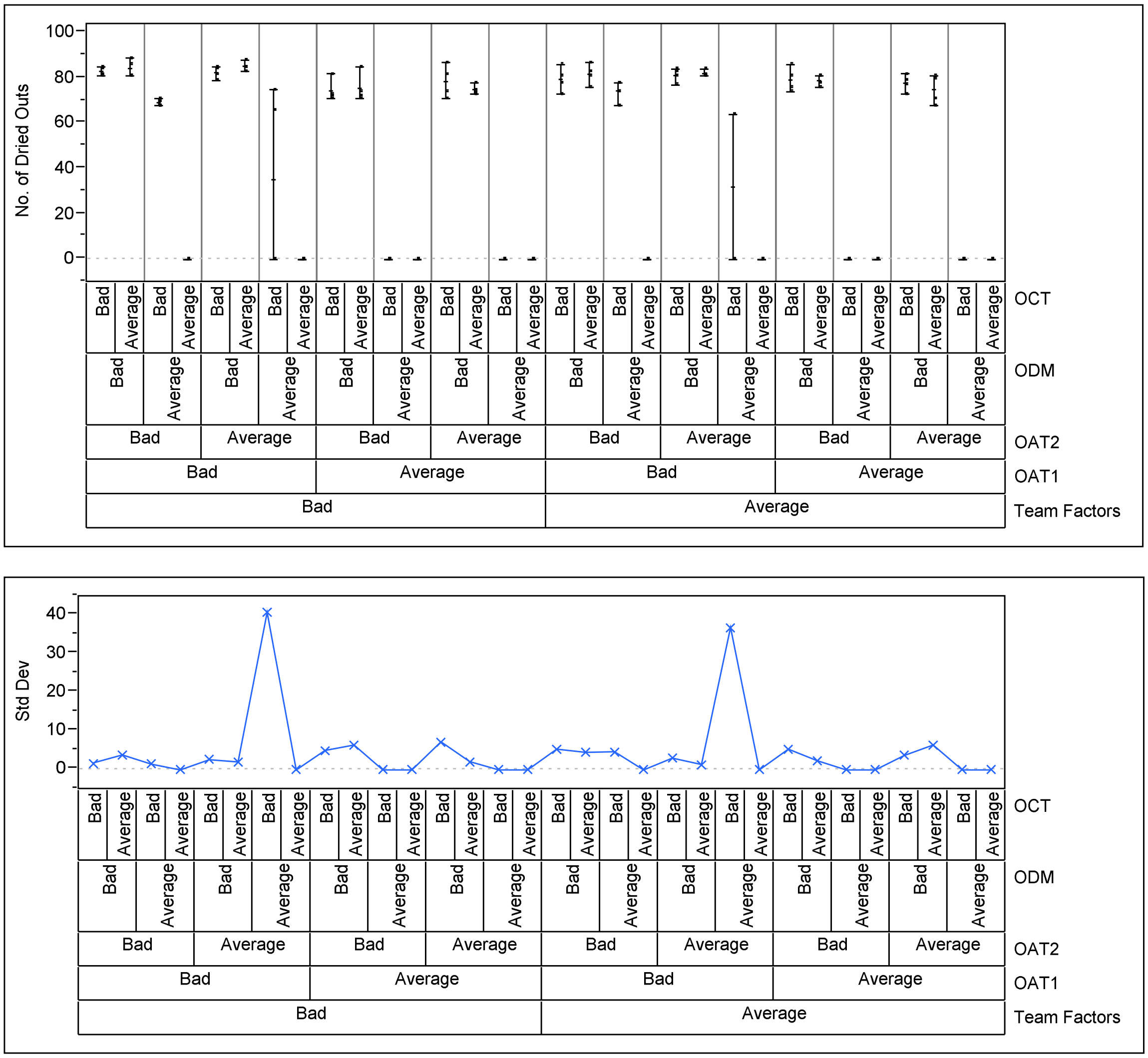


Figure 64: Variability chart for No. of Dry outs - Team factors & crew

Figure 65 provides details of the combinations of communication factors and operators. Figures 64 and figure 65 provide indication that the supervisor is a source of variability in the team, because the value of the standard deviation is the lowest while this factor is fixed at a certain level, i.e. considered as average or bad. This is what we expected since all activities inside the team are centered on the supervisor and he plays the key role in coordination activities.

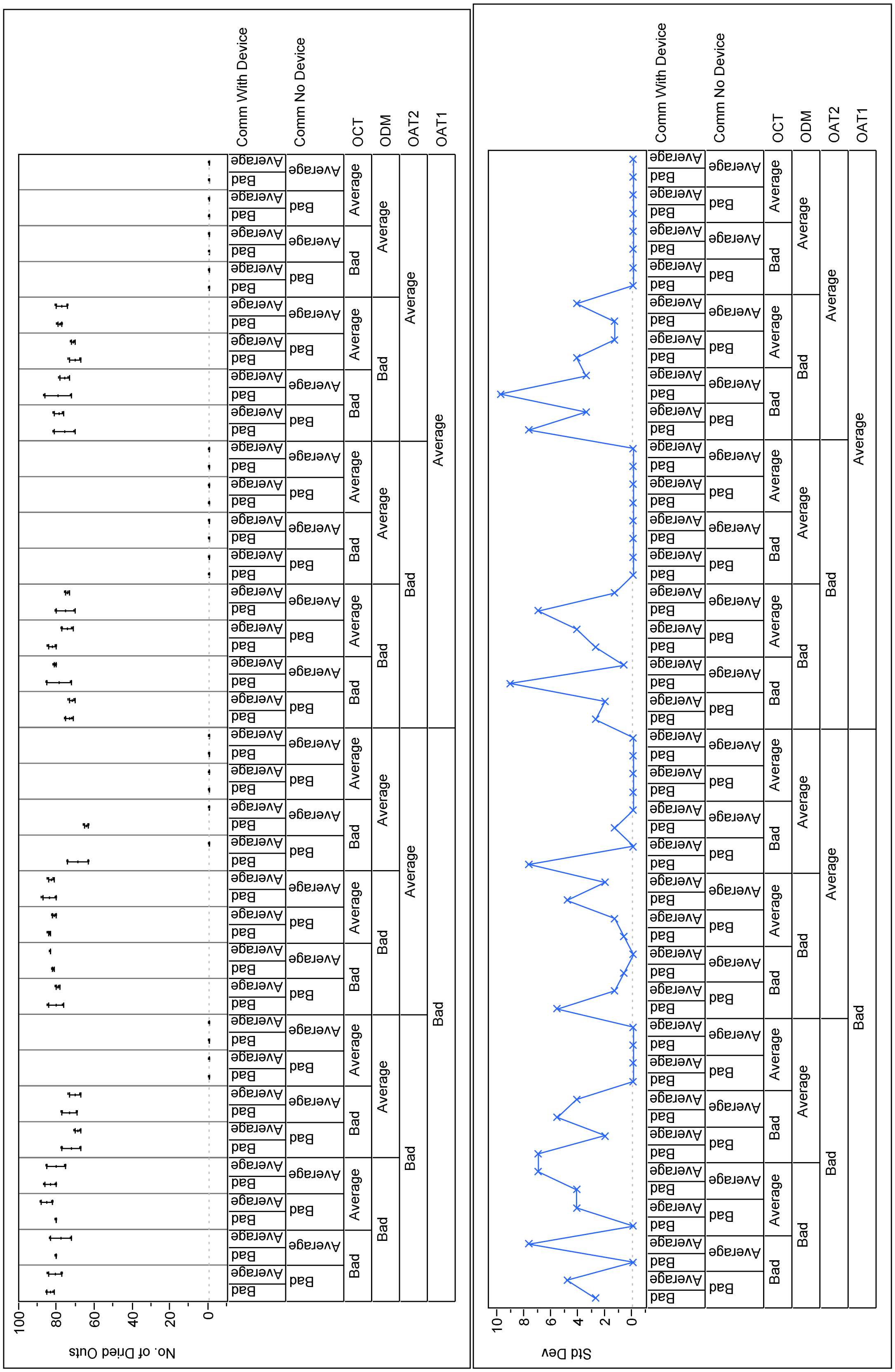


Figure 65: Variability chart for No. of Dry outs – Communication & crew

In case of the Taguchi set, similarly the supervisor (ODM) turned out to be the source of variability in the team. We also processed the cases where no dry out was observed; in 100% of such success cases, the ODM was set to “average” or “good”. So there was not a single case that ODM was set to “bad”, without resulting in dry out state. (Figure 66 and Figure 67)

Figure 66: Variability chart for No. of Dry outs, Taguchi method (a)

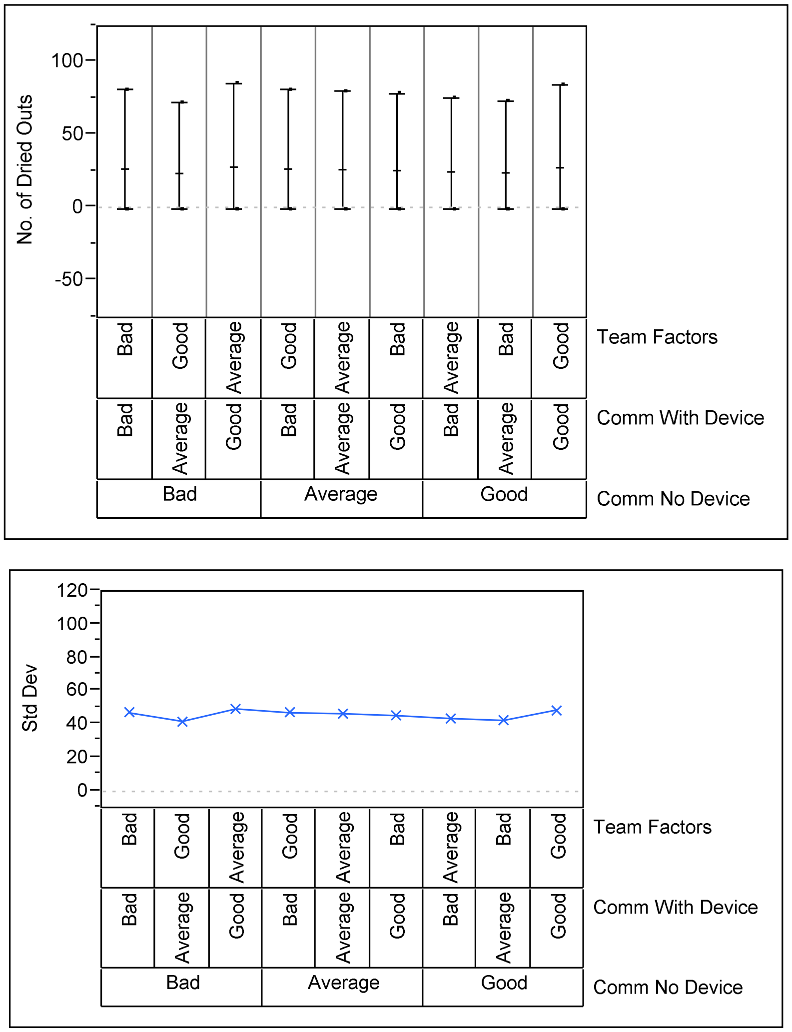


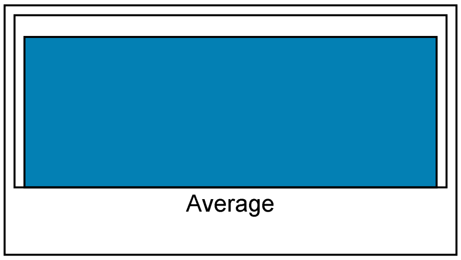
Figure 67: Variability chart for No. of Dry outs, Taguchi method (b)

### 6.4.3 Importance

Since the number of dry out situations has been used as the main performance measure on output, we used the success case (No. of dry outs = 0) to extract additional information on the sensitivity of performance on operator's roles inside the team (Figures 68 and 69). It is clear that in all success cases the qualitative evaluation of ODM individual factors has been set to "average". In other words, if there is a success case one can be sure about the level of PSFs for the supervisor of the team. All other findings make sense since all operators have been actively taking part in both success and failure scenarios. However, by looking at figures 70 and 71 one realizes that the effect of team factors and face-to-face communication could not be captured using this method.

**Distributions Dried out=0**

**ODM**

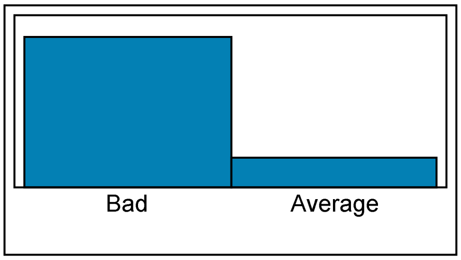


**Frequencies**

| Level | Count | Prob |
|---|---|---|
| Average | 52 | 1.00000 |
| Total | 52 | 1.00000 |

**Distributions Dried out=n0**

**ODM**

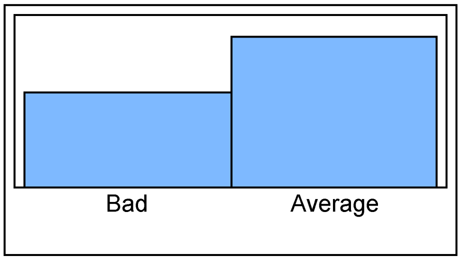


**Frequencies**

| Level | Count | Prob |
|---|---|---|
| Bad | 64 | 0.84211 |
| Average | 12 | 0.15789 |
| Total | 76 | 1.00000 |

**Distributions Dried out=0**

**OCT**

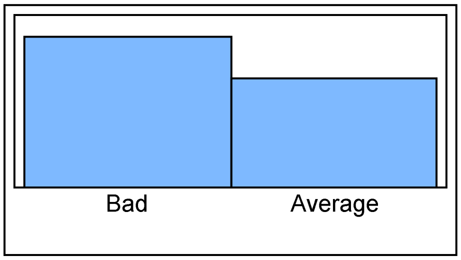


**Frequencies**

| Level | Count | Prob |
|---|---|---|
| Bad | 20 | 0.38462 |
| Average | 32 | 0.61538 |
| Total | 52 | 1.00000 |

**Distributions Dried out=n0**

**OCT**



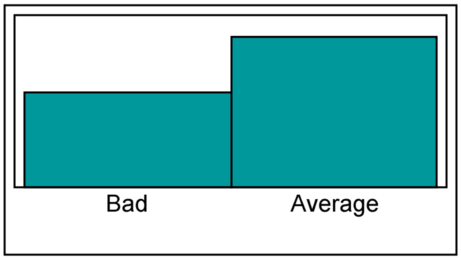
**Frequencies**

| Level | Count | Prob |
|---|---|---|
| Bad | 44 | 0.57895 |
| Average | 32 | 0.42105 |
| Total | 76 | 1.00000 |

Figure 68: Success and failure scenarios, ODM and OCT

## Distributions Dried out=0

### OAT1

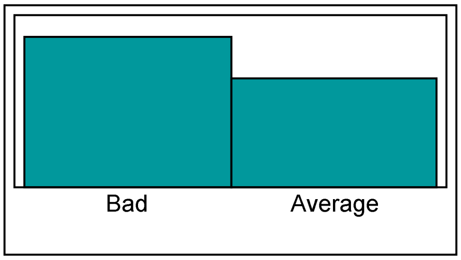


### Frequencies

| Level | Count | Prob |
|---|---|---|
| Bad | 20 | 0.38462 |
| Average | 32 | 0.61538 |
| Total | 52 | 1.00000 |

## Distributions Dried out=n0

### OAT1

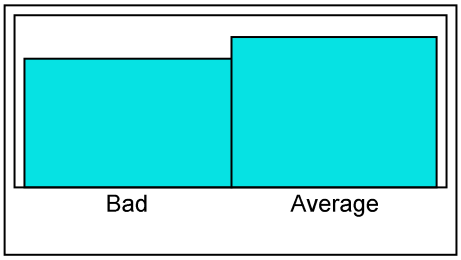


### Frequencies

| Level | Count | Prob |
|---|---|---|
| Bad | 44 | 0.57895 |
| Average | 32 | 0.42105 |
| Total | 76 | 1.00000 |

## Distributions Dried out=0

### OAT2

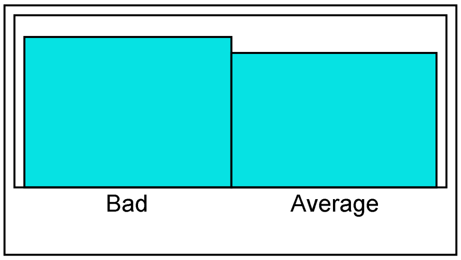


### Frequencies

| Level | Count | Prob |
|---|---|---|
| Bad | 24 | 0.46154 |
| Average | 28 | 0.53846 |
| Total | 52 | 1.00000 |

## Distributions Dried out=n0

### OAT2



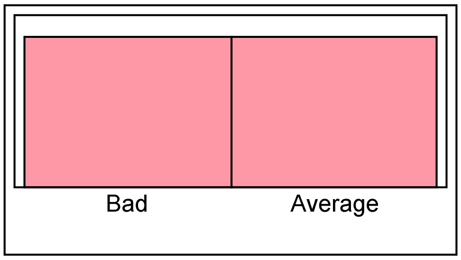
### Frequencies

| Level | Count | Prob |
|---|---|---|
| Bad | 40 | 0.52632 |
| Average | 36 | 0.47368 |
| Total | 76 | 1.00000 |

Figure 69: Success and failure scenarios, OAT1 and OAT2

### Distributions Dried out=0

### Comm No Device

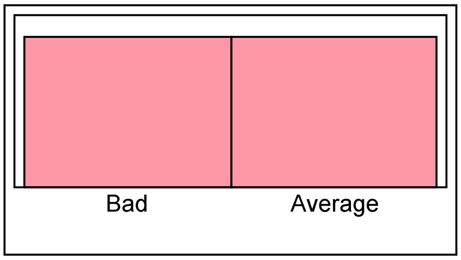


### Frequencies

| Level | Count | Prob |
|---|---|---|
| Bad | 26 | 0.50000 |
| Average | 26 | 0.50000 |
| Total | 52 | 1.00000 |

### Distributions Dried out=n0

### Comm No Device

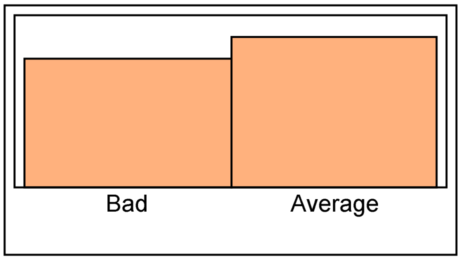


### Frequencies

| Level | Count | Prob |
|---|---|---|
| Bad | 38 | 0.50000 |
| Average | 38 | 0.50000 |
| Total | 76 | 1.00000 |

### Distributions Dried out=0

### Comm With Device

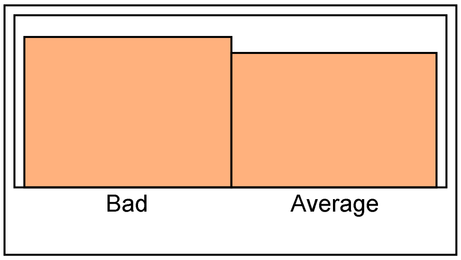


### Frequencies

| Level | Count | Prob |
|---|---|---|
| Bad | 24 | 0.46154 |
| Average | 28 | 0.53846 |
| Total | 52 | 1.00000 |

### Distributions Dried out=n0

### Comm With Device



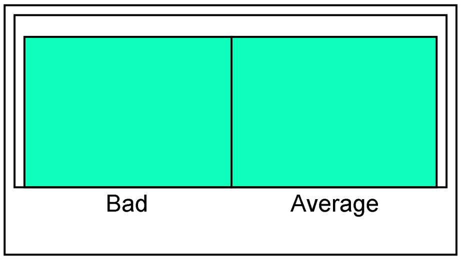
### Frequencies

| Level | Count | Prob |
|---|---|---|
| Bad | 40 | 0.52632 |
| Average | 36 | 0.47368 |
| Total | 76 | 1.00000 |

Figure 70: Success and failure scenarios, Communication

**Distributions Dried out=0**

**Team Factors**

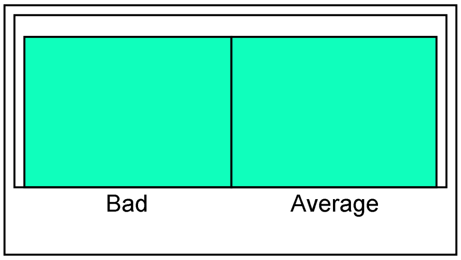


**Frequencies**

| Level | Count | Prob |
|---|---|---|
| Bad | 26 | 0.50000 |
| Average | 26 | 0.50000 |
| Total | 52 | 1.00000 |

**Distributions Dried out=n0**

**Team Factors**



**Frequencies**

| Level | Count | Prob |
|---|---|---|
| Bad | 38 | 0.50000 |
| Average | 38 | 0.50000 |
| Total | 76 | 1.00000 |

Figure 71: Success and failure scenarios, Team factors

## 6.5 Limitations & Sources of Errors

The simulation cases were conducted mainly to demonstrate that the behavior of the operating crew could be investigated by using models of team dynamics and the operators based on methodology proposed by this research. The main objective was to show the capabilities of the model; however, the model provides a large set of capabilities and not all those could have been explored by this study. For instance, there are huge simulation log files containing much detail about what happened in the scenario at each step. Simulation log files contain extensive information about the timeline of operators' actions and errors as well as error recovery activities. They can also be investigated from the communication perspective to derive performance measure for communication complexity based on the number of back and forth links recorded (Sasangohar et al., 2010) and (Stachowski et al., 2009). In addition, the analysis can be improved in order to get more accurate results for future studies: First, the number of simulation runs (100) were rather small and in some cases might mask rare events; the reason for having a rather small set of simulation runs was that the very large magnitude of the simulation log files that would require analysis.

Additionally, the base probabilities used here are assumed and have not been based on any operating history or calibrated method. We also used a set of different initial probabilities between (0.01 and 0.1) and ran the simulation for the worst case again. However this time we could not observe any dry out end states, so we kept the values at 0.1 as way of bumping up the number of interesting cases (standard approach in numerically biasing simulation cases).

Another limitation is that we just modeled explicit communication where the message is basically transferred via a verbal (face-to-face) or device-based channel. However, research has shown that non-explicit communication plays a major role in team performance (Waller et al., 2004), (Stanton et al., 2000) and (Kolbe et al., 2009). Errors in our framework have been defined based on the procedures and regulations so the error list needs to be refreshed with any change in the organization. In addition, the cases that contained a combination of two extreme levels ("good" and "bad") have not been included in the simulation exercise except during the screening stage. We only studied a subset of all possible combinations of levels ("average" and "bad"). The research attempted to address this issue by using the Taguchi samples discussed earlier. However, fully exploring all possible cases may provide new insights.

## *6.6 Comparison & Validation*

It is clear that the simulation results produced are essentially reflective of the team model and the underlying theoretical perspective adopted in this research. However, it is encouraging that the macro-behavior of the simulated team built from a large number of model elements seems to be realistic. Many of the model elements have credible roots in theories and observations; however, different sets of model assumptions can change the results. In this section the findings of this model are compared with some of the most important observations in the literature about operating crew performance. Our observations and findings by conducting this case study fall into two categories: the importance of the supervisor and the effect of communication on the performance of the team. As a complementary effort a comparison was made between data extracted from reports and records of Halden international exercises, and data extracted from the simulation log files which is being discussed in section 6.6.1. The objective was to verify the model with data from real control room operators. Section 6.6.1 summarizes the result of this study. Section 6.6.2 reviews some of the statements made by other researchers in the field and Section 6.6.3 discusses the observations we made.

### 6.6.1 Model Validation

Halden Reactor Project conducted a new HRA benchmark called the "International HRA Empirical Study" (International HRA Empirical Study, NUREG/IA-0216, 2009). This study used insights from earlier HRA benchmark efforts and applied both qualitative and quantitative analyses to provide identical initial information to different HRA analysis teams, including information about the operating crews who were the subjects of simulator exercises. This study used performance shaping factors to allow comparison of degraded operator performance, and provides a template to allow comparison of methods.

Fourteen nuclear power plant (NPP) crews participated in the study at the HAlden huMan-Machine Laboratory (HAMMLAB), a full scope NPP control room simulator. These operating teams included a licensed reactor operator, an assistant reactor/turbine operator, and a shift supervisor. Two types of simulator scenarios were selected for the operating crews; a steam generator tube rupture (SGTR) event, and a loss of feed water (LOFW) event. Both scenarios had a simple (or base) case and a more complex case, in which the familiar scenario was complicated by secondary malfunctions. The performances of the operating crews were observed and documented during simulator runs. The documentation provides a standardized set of contributing elements based on selected performance shaping factors, short operational summaries of the crew actions, and the success or failure of the crews to complete specific actions, within a predefined time window. The objective was to compare the results of HRA analyses produced by the different HRA analysis teams to the actual crew performance results documented in the simulation runs, thus allowing a direct comparison between the empirical data and model predictions. As part of the challenge, the operating crews had to complete their tasks within a specified time, as expected by their training.

The Halden empirical study was the only accessible empirical data which could serve as a basis for validation of some of the macro-level performance of the simulation model proposed in this research. We note that the nature of the Halden exercise, accident scenarios, system characteristics, and data collected through the experiments, significantly limit the scope of this validation effort. Additionally we are limited to the Halden study results as reported in the Final Report, which does not provide some of the more relevant information for our comparison. For instance the Halden data does not include insights into complexities of PSF causal factors and error management activities that are introduced by our methodology.  Due to these limitations our comparison is made at a macro behavior level. This comparison does allow some insights regarding strengths and weaknesses of the method in providing a basis for observing and evaluating the crew behavior.

In order to perform the comparison, comparable teams had to be found among the vast number of team configurations and characteristics offered by our model, and the 14 Halden crews participating in the experiment. We used the data available from Halden “base case” on the fastest and slowest groups from a performance point of view (time for completion of tasks) and compared this data to the best and worst case of operating crew configurations offered by our methodology.

Based on the description provided in Halden “base case” on the general characteristics of the slowest and fastest crews, we selected two of our cases based on similarities found in corresponding PSFs. There are two fast crews and one slow crew among the crews in Haden exercise. Figure 72 provides a summary of the description of fastest and slowest teams in Halden exercise and the associated performance shaping factors. In order to provide a basis for comparison we selected two representative crews from our cases. A configuration of average crew with a bad supervisor and a configuration of average crew (all operators are nominal) under the same circumstances with respect to other factors.

|  | Fast Crew | Slow Crew |
|---|---|---|
| Positive | Good match of procedure to scenario<br>Low complexity of Scenario<br>Clear indications | Good match of procedure to scenario<br>Low complexity of Scenario<br>Clear indications |
|  | Good coordination and communication<br>Good Procedure work<br>Shift supervisor is decisive<br>Shift supervisor keeps good overview<br>Crew easily identifies initiating event<br>High degree of familiarity with procedures<br>Good training | No difficulty with observation or diagnosis |
| Negative | No negative factor | Shift supervisor not focused |
|  |  | Shift supervisor easily interrupted<br>Ineffective use of large screens<br>Problems with thoroughness and attention |

Figure 72: PSFs matrix for Halden base case (NUREG/IA-0216, 2009)

We used the data from our simulation log files on these two cases and extracted (100) data points for each crew. Note that since our simulation is a generic simulation, instead of real time, time steps are being used and our data on response time was based on these time steps. However the data from Halden exercise is in the format of real time. The objective of this validation process was to prove that our simulation is able to provide approximately the same ratio between the response times of the fastest and the slowest crews. Figure 73 summarizes the result of this comparison. Note that the distribution fitted to our data for the response time extracted from our simulation is a lognormal distribution and the figure just provides 5% and 95% boundaries and the median of the distributions. The left hand side axis in the figure shows the response time for our cases in the form of simulation time steps and the right hand side axis shows the response time of the Halden crews (two fast crews, one slow crew) in minutes. In order to better demonstrate the ratio, the right and left hand side axes are in logarithmic scale.

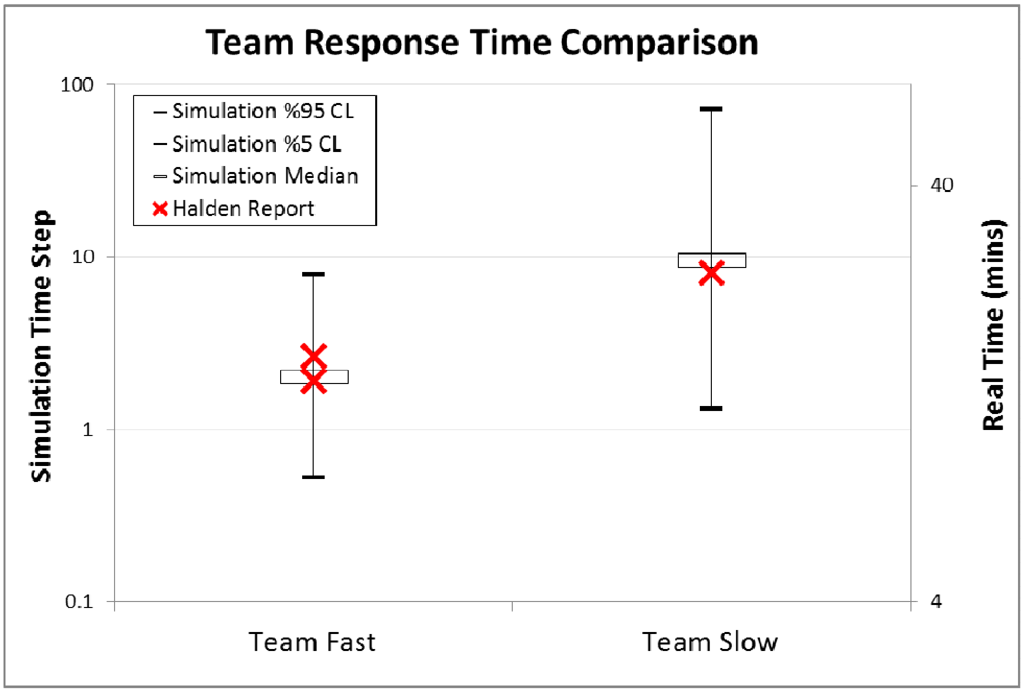


Figure 73: Comparing fastest & slowest teams, Halden exercise & simulation model

The conclusion is that under same circumstances when appropriate real time scale is introduced in the simulation, the simulation is able to predict the same trend in response time as evident by red crosses being not only within the range but also very close to the median of predictions by simulation.

### 6.6.2 Comparison with Theoretical Findings

As discussed in previous chapters, some of the observations already made by other researchers include:

1. Harrington et al. (1993) investigated the effect of team skill training on behavioral markers and noted that NPPs operating crews believe that the

ultimate responsibility for the safe operation rests more with SRO (senior reactor operator, aka supervisor) than with the rest of the crew.

2. Stanton et al. (2000) noted that wheel (star) network communication model is the optimized type of communication for faster performance, however for the person in the hub (center) which is the often supervisor of the team, it can be overloading and sometimes leads to censoring and poor decision making.
3. Petkov et al. (2004) and Ilgen et al. (2004) mentioned the team leader as the most influential person in the team and emphasized the impact of this role on the performance of the team. Petkov et al. (2004) mentioned most of the reliability models describing the operating crew use the leader as the center of the team processes with all monitoring and feedback activities accomplished using communication channels with the leader.
4. Carvalho et al. (2005) mentioned that the supervisor holds the ultimate responsibility and serves as the main communication channel for inside and outside the control room. They also recommended using a senior operator to help the supervisor with his tasks.
5. Bernnen et al. (2007) listed monitoring, feedback, and back up as main team activities; they realized the optimize case for knowledge distribution inside operating crew is when the knowledge of the supervisor who is performing monitoring is the highest.
6. Broberg et al. (2008) reckoned the shift supervisor leadership style as the major factor in qualitative evaluation of PSFs; they defined good leadership style as maintaining good situational awareness and demonstrating quick

responses without consultation. However they didn’t find any clear patterns in communication style of fast and slow groups. So they concluded that this factor should be connected to other PSFs and that it could explain the differences in performance between crew behaviors all by itself.

7. In a recent study by Kim et al. (2011) it is stated that teams with a higher ratio of inappropriate communications tend to have a lower performance score. They used a full scope simulator and five kinds of operator, including shift supervisor, shift technical advisor and equipment operators, and recorded all communications between operators both in the audio and video format. They measured the number of tasks completed by the operators and the team and used subjective analysis to weight the tasks. They calculated the performance score based on operator’s behavior such as communication, and control actions.

Our findings show similarities to conclusions by Petkov et al. (2004), Ilgen et al. (2004), Carvalho et al. (2005) and Broberg et al. (2008), and highlight the role of the supervisor in comparison with other team members. The sensitivity of results to the supervisor characteristics corresponds to work of Harrington et al. (1999) and Stanton et al. (2000), since the communication network implemented in our model is a wheel (star) network centered on the supervisor. There are some comments we would like to make on the theory proposed in the work of Kim et al. (2011) from the timing perspective of actions. They evaluate performance based on the performance scale which considers the number of completed tasks and, in fact, the time for action is not considered as a part of this measure. Higher number of executed actions does not necessarily relate to performance; since activities are performed in a team context, there might be repeated works and error recovery actions which definitely lengthen the scenario time. The consideration of time is a really important aspect of modeling any dynamic entity. In our research the water level of steam generator is the main criteria for the occurrence of the dry out situation. If the operators make frequent delays or are too engaged in error recovery activities, the system reaches its end state at a certain time. Hence, we prefer the timing to be included in measuring performance of the team before any general conclusions about the effectiveness of communication can be made. We cannot comment on work of Bernnen et al. (2007) either since we did not investigate the optimal case for team configuration; however, our findings show that having a good supervisor reduces the probability of occurrence of undesired state to a great extent.

Since we did not find communication to be very impactful on the outcomes, we agree with Broberg et al. (2008) that this factor should be connected to other PSFs and cannot explain the differences in performance between crew behaviors all by itself. However, we found the quality of communication with device to be a critical factor. As mentioned earlier, we have modeled a redundancy between operators inside and outside control room. This redundancy was a major factor in reducing the amount of observed dry out situations. However, it highlights the effect of communication with device; hence, in some cases, when the failure of the communication device and the control room equipment operator occurred at the same time, the dry out situation took place even though the plant (on-site) operator's performance was fine. This finding is similar to statements made by other researchers in the filed such as Patrick et al.

(2006), Sasangohar et al. (2010), Carvalho et al. (2008), Juhasz et al. (2011) and Firth-cozen (2004).

Team and organizational factors did not turn out to have a major impact on the performance while the group and the individual characteristics of team members proved to be more important from the performance point of view.

# Chapter 7: Summary & Conclusions

This chapter provides a brief review of the research findings. Furthermore, this section outlines how this work expends the knowledge and builds upon existing findings by researchers in the same filed.

## *7.1 Summary of Work & Results*

This research has proposed a framework and model of the dynamic behavior of an operating crew and complexities arising from their interactions, using model-based simulation. The domain of interest in this work is the class of operating crew environments that are subject to structured and regulated guidelines with formal procedures providing the core of their response to accident conditions.

The Extended IDAC model developed in this research focuses mainly on the team aspects of operating crew behavior. It not only adds features to the IDAC's models of individual operator cognitive processes and the team's shared problem-solving activities, but also adds communication-related aspects and additional model elements to cover error management activities at the individual operator and team levels.

The Extended IDAC also introduces a significantly expanded model of PSFs that characterize the individual and team responses, and form the basis for quantification of human error probabilities in team context.

In developing the cognitive models for the operators and teams of operators, their behavior and relations, this research integrates findings from multiple disciplines such as cognitive psychology, human factors, organizational factors, and human reliability.

A team error management framework was introduced together with a set of associated PSF models providing a more explicit causal explanation of the crew behavior. Except for a few theoretical frameworks, error management activities have not been considered fully and explicitly in previous efforts. Collaborative information collection method developed and implemented in this research simulate the contributions of various team members in gathering important information under the supervision of the team leader.

A team decision-making model responsive to dynamic changes in situational context was also designed and implemented, covering team discussions and consultation activities inside the team. In addition, a distributed action execution model was also defined and implemented to cover the complexities associated with assigning tasks to team members and the effect of including redundancy in operator's roles on team performance.

To provide a rich contextual environment for the team response, the Extended IDAC model simulation was fully integrated with a detailed hardware model in order simulate accident scenarios involving hardware and crew interactions. The resulting simulation platform (CREWSIM), developed by applying object-based methodologies is a practical tool for simulating crew behavior in response to system abnormalities. A simulation model of human interaction with complex system can be also utilized as a discovery instrument. One specific aim might be to uncover the critical aspects of the system that may need better probing to collect quality data in the future. Object-based simulation is a proper choice to fulfill this vision. This is mainly because a distributed model of independent objects is not built based on predefined scenarios. The level of knowledge and autonomy provided to the objects allow them to interact in simulation environment to explore all scenarios that might have been very difficult if not impossible to envision in the modeling stage.

While the CREWSIM model library in MATLAB Simulink was developed primarily to represent key roles of the operating crew of a NPP control rooms with capability to build different team compositions, configuration, and characteristics, it can be used to represent many other operating teams and contexts by relatively minor changes. Such changes are made easy through CREWSIM's graphical model building and editing features.

We aimed at demonstrating the crew model's ability to produce macro-behaviors that have high degree of face validity and are traceable to root causes that have theoretical or empirical basses. The simulation platform developed are in this work can serve as a "laboratory " to test an operating team's performance under varying contextual factor set as input conditions.

Extensive simulation runs and quantitative and qualitative examination of the resulting scenarios provided ample evidence of face validity of the proposed team model and simulation platform. Further, while performing experiments with real crews and real scenarios to validate the model was not feasible due to resource limitations and other practical constraints, the International Empirical Study conducted at Halden Laboratories in Norway provided an opportunity to perform a limited comparison of the proposed model behavior with actual performances of the crews participating in the exercise. This comparison showed the explanatory power of the proposed model with respect to some observable aspects of the crew performance. Finally, the simulated scenarios in the case study of this work reproduce a number of macro-level behaviors identified in several of the theoretical frameworks discussed in the literature.

It is clear that the simulation results produced are essentially reflective of the team model and the underlying theoretical perspective adopted in this research. However, it is encouraging that the macro-behavior of the simulated team built from a large number of model elements seem to be very realistic and of face validity. Many of the model elements have credible roots in theories and observations; however, different sets of model assumptions can change the results.

We were able to comment on some of the existing theories in the literature since the model enabled us to observe the same behavior. More comprehensive reports on complexities of team related issues and how they affect the entire system risk can be produced by using the data provided in simulation log files. This includes timing properties of the operator's actions, error recovery process and related actions and their effect on the number of undesired system state, timeline of the scenario, and complexity of communications with respect to number of people involved in each communication, and the number of communications before an action is actually accomplished.

## 7.2 Future Work

This research was focused only on the simulation modeling of team dynamics and the impact of individual and team PSFs on team performance. Currently, there are intriguing and unexplored research opportunities in using the developed modeling framework to understand the impact of other team-related issues such as different communication patterns and different team configurations. Understanding how to create efficient and effective teams, and how to train them as a team, remains an important area of research. This research represents an initial step in that direction. As a further research step, a separate study has been designed to use the developed models to compare the performance of three teams of operators with different communication patterns for the same situation. Following is a list of recommended topics to continue this line of research:

1. Develop a post processing routine in order to derive a number of different communication measures that reflect the quantity, directionality, timing and type of communications that occur. These measures are being tracked per unit time, and can be captured at the individual level or at the team level.

2. Explore the frequency and complexity of interaction patterns used by the team for sharing knowledge, directing attention and determining next steps, among others. Ideally this would be done with respect to the number of team members and the number of communication loops, in order to derive measures for determining the complexity of interaction patterns and the impact of such complexities on performance.

3. Use CREWSIM library to developed models of teams with different sizes and role assignments to impact on performance, and types and cause of error.

4. Use operating data and experimental settings to perform more extensive calibration and validation of the model. Since many features of the crew model and simulation rules are generic, the sources of validation data that can be tapped include non-nuclear applications such as process plants, aviation.

# Appendix A: CREWSIM User's Guide

## Getting Started

This document provides guidelines for using CREWSIM 1.0, a library developed in MATLAB Simulink which provides tools for modeling the control crew of a four steam generator feed water system. The hardware system is a simplified version of the feed water system. Through using this document one learns how to understand the existing simulation model, how to use Simulink model editor and CREWSIM library blocks to define simulation models for different configurations of control crew as well as how to customize different blocks in the library to best reflect the diversities inside the team of operators; in addition this document provides guidelines on how to change the parameters of the simulation and perform different simulation runs; while the input of the simulation process is the model with customized parameters which are based on the desired configuration and structure, the output is the simulation log files.

## What is CREWSIM?

CREWSIM is a custom defined library in MATLAB Simulink. CREWSIM 1.0 is the first version designed and developed by the "University of Maryland Center for Risk and Reliability" and aims at helping users develop models of operating crew and run simulations on such models in order to investigate the dynamic behavior of operating crew in the context of a nuclear power plant. The current version is focused on the operating crew of a simplified feed water system in a four steam generator plant. CREWSIM is developed inside MATLAB Simulink environment and is based on the simple idea of representing the complex system by using models of identified active and passive objects in the context of the system and viewing the system as a network of connected objects. The idea is to translate the system into a representative model consisting of reliability block diagrams. CREWSIM includes the representative blocks for different roles inside the operating crew of a typical representation of feed water system, these roles being: the decision maker, the action taker and the consultant.

## About MATLAB Simulink[12]

Simulink® is an environment for multi-domain simulation and Model-Based Design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries that let you design, simulate, implement, and test a variety of time-varying systems, including communications, controls, signal processing, video processing, and image processing. Simulink provides the tools to model and simulate almost any real-world problem. Simulink has a graphical user interface (GUI) for building models as block diagrams. Simulink also includes a comprehensive block library of components, and connectors and you can also create your own blocks. The interactive graphical environment simplifies the modeling process. Models are hierarchical, so one can build models using both top-down and bottom-up approaches. The system can be viewed at a high level, and then double-click blocks to see increasing levels of model detail. This environment provides insight into how a model is organized and how its parts interact. After defining a model, one can simulate its dynamic behavior using a choice of mathematical integration methods, either from the Simulink menus or by entering commands in the MATLAB Command Window; for example CREWSIM uses various developed

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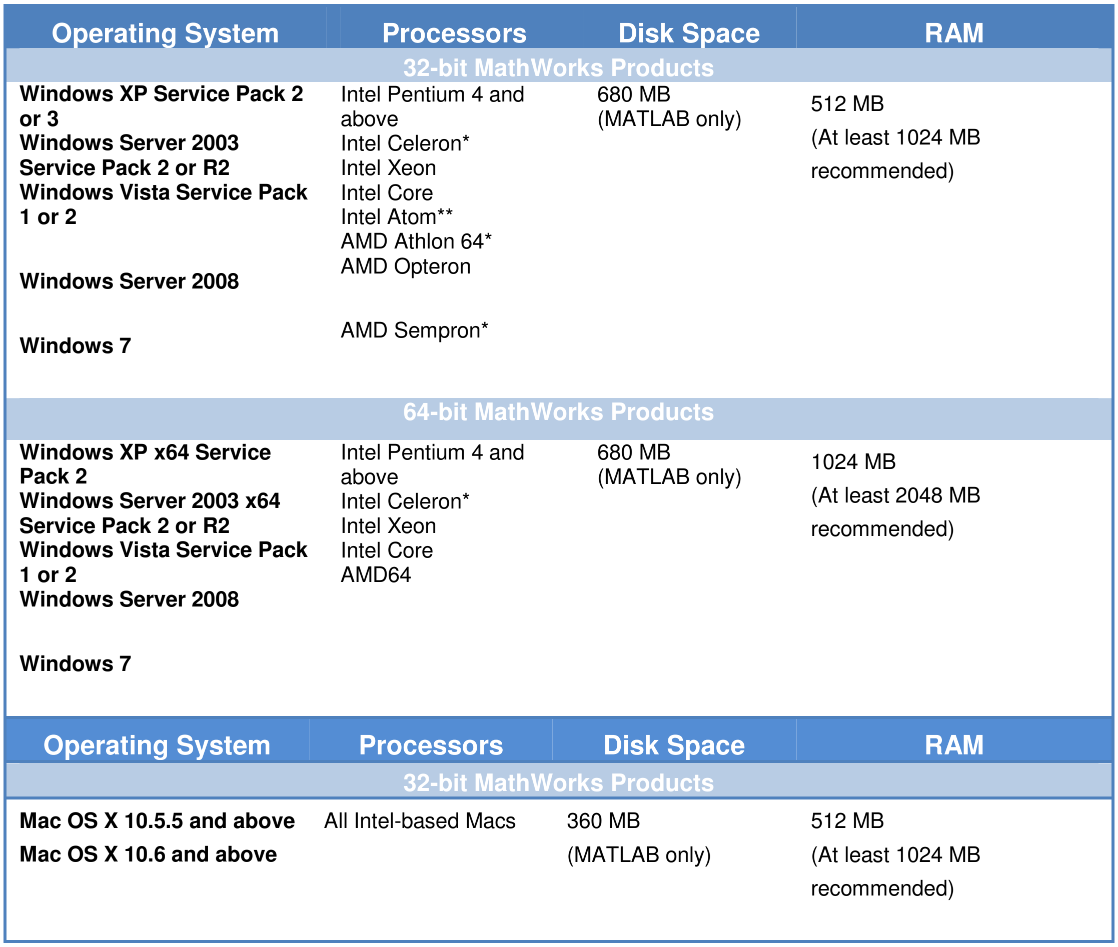
[12] http://www.mathworks.com/help/toolbox/simulink

blocks of embedded MATLAB codes and functions inside Simulink which characterize the dynamics of system. Simulink menus are convenient for interactive work, while the MATLAB command line is useful for running a batch of simulations. Using scopes and other display blocks, one can see the simulation results while the simulation runs. One can then change parameters and see what happens for "what if" exploration. The simulation results can be put in the MATLAB workspace for post processing and visualization. Simulink software is tightly integrated with the MATLAB environment. It requires MATLAB to run, depending on it to define and evaluate model and block parameters. Simulink uses MATLAB features in order to perform functions within a model, through integrated calls to MATLAB operators and functions.

## Operating Requirements

CREWSIM is currently developed in MATLAB Simulink version 7.14.0.739 (R2012a); Simulink is a toolbox integrated into MATLAB software hence it is only available via MATLAB environment; hence it is only available via MATLAB environment. The following table[13] lists the minimum system requirements.



| Operating System | Processors | Disk Space | RAM |
|---|---|---|---|
| 32-bit MathWorks Products | | | |
| **Windows XP Service Pack 2 or 3**<br>**Windows Server 2003 Service Pack 2 or R2**<br>**Windows Vista Service Pack 1 or 2**<br>**Windows Server 2008**<br>**Windows 7** | Intel Pentium 4 and above<br>Intel Celeron*<br>Intel Xeon<br>Intel Core<br>Intel Atom**<br>AMD Athlon 64*<br>AMD Opteron<br>AMD Sempron* | 680 MB (MATLAB only) | 512 MB<br>(At least 1024 MB recommended) |
| 64-bit MathWorks Products | | | |
| **Windows XP x64 Service Pack 2**<br>**Windows Server 2003 x64 Service Pack 2 or R2**<br>**Windows Vista Service Pack 1 or 2**<br>**Windows Server 2008**<br>**Windows 7** | Intel Pentium 4 and above<br>Intel Celeron*<br>Intel Xeon<br>Intel Core<br>AMD64 | 680 MB (MATLAB only) | 1024 MB<br>(At least 2048 MB recommended) |

| Operating System | Processors | Disk Space | RAM |
|---|---|---|---|
| 32-bit MathWorks Products | | | |
| **Mac OS X 10.5.5 and above**<br>**Mac OS X 10.6 and above** | All Intel-based Macs | 360 MB<br>(MATLAB only) | 512 MB<br>(At least 1024 MB recommended) |

MATLAB needs to be running before one can open the Simulink Library Browser. Simulink is included in any default installation of MATLAB. Once the user installs the MATLAB, activates it and runs it, Simulink model editor becomes available. MATLAB Simulink can be opened by clicking its icon on the Simulink icon on the

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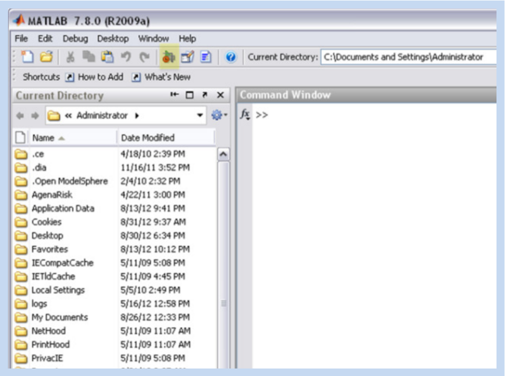
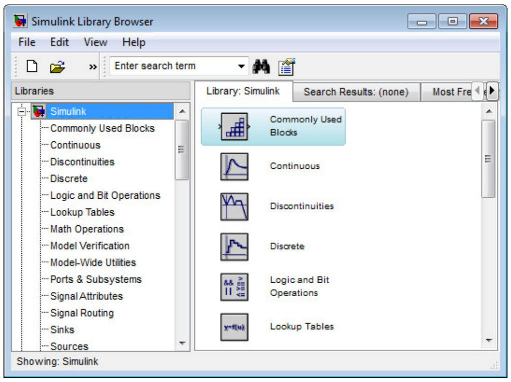
[13] Tables are extracted from Mathworks.com

upper left hand side of the main MATLAB environment (Highlighted in the picture) or by typing “Simulink” in MATLAB command window.



Current Directory: C:\Documents and Settings\Administrator

| Name | Date Modified |
|---|---|
| .ce | 4/18/10 2:39 PM |
| .dia | 11/16/11 3:52 PM |
| .Open ModelSphere | 2/4/10 2:32 PM |
| AgenaRisk | 4/22/11 3:00 PM |
| Application Data | 8/13/12 9:41 PM |
| Cookies | 8/31/12 9:37 AM |
| Desktop | 8/30/12 6:34 PM |
| Favorites | 8/13/12 10:12 PM |
| IECompatCache | 5/11/09 5:08 PM |
| IETldCache | 5/11/09 4:45 PM |
| Local Settings | 5/5/10 2:49 PM |
| logs | 5/16/12 12:58 PM |
| My Documents | 8/26/12 12:33 PM |
| NetHood | 5/11/09 11:07 AM |
| PrintHood | 5/11/09 11:07 AM |
| PrivacIE | 5/11/09 5:08 PM |



## Model Development in MATLAB Simulink Environment

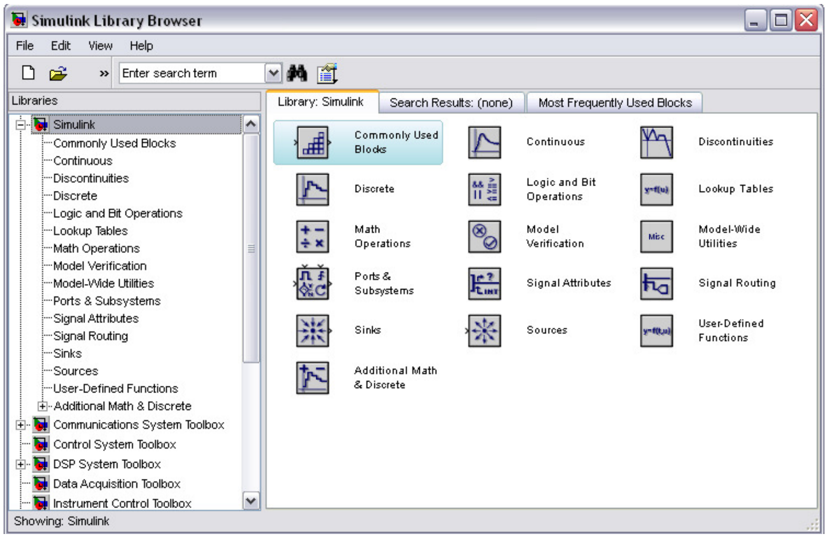
In Model-Based Simulation, a system model is at the center of the simulation activities. The model is an executable specification of the system. There are six steps to model any technical system:

1. Defining the System
2. Identifying System Components
3. Modeling the System Dynamics with Equations
4. Building the Simulink Block Diagrams
5. Running the Simulation
6. Validating the Simulation Results

The first step in modeling a dynamic system is to fully define the system. If a large system is being modeled that can be broken into parts, one should model each subcomponent on its own. Then, after building each component, one can integrate them into a complete model of the system. The most effective way to build a model of this system is to consider each of these subsystems independently.

The second step in the modeling process is to identify the system components. Three types of components define a system:

- Parameters : System values that remain constant unless you change them
- States : Variables in the system that change over time
- Signals : Input and output values that change dynamically during a simulation



In Simulink, parameters and states are represented by blocks, while signals are represented by the lines that connect blocks. For each subsystem that is identified, the following questions need to be answered: How many input signals does the subsystem have? How many output signals does the subsystem have? How many states (variables) does the subsystem have? What are the parameters (constants) in the subsystem? Are there any intermediate (internal) signals in the subsystem? Once these questions are answered, by using a comprehensive list of system components you are ready to begin modeling the system. There are different predefined libraries included in MATLAB Simulink. Simulink automatically opens the library browser upon starting; one needs to use the “Commonly used blocks” and CREWSIM library in order to define the simulation model using the methodology proposed by this research. CREWSIM can be accessed by typing "CREWSIM" in MATLAB command line. With the help of CREWSIM library, as well as predefined Simulink blocks such as logical operators, Input/Outputs, Displays, Clocks, Memory blocks and Embedded MATLAB function blocks the complex system of interest can be modeled by following the basic steps of modeling process. The first three steps of modeling process need to be performed outside of the Simulink software environment and based on the technical development approach presented in the main report. Once the system is fully studied and the infrastructure of the system including the low level objects as well as their relationships and association links are studied and identified and a high level model for system configuration is developed, CREWSIM is being called in Simulink environment by using the Simulink library browser and is being used to develop the model inside the Simulink model editor.

## Why using CREWSIM Library?

Since the simulation model needs to be defined by the user in model editor, the application of custom-defined libraries facilitates the process of defining the simulation model. This research has developed CREWSIM as a library in MATLAB Simulink that facilitates defining the model and running the simulation in such that context. The target application domain for this research is the control room of a complex environment such as a nuclear power plant. CREWSIM library developed for such applications is a collection of pre-defined models of human operators, and different hardware components. Such pre-defined classes of components can be desirably instantiated and customized to mimic the requested behavior in the specific domain. By assigning states and manipulating the set of attributes and operations for these classes the user is able to obtain system model. The methodology developed by this research, highly depends on the transformation of reliability block diagrams into object-based diagrams to represent the structure of subsystems; the objects are instances of higher level classes that usually represent a specific entity. Once the objects are constructed and submitted to the system, the associated blocks (simulation models) can be customized. The system is defined with a detailed infrastructure as a network of connected abstract block diagrams; and just the simple question, "connected or not?" identifies the links.

In order to use CREWSIM to define the simulation model for a complex hybrid system the following steps need to be taken:

- Developing hardware model by customizing the low level object models of hardware components
- Developing the operating crew model by customizing the object models of operators and their associated communication links
- Integrating these models into the final hybrid system model by using the interfacing code

## The Modeling Methodology behind CREWSIM

The first step of any simulation approach is system modeling which means to create a virtual model of the system with the exact functionality and appropriate level of details. In object-based modeling approaches to simulation, objects are the low level simulation blocks which actively take part in simulation process and their states dynamically change based on simulation parameters. Hence, based on the level of familiarity with the system, the majority of active objects need to be identified. In case of complicated systems, a hierarchical decomposition and study of system and subsystem structure is very helpful to identify the objects. Such objects are supposed to fully reflect different components and their behavioral characteristics. In the object based modeling methodology, every entity in the system represents an object which is an instant of an abstract class. General object classes are defined based on objects categories. This includes system main components, individual human elements and software elements. The attributes of each class have to be identified. Since the study targets the operating crew of industrial plants such as nuclear power plant, a model of the crew and their communication links needs to be developed additionally.

After objects in each group are identified, their behavior needs to be modeled. The simulation environment, MATLAB Simulink provides a wide range of capabilities for simulation modeling; this environment supports block diagram style object modeling and embedded MATLAB functions for modeling the behavior. Since CREWSIM library is used, the general characteristics of the dynamics of behavior for each objects in the associated domain is captured by using an inside controller. The controller is responsible for branch generation. However in order to capture the dynamics of system for the plant one needs to code the equations and for the operating crew, one need to code the rules of behavior separately via using an embedded MATLAB functions. This step requires deep knowledge about system elements and the rules for their internal behavior and external interactions. The operators are different in personal characteristics and cognitive capabilities; such differences are accounted for in this modeling technology by using different quantities for basic attributes and performance shaping factors. These models are then incorporated together to form the integrated simulation model. This approach reflects the complexity of all kinds of relationships including access, control and communications between blocks of different nature.

The second step in the simulation approaches is the knowledge acquisition for scenario generation, which is basically to acquire additional information about the system and its environment; this knowledge is used to automatically generate risk scenarios. In case of object based models, this step includes translating the success logic into failure logic, assigning the probabilities of failure for objects or functionalities at each time step, and to identify a primary set of failure modes for the system. The level of details for failure logic is driven by the PRA objectives and the availability of data. Having the states of components and events, the failure logic of the system and enough rules and conditions, the final state of the system is available in any given condition. In order to replace a piece of system with its representative model for simulation goals, the properties such as time to failure distributions, and the probability of failure per demand as well as common cause failures should be included in the model; in addition the model needs to fully mimic the element's behavior; each component model needs to include knowledge about failures, keep history of its previous states and be able to share information with simulation environment or other elements. In CREWSIM there are certain failure probabilities assigned to basic human functions such as cognitive functions and error management functions as well as failure probabilities for hardware system components to be used as initial values; these values have been assigned subjectively by using expert judgments. Some of these values change over the course of the scenario and some remain constant. Nonetheless all of them are adjustable before the simulation starts to desired values in order to be able to reflect different cases.

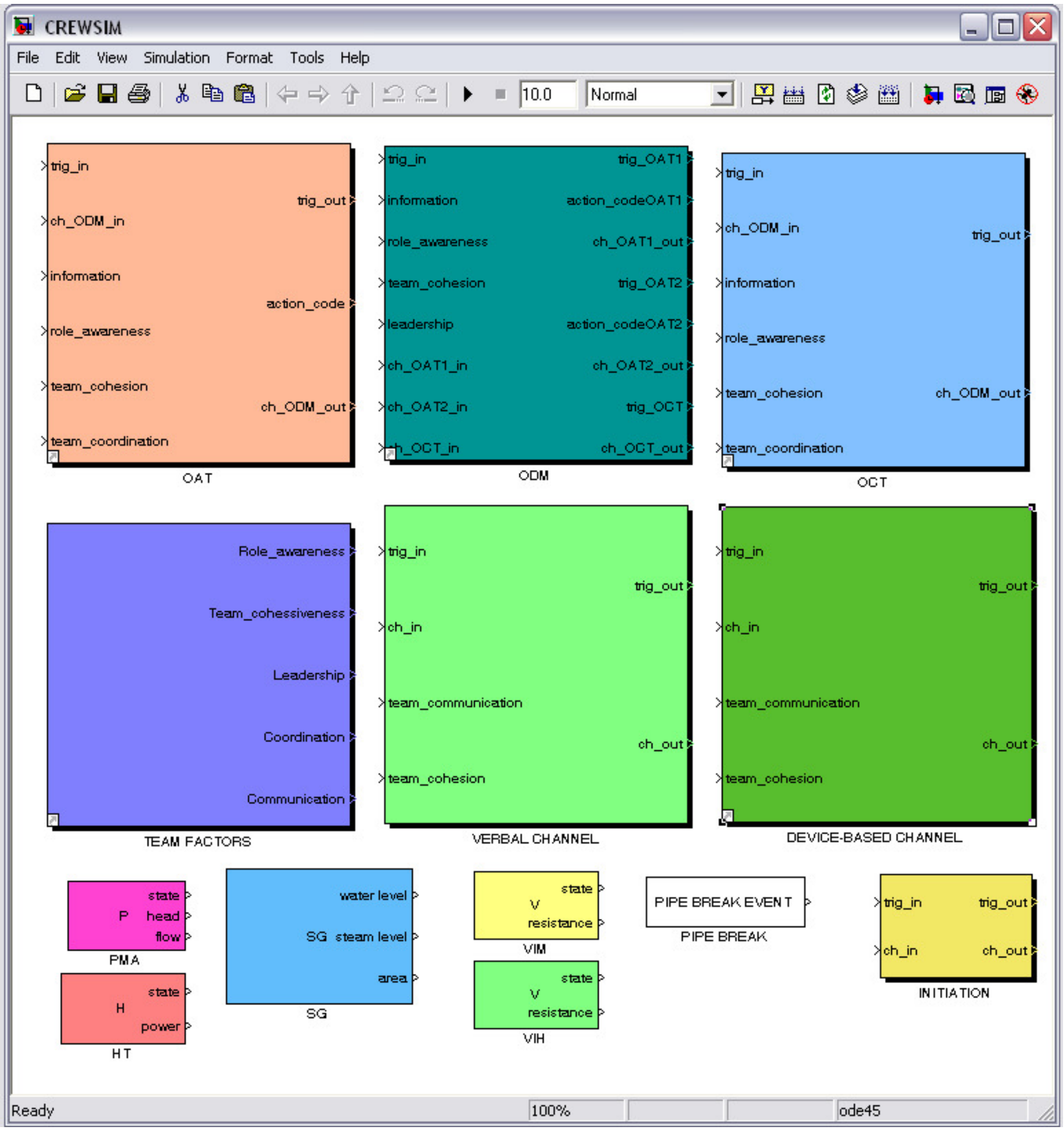
The third step is the risk scenario generation. The simulation controller code is responsible for actuating accident initiating events and plant hardware failures as well as setting up other simulation parameters such as where to store the simulation log files and how to terminate the sequences.

The fourth step is the simulation. This step includes running the simulation model, which results in the generation of scenarios in the format of simulation log files. Since this research is interested in the investigation of scenarios that lead to system failure, failure scenarios are studied and the interaction-based failure modes are highlighted.

The structure of a complex system permits delivery of desired functionality through specific component interactions or behavior. CREWSIM is capable of representing the desired functionality of the individual components, their structure, as well as their interactions. The components in this modeling methodology do not act in isolation but instead interact with each other. A common source of error or system vulnerability is a mismatch at the interface of the blocks/components where data is interchanged that can lead to system failure in the form of an incident/accident. The complete communication model of the system elements can be developed by using CREWSIM to address the variety of interactions. The objective is to capture the operational knowledge of the complex multi-dimensional system, and to apply this knowledge for obtaining representative models for its elements via using CREWSIM Library.

## Using CREWSIM in Simulink Model Editor

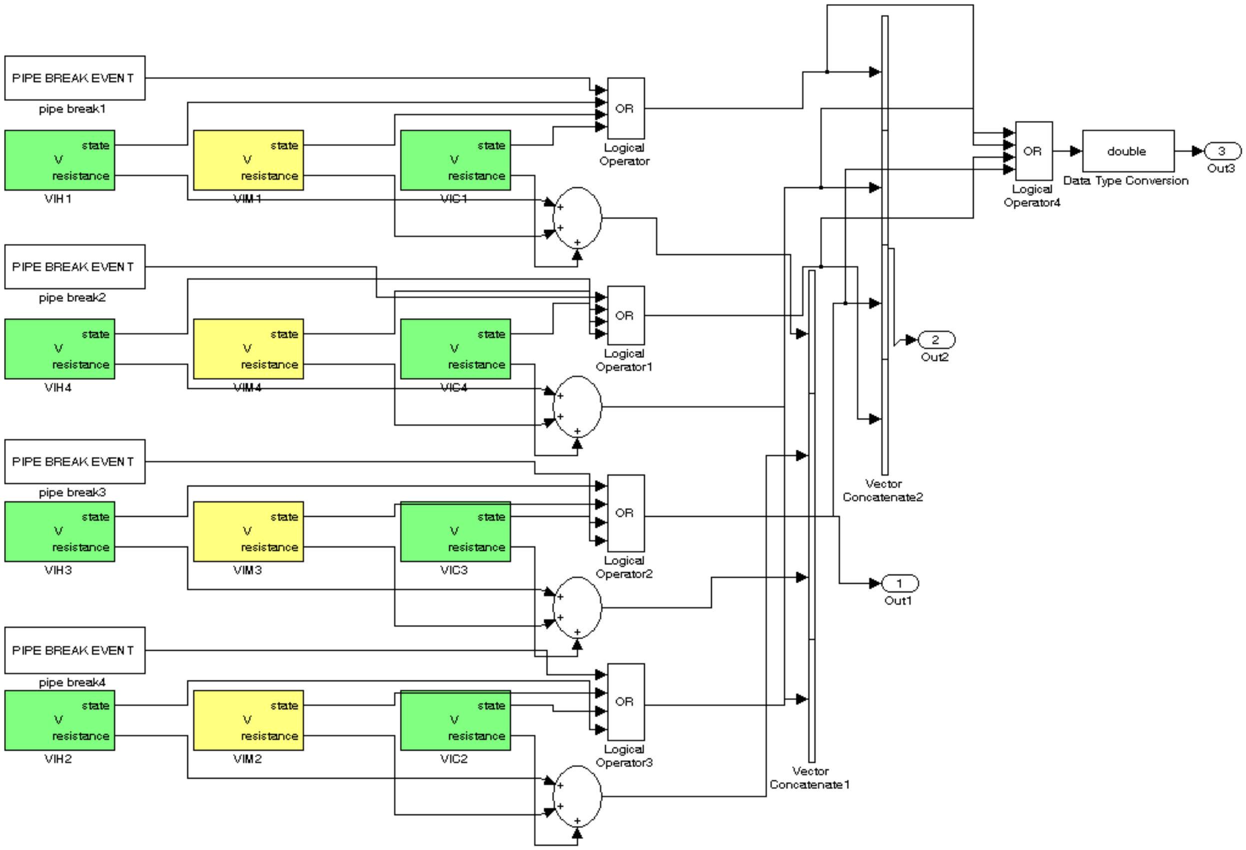
Since we are modeling a nuclear power plant control room, there are three different groups of objects that work together: the hardware system composed of hardware elements such as pumps and valves; the operating crew composed of individual human operators such as the senior operator and reactor operator; and the control panel (interface) which consists of alarms and indicators and the process for activating those elements based on plants parameters. There are active and passive objects. An example of active objects (actors) is the senior operator and an example of a passive object is a message from senior operator to the operator asking for an action. The picture below is a snapshot of the CREWSIM library and its blocks.



## Plant Model

In order to use CREWSIM simulation library, the first step is to develop the hardware system; the hardware system is part of a complex system which consists of different subsystems and hardware components depended on the application, hence the model for hardware system would be the integration of the model of all its subsystems. Each of these subsystems are in turn a configuration of many hardware objects such as boiler feed pumps, check valves, pipes and etc.; all available for use inside

CREWSIM library. The major identified hardware components in this system are: Pumps, Heaters, Valves and Steam generators; these components are connected together via Pipes. The scenario of interest is initiated by a pipe break event occurring in either main or intermediate subsystems. The operating crew needs to perform the accident mitigation steps correctly and in time, otherwise the steam generators would become either solid or dried out. Pumps, Valves and Heaters can fail on-demand randomly and with a constant failure probability during the system operation; such events are the basis of branch generation in the simulation of the plant. Once a component fails it is assumed unrecoverable. Components are modeled as objects to reflect their different nature and characteristics of elements and to improve model reuse. The picture shows different types of valves including check valves and control valve used inside the intermediate subsystem of a feed water system.

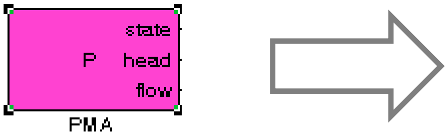


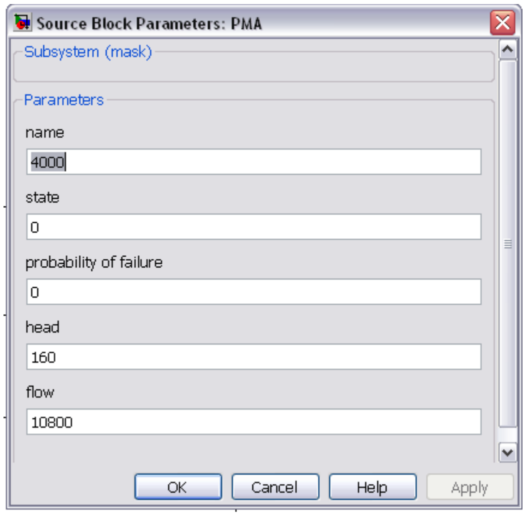
Once the appropriate hardware component is selected and put in the model editor, the associated characteristics of it can be set by clicking on it and setting up the parameters. The above picture illustrates the modeled hierarchy of a redundant system of 4 pipelines and 12 valves and their associated characteristics. A set of adjustable factors for various components of the feed-water system is listed in the next table.

| Component | Attributes |
|---|---|
| Boiler Feed Pumps (Main, Auxiliary) | Name(ID)<br>State(0: Nominal,1:Failed)<br>Status(0:Off, 1:ON)<br>Probability of failure<br>Head<br>Flow |
| Heaters | Name(ID)<br>State(0: Nominal,1:Failed)<br>Status(0:Off, 1:ON)<br>Probability of failure<br>Power |
| Control Valves | Name(ID)<br>State(0: Nominal,1:Failed)<br>Status(0:Closed, 1:Open)<br>Probability of failure<br>Adjusting Factor (0: Fully open, 1: Fully closed) |
| Steam Generators | Name(ID)<br>Water level<br>Steam level<br>Area |

## Boiler Feed Pumps

There are two types of pumps modeled and ready to use in CREWSIM; boiler feed pumps and another type of feed pumps that are considered as auxiliary or emergency pumps. In order to instantiate a pump, there are six characteristics that need to be defined to customize the pump: name, initial state: i.e. whether the pump is functioning or not when the scenario starts, initial status: i.e. whether the pump is on or off when the scenario starts, probability of failure, maximum head and maximum flow allowed for the pump.





Source Block Parameters: PMA

Subsystem (mask)

Parameters

name: 4000

state: 0

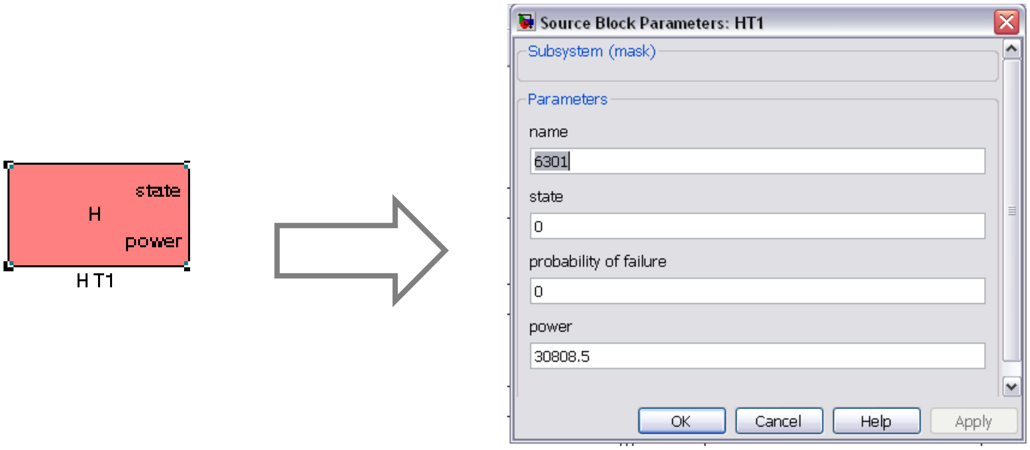
probability of failure: 0

head: 160

flow: 10800

## Heaters

In order to instantiate a heater, there are five characteristics that need to be defined and together they would customize the heater: name, initial state: i.e. whether the heater is functioning or not when the scenario starts, initial status: i.e. whether the heater is on or off when the scenario starts, probability of failure, maximum power allowed for the heater.



name: 6301

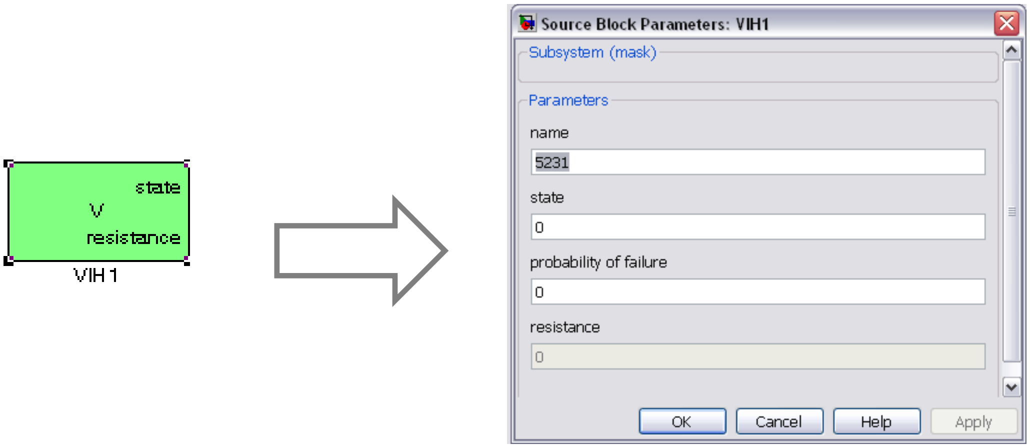
state: 0

probability of failure: 0

power: 30808.5

## Valves

There are two types of valves modeled and available to use in CREWSIM, Control valves and Check valves. In order to instantiate a control valve, there are five characteristics that need to be defined and together they would customize the valve: name, initial state: i.e. whether the valve is functioning or not when the scenario starts, initial status: i.e. whether the valve is open or closed when the scenario starts, probability of failure, and the adjusting factor for the valve, which is basically the ratio of the flow that the valve would allow to pass. Check valves don’t have this feature and they can either be fully closed or fully open.



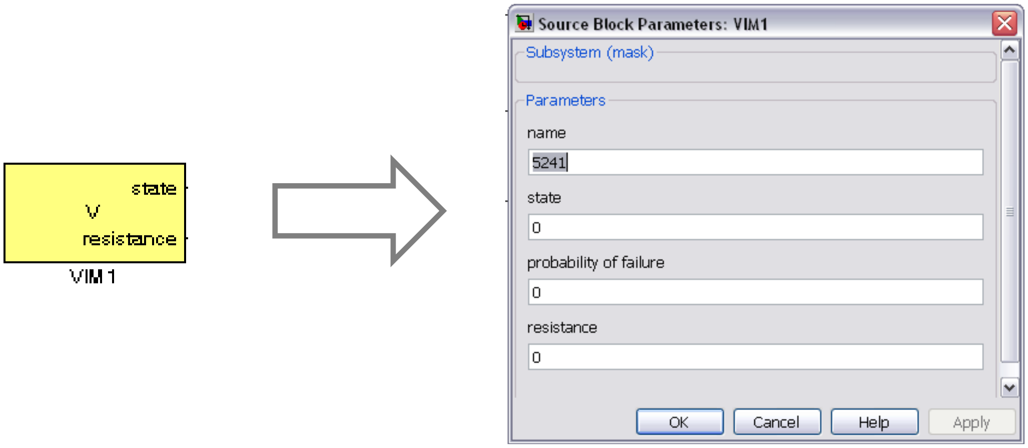
Source Block Parameters: VIH1

name: 5231

state: 0

probability of failure: 0

resistance: 0



Source Block Parameters: VIM1

name: 5241

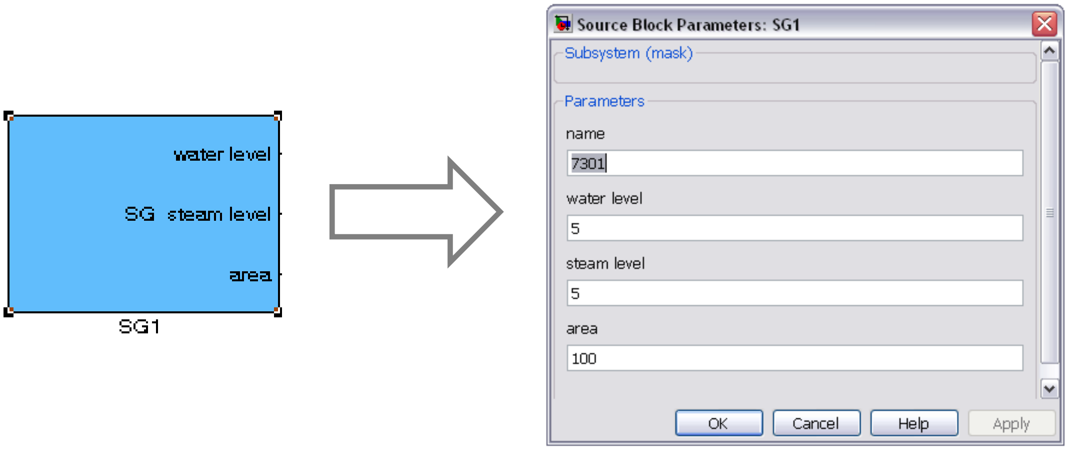
state: 0

probability of failure: 0

resistance: 0

## Steam Generators

In order to instantiate a steam generator, there are four characteristics that need to be defined and together they would customize the steam generator: name, maximum water level, maximum steam level, and the area of its tank.



Source Block Parameters: SG1

name: 7301

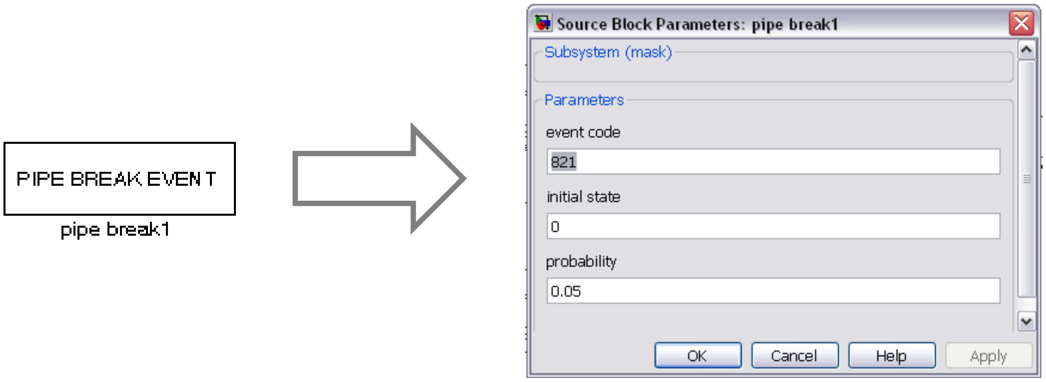
water level: 5

steam level: 5

area: 100

## Pipe Break Event

Since the initiating event in our case study is considered to be a pipe break, such events have been modeled as well. There are three characteristics that need to be defined in order to define a pipe break event: name, initial state: i.e. whether the pipe is broken upon the start of the scenario or is going to break during the scenario, and probability of occurrence.



Source Block Parameters: pipe break1

event code: 821

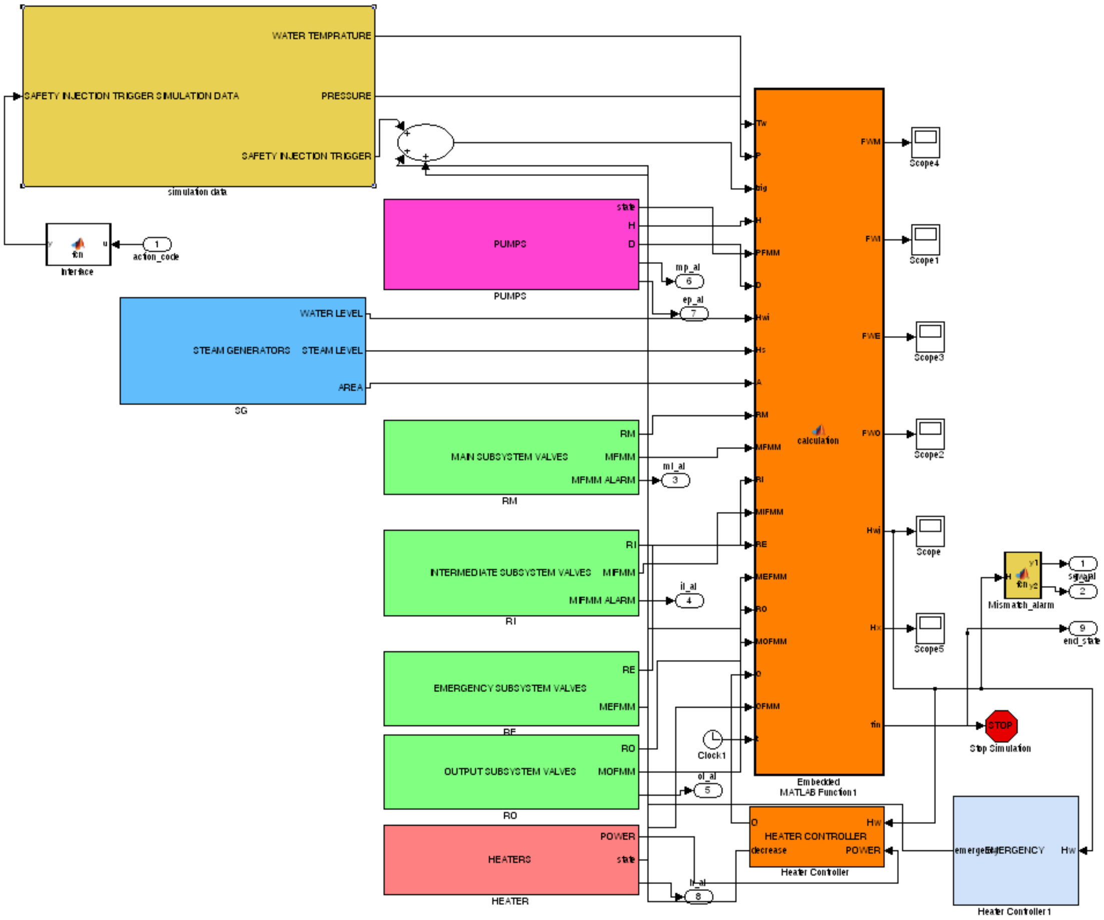
initial state: 0

probability: 0.05

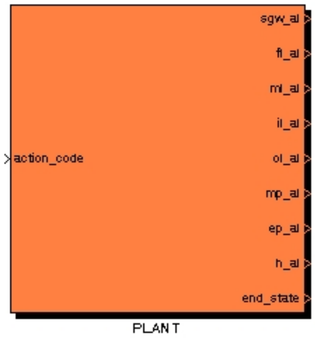
## System Dynamics

Once the main objects of the hardware system are instantiated and set up, the dynamics of the system needs to be modeled. In our case study this was done by developing a MATLAB code which uses the parameters that are provided by hardware components and embeds the equations which mimic the dynamics of the system. This would be different for each system configuration based on the set of desired parameters and the observations one needs to make. Simulink provides

Embedded MATLAB file blocks which would place pieces of MATLAB code inside model wherever is needed. The system dynamics in our case is basically a block with inputs being the states and status of all different object blocks of the hardware system and the outputs being a set of eight alarms each of which represents a major issue in the hardware system. There is also an indication of when the end state event has occurred inside the system. This information is available to all operators. The developed model of the plant which includes a block which encapsulates the dynamics of the hardware system is being shown in the picture below.



The plant in its highest level of abstraction is being represented by a block which is shown in the picture below. The outputs of this model are simply a set of alarms which together determine the system state.



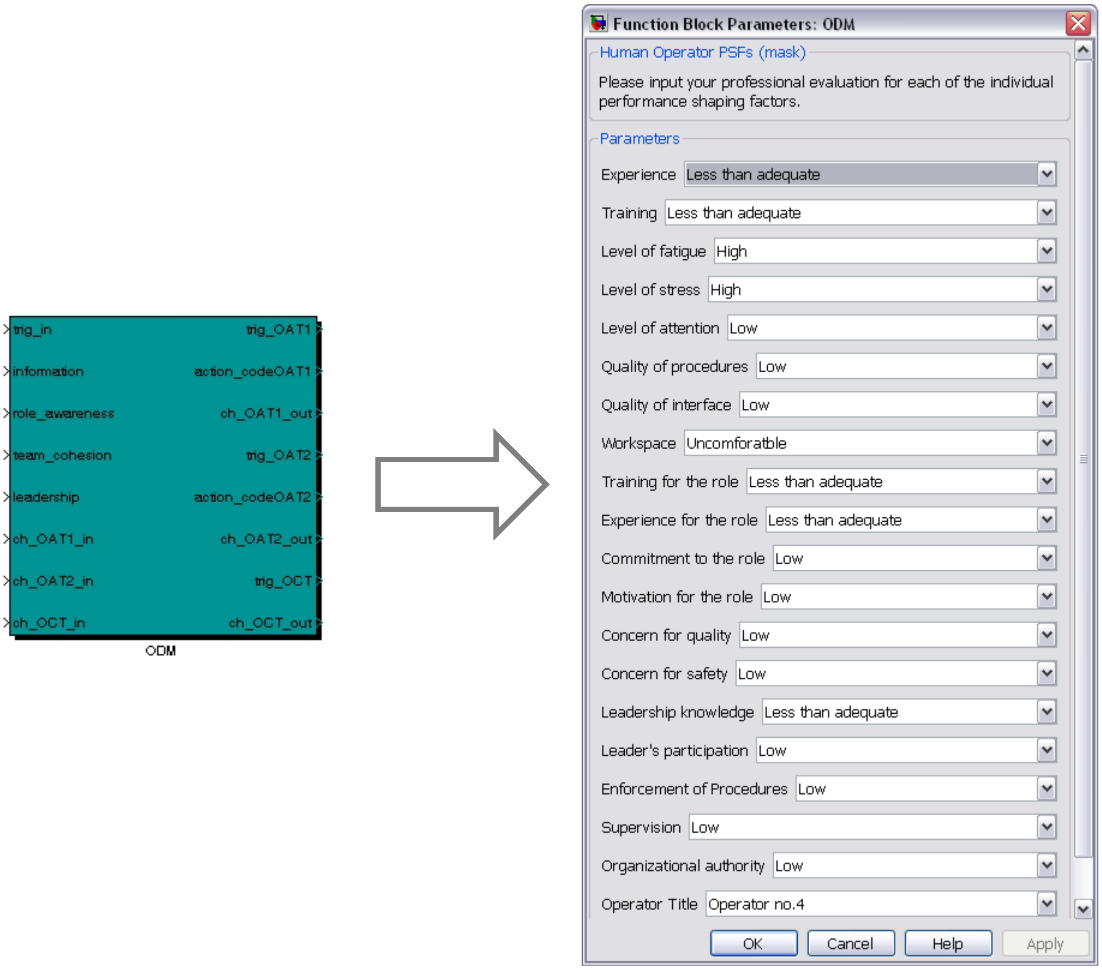
## Crew Model

CREWSIM helps to define the crew operating on a subsystem in a nuclear power plant by providing individual blocks to represent the following roles; the "Decision-Maker" role, the "Action-Taker" role and the "Consultant" role. Operators are connected via two sided communication links, each of which is uniquely characterized by different features of the sender and the receiver. Different blocks in CREWSIM library that are related to the crew model are listed and explained in details in the following sections. Each section is followed by a review on the process of setting up the block parameters which mainly includes how to customize the block and use the built-in features in order to represent different configuration of teams and other simulation parameters to represent different teams with different characteristics.

## Decision Maker

This block represents the role which the shift supervisor takes during the scenario. The decision maker is the team supervisor and is responsible for managing team information-collection and decision-making activities. He is also responsible for distributing the decided action course to different operators. All communication loops are centered on the decision maker and he plays the most important role inside the team which involves leadership and managing different team activities. He is also responsible for team error management activities. This block is activated by a trigger and in turns calls other blocks by activating their associated triggers in the output. This block is capable of triggering other blocks depended on the desired functionality and type of conversation to be established between blocks. Other inputs to this block are team factors, information channel which provides the information on hardware system, and communication channels for input messages from different operators inside the team. Other outputs of this block are the actual action codes sent to the operators and communication channels which carry the output messages to different operators.

By clicking on this block a set of parameters can be set which together represent the individual characteristics of the shift supervisor. Each of these parameters can be set by choosing among different levels provided for the specific feature based on qualitative and comparative judgment; such levels are for instance high, normal or low or in some cases demonstrate less than adequate, average and special training, and so on.



Function Block Parameters: ODM

Human Operator PSFs (mask)

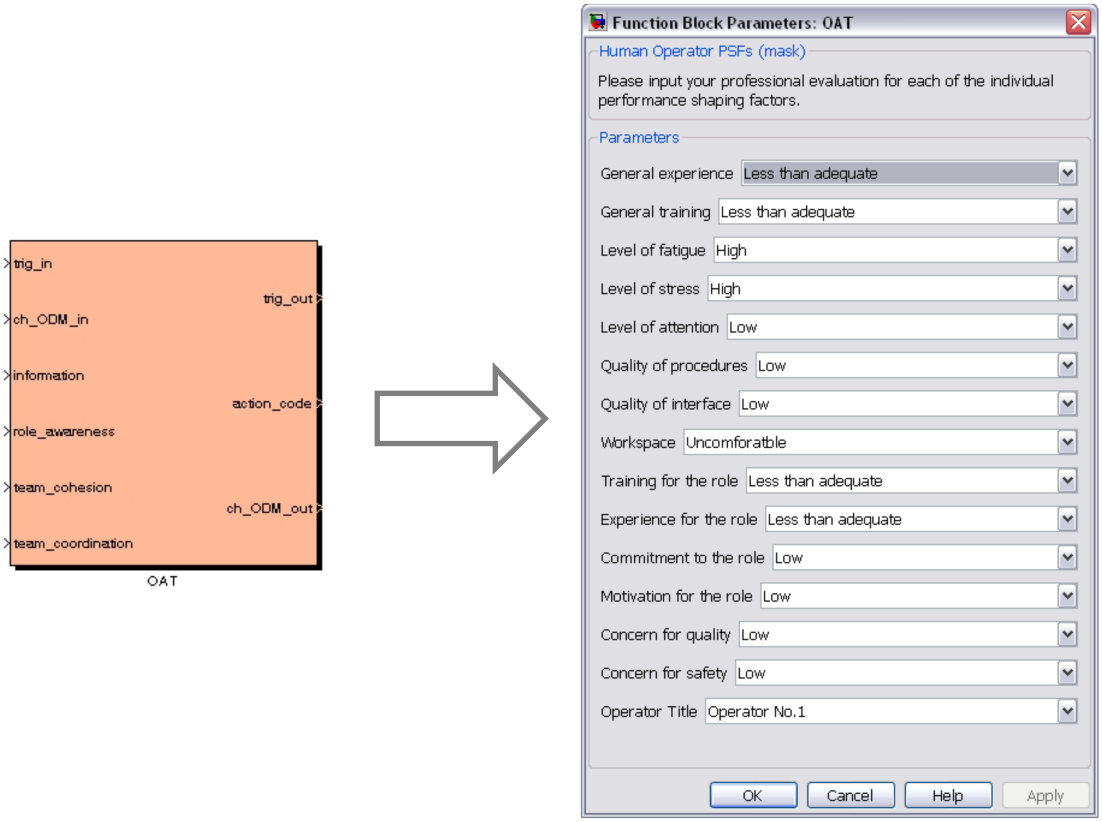
Please input your professional evaluation for each of the individual performance shaping factors.

Parameters

Experience: Less than adequate
Training: Less than adequate
Level of fatigue: High
Level of stress: High
Level of attention: Low
Quality of procedures: Low
Quality of interface: Low
Workspace: Uncomforatble
Training for the role: Less than adequate
Experience for the role: Less than adequate
Commitment to the role: Low
Motivation for the role: Low
Concern for quality: Low
Concern for safety: Low
Leadership knowledge: Less than adequate
Leader's participation: Low
Enforcement of Procedures: Low
Supervision: Low
Organizational authority: Low
Operator Title: Operator no.4

## Action Taker

This block represents the role that the equipment operator takes during the scenario. He is mainly responsible for the operation on hardware components. He also reports the various observations made on the system to the decision maker. There are two different types: the equipment operator located in the plant and the equipment operator located in the control room. This block is being triggered by incoming input information or by other blocks. Other inputs to this block are the information channel which provides the input information from the hardware system, team factors and the communication channel which carries the input message from the decision-maker. This block is capable of triggering the decision-maker block for a conversation. Other outputs of this block are the action code which is performed on the system and the communication channel which carries the output message to the decision-maker. By clicking on this block a set of parameters can be set which together represent the individual characteristics of the equipment operator. Each of these parameters can be set by choosing among different levels provided for the specific feature based on qualitative and comparative judgment; such levels are for instance high, normal or low or in some cases demonstrate less than adequate, average and special training, and so on.



Function Block Parameters: OAT

Human Operator PSFs (mask)

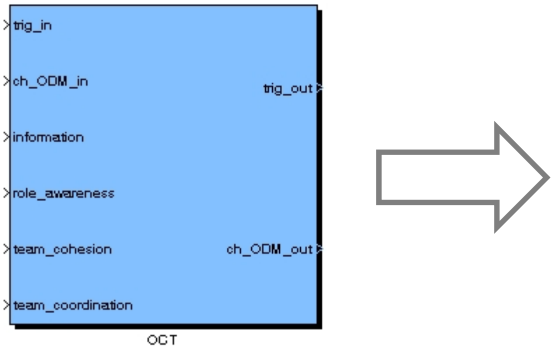
Please input your professional evaluation for each of the individual performance shaping factors.

Parameters

| | |
|---|---|
| General experience | Less than adequate |
| General training | Less than adequate |
| Level of fatigue | High |
| Level of stress | High |
| Level of attention | Low |
| Quality of procedures | Low |
| Quality of interface | Low |
| Workspace | Uncomforatble |
| Training for the role | Less than adequate |
| Experience for the role | Less than adequate |
| Commitment to the role | Low |
| Motivation for the role | Low |
| Concern for quality | Low |
| Concern for safety | Low |
| Operator Title | Operator No.1 |

## Consultant

This block represents the role that the shift technical advisor takes during the scenario. He is mainly responsible for helping the decision-maker to make judgments on system status and decisions on the appropriate action course. This block is being triggered by the decision-maker. Other inputs to this block are the information channel for providing the information on hardware system, team factors and the communication channel for the input messages from the decision-maker. This block triggers the decision maker block for a conversation; the other output of this block is the communication channel which carries the output message. By clicking on this block a set of parameters can be set which together represent the individual characteristics of the shift technical advisor. Each of these parameters can be set by choosing among different levels provided for the specific feature based on qualitative and comparative judgment; such levels are for instance high, normal or low or in some cases demonstrate less than adequate, average and special training, and so on.



Human Operator PSFs (mask)

Please input your professional evaluation for each of the individual performance shaping factors.

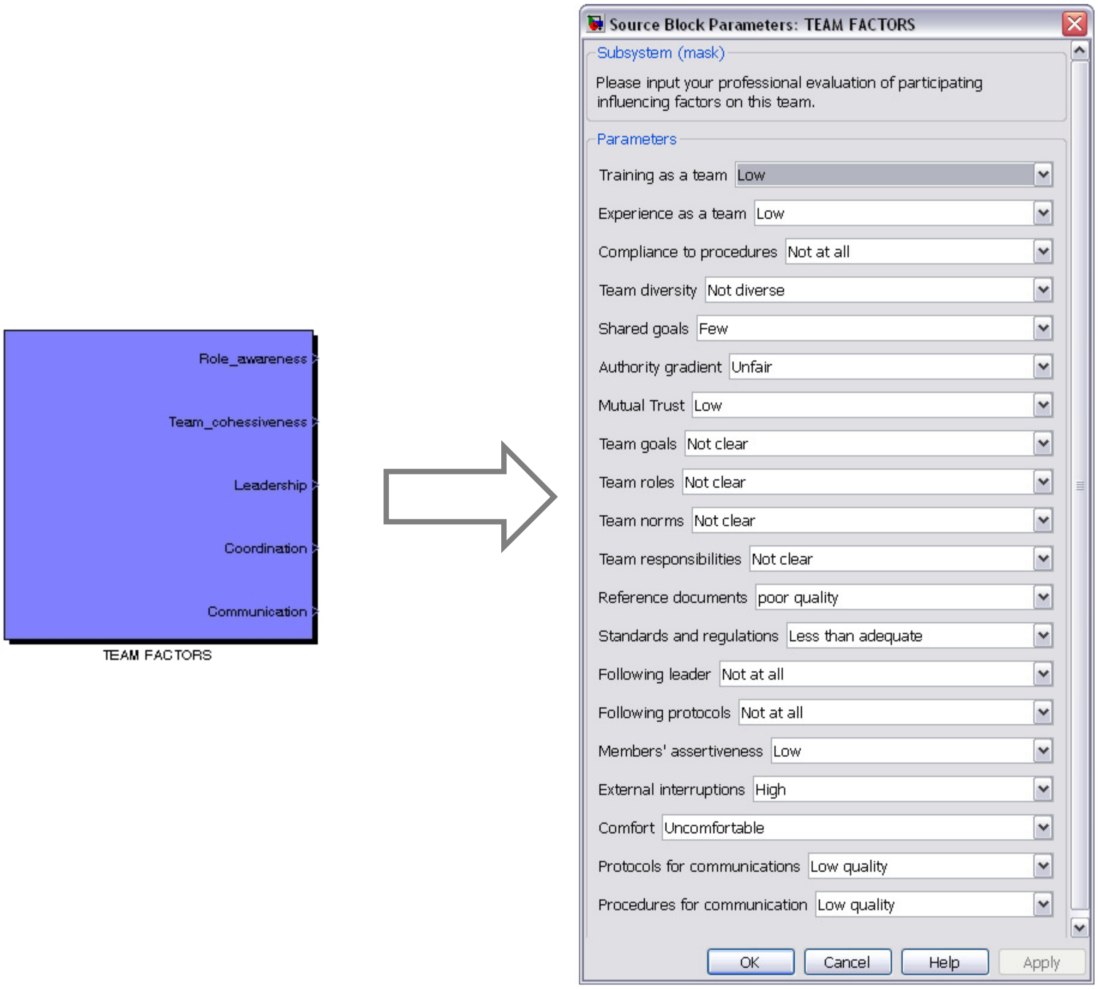
Parameters

General experience: Good
General training: Special training
Level of fatigue: Average
Level of stress: Average
Level of attention: Average
Quality of procedures: Average
Quality of interface: Average
Workspace: Normal
Training for the role: Special training
Experience for the role: Good
Commitment to the role: Average
Motivation for the role: Average
Concern for quality: Average
Concern for safety: Average
Operator Title: Operator No.3

## Team Performance Shaping Factors

This block represents the performance shaping factors which affect the team behavior in general and are related to the organization, the workspace environment and etc. This block does not have any inputs because all the contributing factors are considered as parameters of the simulation and are being adjusted by clicking on the block and selecting among three or two different qualitative levels for the parameter based on the judgment of the user on a comparative basis. This block includes a special mechanism to calculate quantities as outputs which represent the contribution of factors that equally affect all team members and are related to the context of the team such as the organization and environment. These values also represent the mutual feelings that team members have toward each other in an overall sense. These values are inputs to all blocks for all team operators.

By clicking on this block a set of parameters can be set which together represent a certain team. Each of these parameters can be set by choosing among different levels provided for the specific feature based on qualitative and comparative judgment; such levels are for instance high, normal or low or in some cases demonstrate less than adequate, average and special training, or basically yes or not at all and so on.

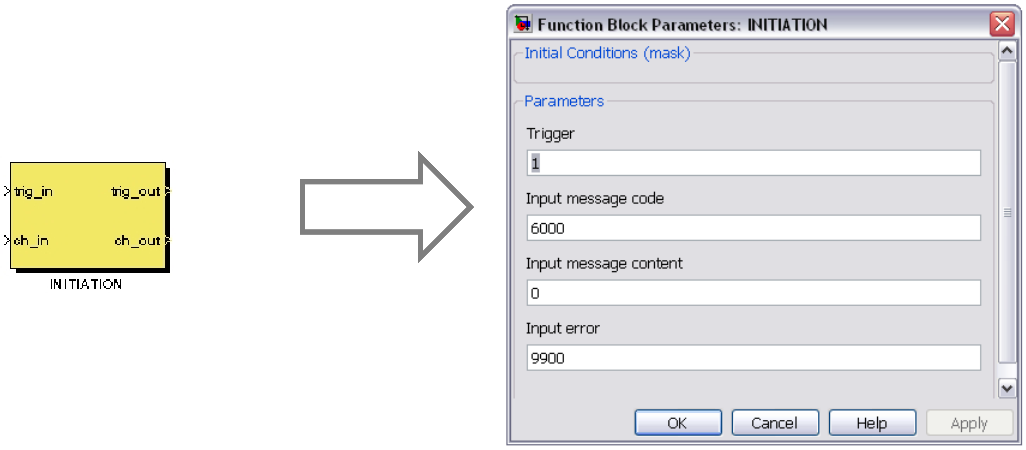


Please input your professional evaluation of participating influencing factors on this team.

Training as a team: Low
Experience as a team: Low
Compliance to procedures: Not at all
Team diversity: Not diverse
Shared goals: Few
Authority gradient: Unfair
Mutual Trust: Low
Team goals: Not clear
Team roles: Not clear
Team norms: Not clear
Team responsibilities: Not clear
Reference documents: poor quality
Standards and regulations: Less than adequate
Following leader: Not at all
Following protocols: Not at all
Members' assertiveness: Low
External interruptions: High
Comfort: Uncomfortable
Protocols for communications: Low quality
Procedures for communication: Low quality

## Initiation

In order to model the feedback loops inside the team, memory blocks (delay blocks) has been used intensively in this approach; hence a specific block has been modeled and included in the library for setting up and assigning initial values to input ports of any operator block; this block prepares the operator blocks to be used in the next coming cycles. The use of this block becomes particularly important at time zero and a few time steps after time zero. By clicking on this block one can define the initial condition for the operator; including the input message and input error just at the beginning of the simulation.



Trigger: 1

Input message code: 6000

Input message content: 0

Input error: 9900

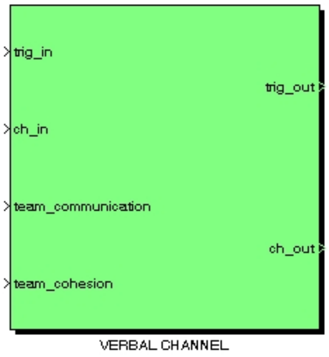
## Communication Model

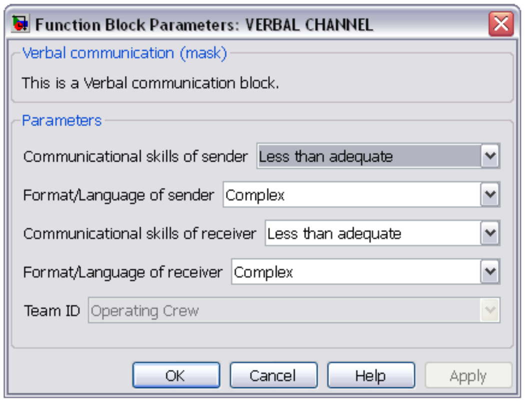
In order to model the interactions of the operating crew inside the control room, and the field operators outside the control room, there is another category of objects in CREWSIM that are related to communication and represent the characteristics of communication links. The communication between inside and outside the control room is not a face-to-face verbal communication and special devices are used to establish such communication links, e.g. wireless devices; thus such communication links need to be modeled via a device-based communication block. Any communication link includes three important elements: Sender, Receiver and the Message. Characteristic of the sender, receiver and the message are foundations to a successful communication. Hence, a communication fails when: the sender fails to send the message or not being trusted to send the message, the receiver distorts or misperceives the message, and the message is inaccurate and distorted. CREWSIM provides two different types of communication links: Verbal (face-to-face) and Device-based. The parameters of each communication link are based on characteristics of the sender, characteristics of the receiver and the nature of the message and the media over which the message is communicated.

## Verbal Communication Link

This block represents a communication process that is taken place inside the control room. This link is triggered by the sender when a conversation starts and its main functionality is to pass the input message to the receiver as an output. If the communication is successful the receiver block would be triggered by this block. Other inputs to this block include the contributing factors that are coming from the team factors block and directly impact the communication quality.

By clicking on this block a set of parameters can be set which together represent the individual characteristics of the sender and receiver. Each of these parameters can be set by choosing among different levels provided based on qualitative and comparative judgment; such as less than adequate, average and good. This block is focused on individual characteristics of the operator that would directly affect the quality of communication such as the format they use.





Verbal communication (mask)

This is a Verbal communication block.

Parameters

Communicational skills of sender: Less than adequate

Format/Language of sender: Complex

Communicational skills of receiver: Less than adequate

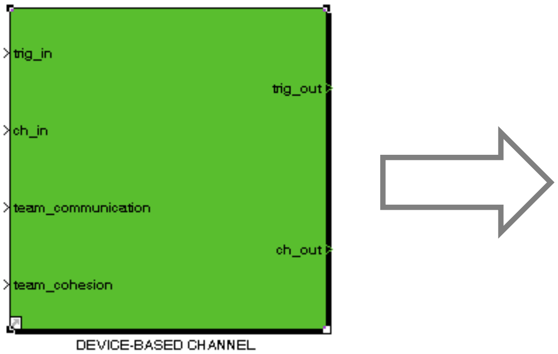
Format/Language of receiver: Complex

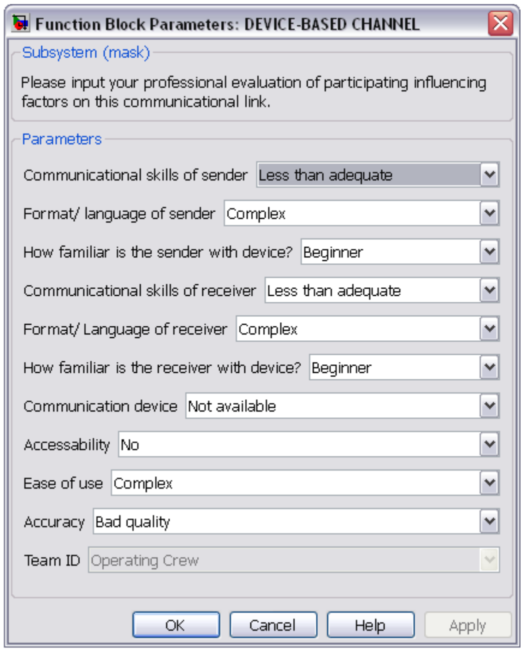
Team ID: Operating Crew

## Device Based Communication Link

This block represents a communication process that is taking place between operators inside the control room with operators outside the control room via a device and therefore is affected by the quality of the device and the environment in which the communication is taking place as well as other factors. This link is triggered by the sender when a conversation starts and its main functionality is to pass the input message to the receiver as an output. If the communication is successful the receiver block would be triggered by this block. Other inputs to this block include the contributing factors that are coming from the team factors block and directly impact the communication quality.

By clicking on this block a set of parameters can be set which together represent the individual characteristics of the sender and receiver and the quality of device. Each of these parameters can be set by choosing among different levels provided for the specific feature based on qualitative and comparative judgment; such as less than adequate, average and good. This block just like the previous block is focused on individual characteristics of the operator that would directly affect the quality of communication such as the format they use.




Function Block Parameters: DEVICE-BASED CHANNEL

Subsystem (mask)

Please input your professional evaluation of participating influencing factors on this communicational link.

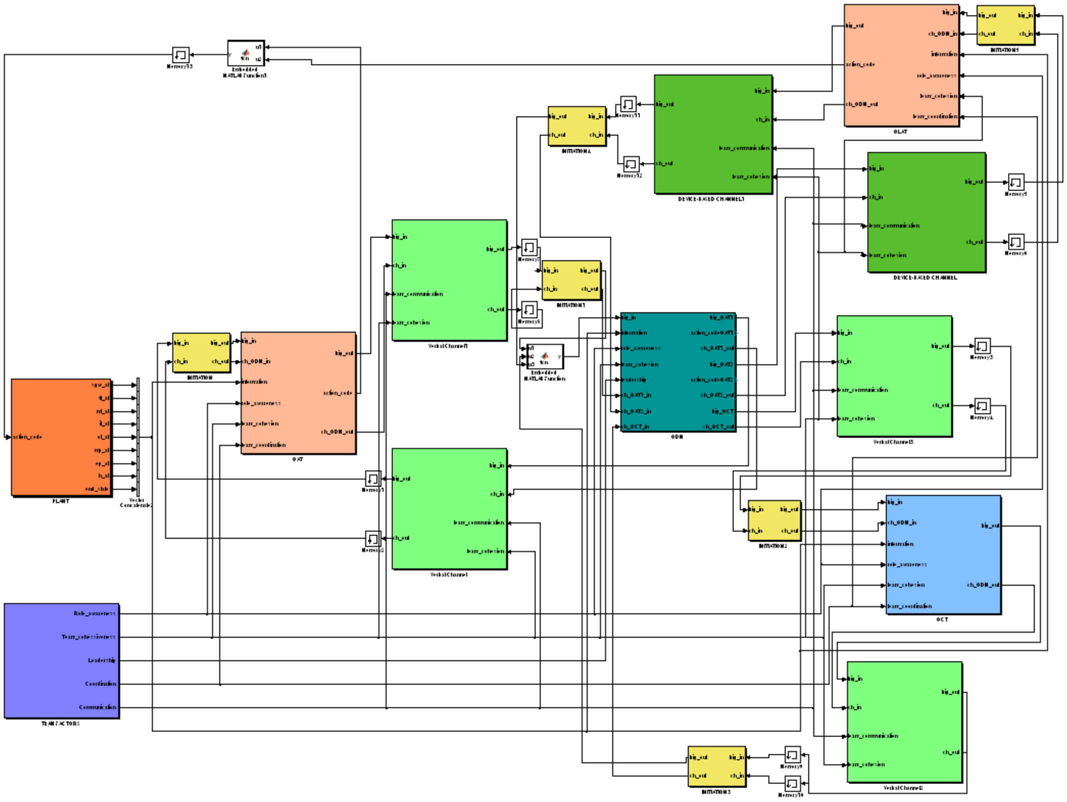
Parameters

Communicational skills of sender: Less than adequate
Format/ language of sender: Complex
How familiar is the sender with device?: Beginner
Communicational skills of receiver: Less than adequate
Format/ Language of receiver: Complex
How familiar is the receiver with device?: Beginner
Communication device: Not available
Accessability: No
Ease of use: Complex
Accuracy: Bad quality
Team ID: Operating Crew

## Simulation

After the blocks are selected and connected together, the model parameters need to be adjusted using the model editor environment by clicking on each block and setting up the associated parameters; After the development of the simulation model is complete (see the picture), a simulator module (code) is used to assign control parameters and simulation variables for each run; this includes the time for each simulation run and the number of simulation runs in a round. The model of the system is loaded using this code and the location of the output file is provided for MATLAB Simulink by this code; hence the output which is the simulation log file is ready after a round is completely executed. This code basically calls the model in a loop and diaries the simulation logs in an output file. These simulation log files are then investigated to better understand the behavior of the operating crew and are the basis for post-processing of the simulation generated scenarios. This simulation model is developed to cover a wide range of possibilities in order to provide a complete and consistent system profile. This simulation experiment is responsible to generate the detailed behavior of the system based on the multilevel simulation model. Each transition for system state is conditioned on its duration, time, state of another component and other parameters. The branching points in the model are designed such that not only the failure of system elements and their functionalities but also the interaction-related errors such as miscommunication and misunderstandings, which generate different paths and scenarios in the system risk profile. During the simulation the states of various subsystems and operator responses dynamically change and time dependent scenarios are generated.

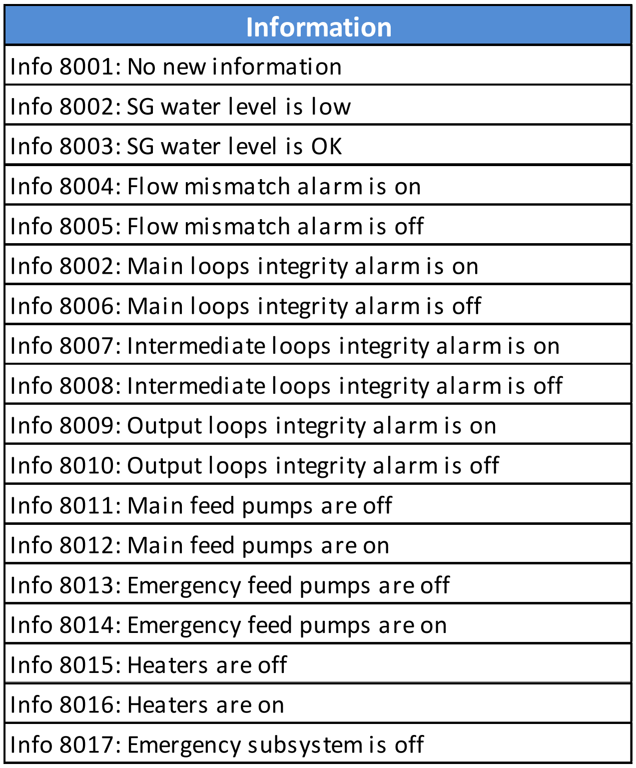
In the case study that has been designed based on the capabilities of CREWSIM, the major identified hardware components include: Pumps, Heaters, Valves and Steam generators; these components are connected together with Pipes. The scenario of interest is initiated by a pipe break event occurring in either main or intermediate subsystems. The operating crew need to perform the accident mitigation steps correctly and in time, otherwise the steam generators would become either solid or dried out. These end-states are determined based on the level of water in the steam generators which should always be above a certain threshold. Pumps, Valves and Heaters can fail on-demand with a constant failure rate during the system operation; such events are the basis of branch generation in the simulation. Once a component fails it is assumed unrecoverable. Components are modeled as objects to reflect their different nature and characteristics of elements and to improve model reuse. There are four operators with different roles and they are responsible for mitigating the accident scenario, by deciding on the situation and performing right actions. There are numerous errors that can happen inside the team and would be considered a branch point from the simulation perspective but not necessarily would lead to an accident scenario. The parameters of interest are: number of accident scenarios, the time of the each scenario and time of operators' important actions. These values are extracted from simulation log files for each case with different team configurations. The final crew model is being illustrated in the picture below.



# Appendix B: Reference Tables

This appendix provides reference tables for the case study used in this research. Tables included are: Information provided by the plant, list of system states, list of operator's decisions and actions as well as exchanged messages, the contents of messages and the list of possible errors and recovery actions that are designed, implemented and used by this case study.

Table below lists the identified plant information provided by alarms and indicators.



| Information |
|---|
| Info 8001: No new information |
| Info 8002: SG water level is low |
| Info 8003: SG water level is OK |
| Info 8004: Flow mismatch alarm is on |
| Info 8005: Flow mismatch alarm is off |
| Info 8002: Main loops integrity alarm is on |
| Info 8006: Main loops integrity alarm is off |
| Info 8007: Intermediate loops integrity alarm is on |
| Info 8008: Intermediate loops integrity alarm is off |
| Info 8009: Output loops integrity alarm is on |
| Info 8010: Output loops integrity alarm is off |
| Info 8011: Main feed pumps are off |
| Info 8012: Main feed pumps are on |
| Info 8013: Emergency feed pumps are off |
| Info 8014: Emergency feed pumps are on |
| Info 8015: Heaters are off |
| Info 8016: Heaters are on |
| Info 8017: Emergency subsystem is off |

Table below lists the identified system states for the simplified version of feed water system.

| System State |
|---|
| System State 7001: Normal |
| System State 7002: Flow mismatch |
| System State 7003: Main loops lost integrity |
| System State 7004: Intermediate loops lost integrity |
| System State 7005: Output loops lost integrity |
| System State 7008: Loss of heat source |
| System State 7009: loss of main pumps |
| System State 7010: Loss of emergency pumps |
| System State 7011: SG water level is not stable |
| System State 7012: Emergency feed pumps are off |
| System State 7013: Emergency feed pumps are on |
| System State 7014: Heaters are off |
| System State 7015: Heaters are on |
| System State 7016: Emergency subsystem is off |
| System State 7017: Emergency subsystem is on |
| System State 7018: Broken subsystem is not isolated |
| System State 7019: Broken subsystem is isolated. |
| System State 7200: Not normal |
| System State 7000: Unknown system state |

The table below lists the identified decisions for the operating crew of the proposed feed water system.

| Decision |
|---|
| Decision 4001: No decision |
| Decision 4010: Close intermediate valves |
| Decision 4020: Open intermediate valves |
| Decision 4030: Turn off heaters |
| Decision 4040: Turn on heaters |
| Decision 4050: Turn on main pumps |
| Decision 4060: Turn off main pumps |
| Decision 4070: Turn on emergency pump |
| Decision 4080: Turn off emergency pump |
| Decision 4090: Activate emergency subsystem |
| Decision 4000: Unknown decision |

The table below lists the identified actions performed by the operating crew on the hardware system.

| Action |
|---|
| Action 5900: No action on system |
| Action 5950: No possible recovery action on system |
| Action 5010: Verify main pumps status |
| Action 5012: Verify emergency pumps status |
| Action 5016: Verify heaters status |
| Action 5020: Verify intermediate subsystem valves status |
| Action 5024: Turn off main pumps |
| Action 5025: Turn on main pumps |
| Action 5026: Turn off emergency pumps |
| Action 5027: Turn on emergency pumps |
| Action 5030: Turn off heaters |
| Action 5031: Turn on heaters |
| Action 5034: Close intermediate subsystem valves |
| Action 5035: Open intermediate subsystem valves |
| Action 5400: Activate emergency trigger |
| Action 5500: Unknown action |
| Action 5950: No possible recovery action on system |
| Action 5525: Repeat message processing |
| Action 5515: Repeat information processing |
| Action 5530: Verify system information |

The table below lists the types of messages used by the operating crew.

| Message |
|---|
| Message 6000: No message |
| Message 6001: Observation from system |
| Message 6002: Request for more information |
| Message 6003: Request for action on system |
| Message 6004: Request for advice on system state |
| Message 6114: Request for advice on decision |
| Message 6005: Advice on system state |
| Message 6006: Advice for decision |
| Message 6007: Judgment on system state |
| Message 6008: Judgment on decision |
| Message 6100: Confirmation for receiving observation |
| Message 6102: Confirmation for receiving advice |
| Message 6103: Confirmation for receiving judgment |
| Message 6104: Confirmation for performing request |
| Message 6210: Report of the error |
| Message 6120: Request for resending the message |
| Message 6125: Request for Repeat message processing |
| Message 6200: Unknown message |

The table below lists the content of the messages used by the operating crew.

| Message Content |
|---|
| If the message is an observation on system: The content is Information code. |
| If the message is a judgment on system state: The content is the System State code. |
| If the message is a judgment on decision: The content is the Decision code. |
| If the message is an advice on system state: The content is the Advice code. |
| If the message is an advice on a decision: The content is the Decision code. |
| If the message is the request for an action on system :The content is the Action code. |
| If the message is erroneous: The content is irrelevant/unknown. |
| If the message is to report an error: The content is the error code. |

The table below lists the identified errors in the context of the operating crew.

| Error |
|---|
| Error 9010: Operator is not available |
| Error 9020: Information is not available to operator |
| Error 9030: Message is not available to operator |
| Error 9040: Operator missed the object information |
| Error 9050: Operator received partial information on object |
| Error 9060: Operator observed wrong object |
| Error 9070: Operator observed object with delay |
| Error 9080: Operator missed the message |
| Error 9090: Operator received an incomplete message |
| Error 9100: Operator received wrong message |
| Error 9110: Operator received message with delay |
| Error 9120: Operator is unable to diagnose the situation |
| Error 9130: Operator made a faulty diagnosis |
| Error 9140: Operator is unable to make a decision |
| Error 9150: Operator made a wrong decision |
| Error 9160: Operator made a delayed decision |
| Error 9170: Operator is unable to perform the action |
| Error 9180: Operator performed the wrong action on object |
| Error 9190: Operator performed the action on wrong object |
| Error 9200: Operator performed the action in wrong time |
| Error 9210: Operator is unable to send the message |
| Error 9220: Operator sent an incomplete message |
| Error 9230: Operator sent the wrong message |
| Error 9240: Operator sent the message with delay |
| Error 9900: No error |
| Error 9000: Unknown error |
| Error 5000: Error has not been recognized by operator |
| Error 5100: Error has not been indicated because it was not recognized by operator |
| Error 5200: Error has not been indicated by operator to the rest of the team |
| Error 5300: Error has not been corrected because it was not recognized by operator |
| Error 5400: Error has not been corrected because it was not recognized & indicated by operator |
| Error 5500: Error has not been corrected because it was not indicated by operator |
| Error 5600: Error has not been corrected by operator |

# Appendix C: Sample CREWSIM Simulation Log File

```
component no.821 has already failed.
Time = 1.8
_______________________________________________
start:*********
    1.8000

======================================================================
Operator no.2.
======================================================================
Recognizing the situation: ----------
Input message:
Message 6200: Unknown message.
Input error:
Error 9030: Message is not available to operator.
System State 7000: Unknown system state.
Error 9120: Operator is unable to diagnose the situation.
Making a decision: ----------
Decision 4001: No decision.
Error 9140: Operator is unable to make a decision.
Executing action: ----------
Output message:
Message 6001: Observation from system.
Action 5900: No action on system.
Output Error:
Error 9170: Operator is unable to perform the action.
Start of Error Recovery--------------------------------
Action 5900: No action on system.
Message 6001: Observation from system.
Error 9610: Error has not been corrected by team because it was not
recognized & indicated by anyone.
End of Error Recovery---------------------
start:*********
    1.8000

start:*********
    1.8000

start:*********
    1.8000

======================================================================
Operator no.4.
======================================================================
Recognizing the situation: ----------
Input message (from operator no.1,no.2 and no.3):
Message 6000: No message.
Message 6200: Unknown message.
Message 6000: No message.
Input error (from operator no.1, no.2 and no.3):
Error 9900: No error.
Error 9030: Message is not available to operator.
Error 9900: No error.
System State 7004: Intermediate loops lost integrity.
Output Error (to operator no.1,no.2,no.3):
Error 9900: No error.
Error 9900: No error.
Error 9900: No error.
Making a decision: ----------
```

```
Decision 4090: Activate emergency subsystem.
Output Error (to operator no.1,no.2,no.3):
Error 9900: No error.
Error 9900: No error.
Error 9900: No error.
Executing action: ----------
Output message (to operator no.1, no.2 and no.3):
Message 6000: No message.
Message 6000: No message.
Message 6000: No message.
Output error (to operator no.1, no.2 and no.3):
Error 9900: No error.
Error 9006: Unknown message.
Error 9900: No error.
Start of Error Recovery--------------------------------
Operator is recognizing the error.
Error 9006: Unknown message.
Operator is indicating the error.
Indication message:
Error 9006: Unknown message.
Operator is correcting the error.
Error is being corrected.
Action 5900: No action on system.
Message 6120: Request for resending the message.
Error 9900: No error.
End of Error Recovery---------------------
Communication in team.1 failed.
start:*********
    1.8000

=======================================================================
Operator no.1.
=======================================================================
Recognizing the situation: ----------
Input message:
Message 6000: No message.
Input error:
Error 9900: No error.
System State 7004: Intermediate loops lost integrity.
Error 9900: No error.
Making a decision: ----------
Decision 4090: Activate emergency subsystem.
Error 9900: No error.
Executing action: ----------
Output message:
Message 6001: Observation from system.
Action 5900: No action on system.
Output Error:
Error 9900: No error.
No error.
start:*********
    1.8000

=======================================================================
Operator no.3.
=======================================================================
Recognizing the situation: ----------
Input message:
Message 6000: No message.
Input error:
Error 9900: No error.
System State 7001: Normal.
Error 9900: No error.
```

```
Making a decision: ----------
Decision 4001: No decision.
Error 9900: No error.
Executing action: ----------
Output message:
Message 6000: No message.
Action 5900: No action on system.
Output error:
Error 9900: No error.
No error.
No error.
No error.
component no.821 has already failed.
Time = 1.9
_______________________________________________
start:*********
    1.9000

======================================================================
Operator no.2.
======================================================================
Recognizing the situation: ----------
Input message:
Message 6200: Unknown message.
Input error:
Error 9030: Message is not available to operator.
System State 7000: Unknown system state.
Error 9120: Operator is unable to diagnose the situation.
Making a decision: ----------
Decision 4001: No decision.
Error 9140: Operator is unable to make a decision.
Executing action: ----------
Output message:
Message 6001: Observation from system.
Action 5900: No action on system.
Output Error:
Error 9170: Operator is unable to perform the action.
Start of Error Recovery--------------------------------
Action 5900: No action on system.
Message 6001: Observation from system.
Error 9610: Error has not been corrected by team because it was not
recognized & indicated by anyone.
End of Error Recovery---------------------
start:*********
    1.9000

start:*********
    1.9000

start:*********
    1.9000

======================================================================
Operator no.4.
======================================================================
Recognizing the situation: ----------
Input message (from operator no.1,no.2 and no.3):
Message 6001: Observation from system.
Message 6200: Unknown message.
Message 6000: No message.
Input error (from operator no.1, no.2 and no.3):
Error 9900: No error.
Error 9030: Message is not available to operator.
```

```
Error 9900: No error.
System State 7004: Intermediate loops lost integrity.
Output Error (to operator no.1,no.2,no.3):
Error 9900: No error.
Error 9900: No error.
Error 9900: No error.
Making a decision: ----------
Decision 4090: Activate emergency subsystem.
Output Error (to operator no.1,no.2,no.3):
Error 9900: No error.
Error 9900: No error.
Error 9900: No error.
Executing action: ----------
Output message (to operator no.1, no.2 and no.3):
Message 6003: Request for action on system.
Message 6000: No message.
Message 6000: No message.
Output error (to operator no.1, no.2 and no.3):
Error 9900: No error.
Error 9030: Message is not available to operator.
Error 9900: No error.
Start of Error Recovery--------------------------------
Operator is recognizing the error.
Error 9030: Message is not available to operator.
Operator is indicating the error.
Indication message:
Error 9030: Message is not available to operator.
Operator is correcting the error.
Error is being corrected.
Recvery Action 5950: No possible recovery action on system.
Message 6000: No message.
Error 9030: Message is not available to operator.
End of Error Recovery---------------------
Communication in team.1 failed.
start:*********
    1.9000

========================================================================
Operator no.1.
========================================================================
Recognizing the situation: ----------
Input message:
Message 6000: No message.
Input error:
Error 9900: No error.
System State 7004: Intermediate loops lost integrity.
Error 9900: No error.
Making a decision: ----------
Decision 4090: Activate emergency subsystem.
Error 9900: No error.
Executing action: ----------
Output message:
Message 6001: Observation from system.
Action 5900: No action on system.
Output Error:
Error 9900: No error.
No error.
start:*********
    1.9000

========================================================================
Operator no.3.
========================================================================
```

```
Recognizing the situation: ----------
Input message:
Message 6000: No message.
Input error:
Error 9900: No error.
System State 7001: Normal.
Error 9900: No error.
Making a decision: ----------
Decision 4001: No decision.
Error 9900: No error.
Executing action: ----------
Output message:
Message 6000: No message.
Action 5900: No action on system.
Output error:
Error 9900: No error.
No error.
No error.
No error.
component no.821 has already failed.
Time = 2
________________________________________
start:*********
     2

======================================================================
Operator no.2.
======================================================================
Recognizing the situation: ----------
Input message:
Message 6200: Unknown message.
Input error:
Error 9030: Message is not available to operator.
System State 7000: Unknown system state.
Error 9120: Operator is unable to diagnose the situation.
Making a decision: ----------
Decision 4001: No decision.
Error 9140: Operator is unable to make a decision.
Executing action: ----------
Output message:
Message 6001: Observation from system.
Action 5900: No action on system.
Output Error:
Error 9170: Operator is unable to perform the action.
Start of Error Recovery--------------------------------
Action 5900: No action on system.
Message 6001: Observation from system.
Error 9610: Error has not been corrected by team because it was not
recognized & indicated by anyone.
End of Error Recovery---------------------
start:*********
     2

start:*********
     2

start:*********
     2

======================================================================
Operator no.4.
======================================================================
Recognizing the situation: ----------
```

```
Input message (from operator no.1,no.2 and no.3):
Message 6001: Observation from system.
Message 6200: Unknown message.
Message 6000: No message.
Input error (from operator no.1, no.2 and no.3):
Error 9900: No error.
Error 9030: Message is not available to operator.
Error 9900: No error.
System State 7004: Intermediate loops lost integrity.
Output Error (to operator no.1,no.2,no.3):
Error 9900: No error.
Error 9900: No error.
Error 9900: No error.
Making a decision: ----------
Decision 4090: Activate emergency subsystem.
Output Error (to operator no.1,no.2,no.3):
Error 9900: No error.
Error 9900: No error.
Error 9900: No error.
Executing action: ----------
Output message (to operator no.1, no.2 and no.3):
Message 6003: Request for action on system.
Message 6000: No message.
Message 6000: No message.
Output error (to operator no.1, no.2 and no.3):
Error 9900: No error.
Error 9030: Message is not available to operator.
Error 9900: No error.
Start of Error Recovery--------------------------------
Operator is recognizing the error.
Error 9030: Message is not available to operator.
Operator is indicating the error.
Indication message:
Error 9030: Message is not available to operator.
Operator is correcting the error.
Error is being corrected.
Recvery Action 5950: No possible recovery action on system.
Message 6000: No message.
Error 9030: Message is not available to operator.
End of Error Recovery---------------------
Communication in team.1 failed.
start:*********
     2

=======================================================================
Operator no.1.
=======================================================================
Recognizing the situation: ----------
Input message:
Message 6000: No message.
Input error:
Error 9900: No error.
System State 7004: Intermediate loops lost integrity.
Error 9900: No error.
Making a decision: ----------
Decision 4090: Activate emergency subsystem.
Error 9900: No error.
Executing action: ----------
Output message:
Message 6001: Observation from system.
Action 5900: No action on system.
Output Error:
Error 9900: No error.
```

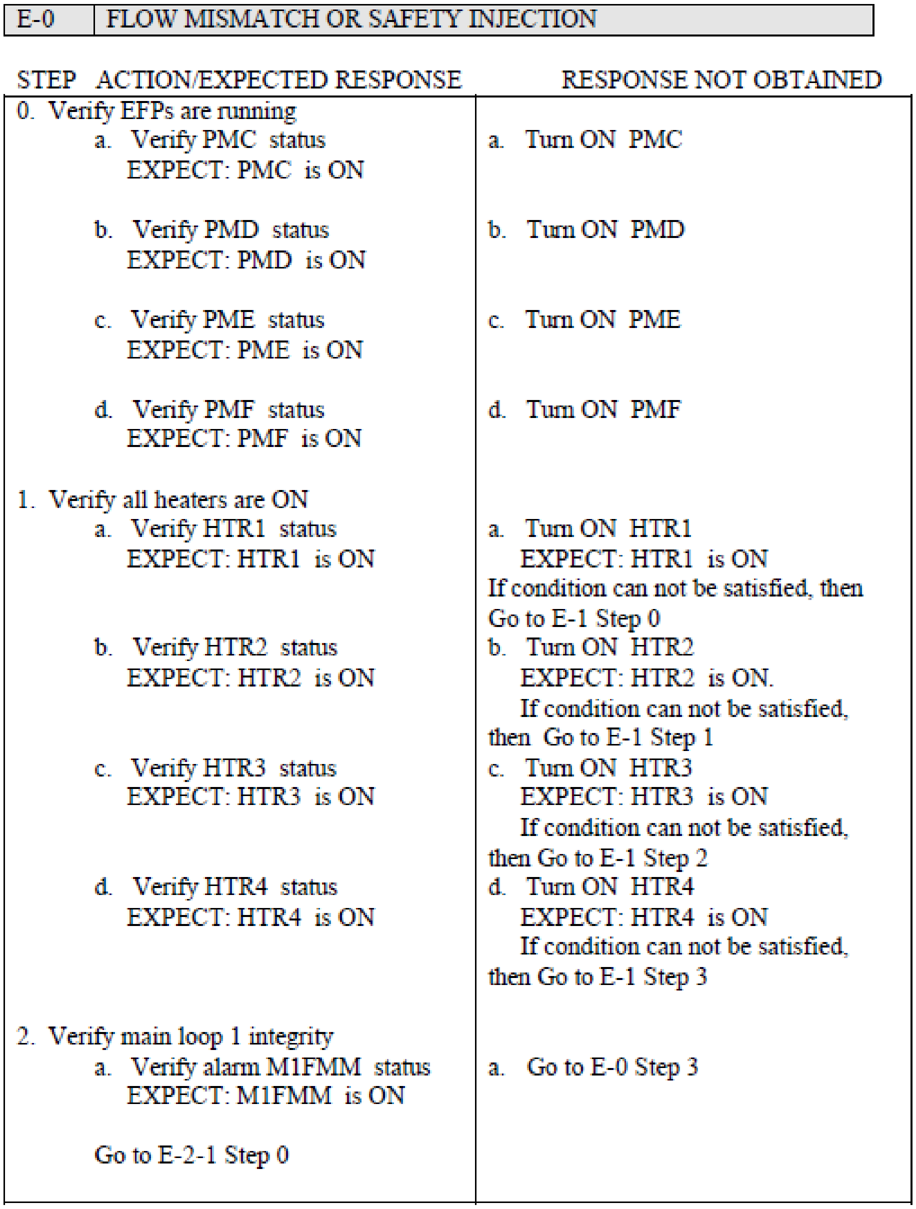
```
No error.
start:*********
     2

=======================================================================
Operator no.3.
=======================================================================
Recognizing the situation: ----------
Input message:
Message 6000: No message.
Input error:
Error 9900: No error.
System State 7001: Normal.
Error 9900: No error.
Making a decision: ----------
Decision 4001: No decision.
Error 9900: No error.
Executing action: ----------
Output message:
Message 6000: No message.
Action 5900: No action on system.
Output error:
Error 9900: No error.
No error.
No error.
No error.
component no.821 has already failed.
Time = 2.1
_______________________________________________
start:*********
    2.1000

=======================================================================
Operator no.2.
=======================================================================
Recognizing the situation: ----------
Input message:
Message 6200: Unknown message.
Input error:
Error 9030: Message is not available to operator.
System State 7000: Unknown system state.
Error 9120: Operator is unable to diagnose the situation.
Making a decision: ----------
Decision 4001: No decision.
Error 9140: Operator is unable to make a decision.
Executing action: ----------
Output message:
Message 6001: Observation from system.
Action 5900: No action on system.
Output Error:
Error 9170: Operator is unable to perform the action.
Start of Error Recovery--------------------------------
Action 5900: No action on system.
Message 6001: Observation from system.
Error 9610: Error has not been corrected by team because it was not
recognized & indicated by anyone.
End of Error Recovery---------------------
start:*********
    2.1000

start:*********
    2.1000
```

```
start:*********
    2.1000

========================================================================
Operator no.4.
========================================================================
Recognizing the situation: ----------
Input message (from operator no.1,no.2 and no.3):
Message 6001: Observation from system.
Message 6200: Unknown message.
Message 6000: No message.
Input error (from operator no.1, no.2 and no.3):
Error 9900: No error.
Error 9030: Message is not available to operator.
Error 9900: No error.
System State 7004: Intermediate loops lost integrity.
Output Error (to operator no.1,no.2,no.3):
Error 9900: No error.
Error 9900: No error.
Error 9900: No error.
Making a decision: ----------
Decision 4090: Activate emergency subsystem.
Output Error (to operator no.1,no.2,no.3):
Error 9900: No error.
Error 9900: No error.
Error 9900: No error.
Executing action: ----------
Output message (to operator no.1, no.2 and no.3):
Message 6003: Request for action on system.
Message 6000: No message.
Message 6000: No message.
Output error (to operator no.1, no.2 and no.3):
Error 9900: No error.
Error 9030: Message is not available to operator.
Error 9900: No error.
Start of Error Recovery--------------------------------
Operator is recognizing the error.
Error 9030: Message is not available to operator.
Operator is indicating the error.
Indication message:
Error 9030: Message is not available to operator.
Operator is correcting the error.
Error is being corrected.
Recvery Action 5950: No possible recovery action on system.
Message 6000: No message.
Error 9030: Message is not available to operator.
End of Error Recovery---------------------
Communication in team.1 failed.
start:*********
    2.1000

========================================================================
Operator no.1.
========================================================================
Recognizing the situation: ----------
Input message:
Message 6003: Request for action on system.
Input error:
Error 9900: No error.
System State 7004: Intermediate loops lost integrity.
Error 9900: No error.
Making a decision: ----------
Decision 4090: Activate emergency subsystem.
```

```
Error 9900: No error.
Executing action: ----------
Output message:
Message 6104: Confirmation for performing request.
Action 5400: Activate emergency trigger.
Output Error:
Error 9900: No error.
No error.
start:*********
    2.1000

=======================================================================
Operator no.3.
=======================================================================
Recognizing the situation: ----------
Input message:
Message 6000: No message.
Input error:
Error 9900: No error.
System State 7001: Normal.
Error 9900: No error.
Making a decision: ----------
Decision 4001: No decision.
Error 9900: No error.
Executing action: ----------
Output message:
Message 6000: No message.
Action 5900: No action on system.
Output error:
Error 9900: No error.
No error.
No error.
No error.
```

# Appendix D: Emergency Operating Procedures[14]

The Emergency Operating Procedures (EOPs) used by the operating crew of the case study (Chapter 5) are described in this appendix.



| E-0 | FLOW MISMATCH OR SAFETY INJECTION |
|---|---|
| **STEP ACTION/EXPECTED RESPONSE** | **RESPONSE NOT OBTAINED** |
| 0. Verify EFPs are running | |
| a. Verify PMC status<br>EXPECT: PMC is ON | a. Turn ON PMC |
| b. Verify PMD status<br>EXPECT: PMD is ON | b. Turn ON PMD |
| c. Verify PME status<br>EXPECT: PME is ON | c. Turn ON PME |
| d. Verify PMF status<br>EXPECT: PMF is ON | d. Turn ON PMF |
| 1. Verify all heaters are ON | |
| a. Verify HTR1 status<br>EXPECT: HTR1 is ON | a. Turn ON HTR1<br>EXPECT: HTR1 is ON<br>If condition can not be satisfied, then Go to E-1 Step 0 |
| b. Verify HTR2 status<br>EXPECT: HTR2 is ON | b. Turn ON HTR2<br>EXPECT: HTR2 is ON.<br>If condition can not be satisfied, then Go to E-1 Step 1 |
| c. Verify HTR3 status<br>EXPECT: HTR3 is ON | c. Turn ON HTR3<br>EXPECT: HTR3 is ON<br>If condition can not be satisfied, then Go to E-1 Step 2 |
| d. Verify HTR4 status<br>EXPECT: HTR4 is ON | d. Turn ON HTR4<br>EXPECT: HTR4 is ON<br>If condition can not be satisfied, then Go to E-1 Step 3 |
| 2. Verify main loop 1 integrity | |
| a. Verify alarm M1FMM status<br>EXPECT: M1FMM is ON | a. Go to E-0 Step 3 |
| Go to E-2-1 Step 0 | |

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[14] Chang (1999)

| STEP ACTION/EXPECTED RESPONSE | RESPONSE NOT OBTAINED |
|---|---|
| 3. Verify main loop 2 integrity | a. Go to E-0 Step 4 |
| a. Verify alarm M2FMM status<br>EXPECT: M2FMM is ON | |
| Go to E-2-1 Step 1 | |
| 4. Verify interface loop integrity | |
| a. Verify alarm MIFMM status<br>EXPECT: MIFMM is ON | a. Go to E-0 Step 5 |
| Go to E-2-2 Step 0 | |
| 5. Verify Steam Generator output loops integrity | |
| a. Verify alarm IOFMM status<br>EXPECT: IOFMM is ON | a. Go to E-0 Step 0 |
| Go to E-3 Step 0 | |

## E-1 LOSS OF HEAT SOURCE

| STEP ACTION/EXPECTED RESPONSE | RESPONSE NOT OBTAINED |
|---|---|
| 0. HTR1 lost its function | |
| a. Verify HTR1 status<br>EXPECT: HTR1 is OFF | a. Go to E-1 Step 1 |
| b. Close VMM3<br>EXPECT: FWE1 flow stops | b. Turn OFF PMC<br>EXPECT: FWE1 flow stops |
| c. Close VIM1<br>EXPECT: FWI1 flow stops | c. Close VIH1<br>EXPECT: FWI1 flow stops |
| d. Control until requirement satisfied.<br>Control VIM2 to make SG2 LEVEL reading STABLE<br>-- AND --<br>Control VIM3 to make SG3 LEVEL reading STABLE<br>-- AND --<br>Control VIM4 to make SG4 LEVEL reading STABLE | |
| Go to E-1 Step 1 | |
| 1. HTR2 lost its function | |
| a. Verify HTR2 status<br>EXPECT: HTR2 is OFF | a. Go to E-1 Step 2 |
| b. Close VMM4<br>EXPECT: FWE2 flow stops | b. Turn OFF PMD<br>EXPECT: FWE2 flow stops |
| c. Close VIM2<br>EXPECT: FWI2 flow stops | c. Close VIH2<br>EXPECT: FWI2 flow stops |

| STEP ACTION/EXPECTED RESPONSE | RESPONSE NOT OBTAINED |
|---|---|
| d. Control until requirement satisfied.<br>Control VIM1 to make SG1 LEVEL reading STABLE<br>-- AND --<br>Control VIM3 to make SG3 LEVEL reading STABLE<br>-- AND --<br>Control VIM4 to make SG4 LEVEL reading STABLE<br>Go to E-1 Step 2 | |
| 2. HTR3 lost its function | |
| a. Verify HTR3 status<br>EXPECT: HTR3 is OFF | a. Go to E-1 Step 3 |
| b. Close VMM5<br>EXPECT: FWE3 flow stops | b. Turn OFF PME<br>EXPECT: FWE3 flow stops |
| c. Close VIM3<br>EXPECT: FWI3 flow stops | c. Close VIH3<br>EXPECT: FWI3 flow stops |
| d. Control until requirement satisfied.<br>Control VIM1 to make SG1 LEVEL reading STABLE<br>-- AND --<br>Control VIM2 to make SG2 LEVEL reading STABLE<br>-- AND --<br>Control VIM4 to make SG4 LEVEL reading STABLE<br>Go to E-1 Step 3 | |
| 3. HTR4 lost its function | |
| a. Verify HTR4 status<br>EXPECT: HTR4 is OFF | a. Go to E-0 Step 2 |
| b. Close VMM6<br>EXPECT: FWE4 flow stops | b. Turn OFF PMF<br>EXPECT: FWE4 flow stops |

| STEP ACTION/EXPECTED RESPONSE | RESPONSE NOT OBTAINED |
|---|---|
| c. Close VIM4<br>EXPECT: FWI4 flow stops | c. Close VIH4<br>EXPECT: FWI4 flow stops |
| d. Control until requirement satisfied.<br>Control VIM1 to make SG1 LEVEL reading STABLE<br>-- AND --<br>Control VIM2 to make SG2 LEVEL reading STABLE<br>-- AND --<br>Control VIM3 to make SG3 LEVEL reading STABLE<br>Go to E-0 Step 2 | |

## E-2-1 MAIN LOOPS LOSS INTEGRITY

| STEP ACTION/EXPECTED RESPONSE | RESPONSE NOT OBTAINED |
|---|---|
| 0. "Main loop 2 leakage recovery" | |
| a. Open VMM3 to 100 degrees | |
| b. Open VMM4 to 100 degrees | |
| c. Open VMM5 to 100 degrees | |
| d. Open VMM6 to 100 degrees | |
| e. Verify M2FMM status<br>EXPECT: M2FMM is ON | e. Go to E-2-1 Step 1 |
| f. Turn OFF PMA | |
| g. Control until requirement satisfied.<br>Control VMM3 to make SG1 LEVEL reading STABLE<br>-- AND --<br>Control VMM4 to make SG2 LEVEL reading STABLE<br>-- AND --<br>Control VMM5 to make SG3 LEVEL reading STABLE<br>-- AND --<br>Control VMM6 to make SG4 LEVEL reading STABLE | |
| Go to E-2-1 Step 1 | |

## E-2-2 INTERFACE LOOPS LOSS INTEGRITY

| STEP ACTION/EXPECTED RESPONSE | RESPONSE NOT OBTAINED |
|---|---|
| 0. Interface loop leakage recovery | |
| a. Open VMM3 to 100 degrees | |
| b. Open VMM4 to 100 degrees | |
| c. Open VMM5 to 100 degrees | |
| d. Open VMM6 to 100 degrees | |
| e. Verify SUMP1 LEVEL status<br>EXPECT: SUMP1 LEVEL is STABLE | e. Go to E-2-2 Step 1 |
| f. Verify SUMP2 LEVEL status<br>EXPECT: SUMP2 LEVEL is STABLE | f. Go to E-2-2 Step 2 |
| g. Verify SUMP3 LEVEL status<br>EXPECT: SUMP3 LEVEL is STABLE | g. Go to E-2-2 Step 3 |
| h. Verify SUMP4 LEVEL status<br>EXPECT: SUMP4 LEVEL is STABLE | h. Go to E-2-2 Step 4 |
| Go to E-0 Step 6 | |
| 1. Interface loop 1 lost integrity | |
| a. Turn OFF HTR1 | |
| b. Close VMM3 | |
| c. Close VIM1<br>EXPECT: FWI1 flow stops | c. Close VIH1<br>EXPECT: FWI1 flow stops |

| STEP ACTION/EXPECTED RESPONSE | RESPONSE NOT OBTAINED |
|---|---|
| d. Control until requirement satisfied.<br>Control VIM2 to make SG2 LEVEL reading STABLE<br>-- AND --<br>Control VIM3 to make SG3 LEVEL reading STABLE<br>-- AND --<br>Control VIM4 to make SG4 LEVEL reading STABLE<br>Go to E-2-2 Step 0 | |
| 2. Interface loop 2 lost integrity<br>a. Turn OFF HTR2 | |
| b. Close VMM4 | |
| c. Close VIM2<br>EXPECT: FWI2 flow stops | c. Close VIH2<br>EXPECT: FWI2 flow stops |
| d. Control until requirement satisfied.<br>Control VIM1 to make SG1 LEVEL reading STABLE<br>-- AND --<br>Control VIM3 to make SG3 LEVEL reading STABLE<br>-- AND --<br>Control VIM4 to make SG4 LEVEL reading STABLE<br>Go to E-2-2 Step 0 | |
| 3. Interface loop 3 lost integrity<br>a. Turn OFF HTR3 | |
| b. Close VMM5 | |
| c. Close VIM3<br>EXPECT: FWI3 flow stops | c. Close VIH3<br>EXPECT: FWI3 flow stops |

| STEP ACTION/EXPECTED RESPONSE | RESPONSE NOT OBTAINED |
|---|---|
| d. Control until requirement satisfied.<br>Control VIM1 to make SG1 LEVEL reading STABLE<br>-- AND --<br>Control VIM2 to make SG2 LEVEL reading STABLE<br>-- AND --<br>Control VIM4 to make SG4 LEVEL reading STABLE<br>Go to E-2-2 Step 0 | |
| 4. Interface loop 4 lost integrity | |
| a. Turn OFF HTR4 | |
| b. Close VMM6 | |
| c. Close VIM4<br>EXPECT: FWI4 flow stops | c. Close VIH4<br>EXPECT: FWI4 flow stops |
| d. Control until requirement satisfied.<br>Control VIM1 to make SG1 LEVEL reading STABLE<br>-- AND --<br>Control VIM2 to make SG2 LEVEL reading STABLE<br>-- AND --<br>Control VIM3 to make SG3 LEVEL reading STABLE<br>Go to E-2-2 Step 0 | |

## E-3 LOSS HEAT SOURCE OR OUTPUT LOOPS LOSS INTEGRITY

| STEP ACTION/EXPECTED RESPONSE | RESPONSE NOT OBTAINED |
|---|---|
| 0. Check heat sources working status | |
| a. Verify HTR1 status<br>EXPECT: HTR1 is ON | a. Go to E-1 Step 0 |
| b. Verify HTR2 status<br>EXPECT: HTR2 is ON | b. Go to E-1 Step 1 |
| c. Verify HTR3 status<br>EXPECT: HTR3 is ON | c. Go to E-1 Step 2 |
| d. Verify HTR4 status<br>EXPECT: HTR4 is ON | d. Go to E-1 Step 3 |
| Go to E-3 Step 1 | |
| 1. Verify output loop 1 integrity | |
| a. Verify SG1FMM status<br>EXPECT: SG1FMM is ON | |
| b. Turn OFF HTR1 | |
| c. Close VMM3 | |
| d. Close VIM1<br>EXPECT: FWI1 flow stops | d. Close VIH1<br>EXPECT: FWI1 flow stops |
| e. Control until requirement satisfied.<br>Control VIM2 to make SG2 LEVEL reading STABLE<br>-- AND --<br>Control VIM3 to make SG3 LEVEL reading STABLE<br>-- AND --<br>Control VIM4 to make SG4 LEVEL reading STABLE | |
| Go to E-3 Step 2 | |
| 2. Verify output loop 2 integrity | |
| a. Verify SG2FMM status<br>EXPECT: SG2FMM is ON | a. Go to E-3 Step 3 |

| STEP ACTION/EXPECTED RESPONSE | RESPONSE NOT OBTAINED |
|---|---|
| b. Turn OFF HTR2 | |
| c. Close VMM4 | |
| d. Close VIM2<br>EXPECT: FWI2 flow stops | d. Close VIH2<br>EXPECT: FWI2 flow stops |
| e. Control until requirement satisfied.<br>Control VIM1 to make SG1 LEVEL reading STABLE<br>-- AND --<br>Control VIM3 to make SG3 LEVEL reading STABLE<br>-- AND --<br>Control VIM4 to make SG4 LEVEL reading STABLE<br><br>Go to E-3 Step 3 | |
| 3. Verify output loop 3 integrity | |
| a. Verify SG3FMM status<br>EXPECT: SG3FMM is ON | |
| b. Turn OFF HTR3 | |
| c. Close VMM5 | |
| d. Close VIM3<br>EXPECT: FWI3 flow stops | d. Close VIH3<br>EXPECT: FWI3 flow stops |
| e. Control until requirement satisfied.<br>Control VIM1 to make SG1 LEVEL reading STABLE<br>-- AND --<br>Control VIM2 to make SG2 LEVEL reading STABLE<br>-- AND --<br>Control VIM4 to make SG4 LEVEL reading STABLE<br><br>Go to E-3 Step 4 | |

| STEP ACTION/EXPECTED RESPONSE | RESPONSE NOT OBTAINED |
|---|---|
| 4. Verify output loop 4 integrity | |
| a. Verify SG4FMM status<br>EXPECT: SG3FMM is ON | a. Go to E-0 Step 5 |
| b. Turn OFF HTR4 | |
| c. Close VMM6 | |
| d. Close VIM4<br>EXPECT: FWI4 flow stops | d. Close VIH4<br>EXPECT: FWI4 flow stops |
| e. Control until requirement satisfied.<br>Control VIM1 to make SG1 LEVEL reading STABLE<br>-- AND --<br>Control VIM2 to make SG2 LEVEL reading STABLE<br>-- AND --<br>Control VIM3 to make SG3 LEVEL reading STABLE | |
| Go to E-0 Step 5 | |

# Bibliography

Antony J., Somasundarum V., Fergusson C., Blecharz P., Applications of Taguchi approach to statistical design of experiments in Czech Republican industries, International Journal of Productivity and Performance Management, 2004.

Arrow H., McGrath J.E., Berdahl J.L., Small groups as complex systems: Formation, coordination, development, and adaptation. Thousand Oaks, CA Sage, 2000.

Banbury S., Tremblay S., A cognitive approach to situation awareness, theory and application, Ashgate, 2004.

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

Blackman H.S., Gertman D.I., Boring R.L., Human Error quantification using performance shaping factors in the SPAR-H method, 52nd annual meeting of the human factors ad ergonomics society, 2008.

Bland J., About Gender: Interactionism, 2001.

Blendell C., Henderson S., Molloy J., Pascual R., Team performance shaping factors in IPME (Integrated Performance Modeling Environment), 2001.

Boring R. L., Modeling human reliability analysis using MIDAS, International workshop on future control station designs and human performance issues in NPPs, Idaho national laboratory, 2006.

Boring R. L., Gertman D. I., Tran T. Q., Gore B. F., Framework for the application of MIDAS for modeling control room crew performance at NPPs, 52nd Annual meeting of the human factors and ergonomics Society, 2008.

Brennen S.D., Strong R.J., Ryder C.J., Blendell C., Molloy J.J., Teams, Computer Modeling, and Design, IEEE Transactions on Systems, Man, and Cybernetics, 2007.

Broberga H., Hildebrandta M., Massaiua S., Braaruda P., and Johanssona B., The International HRA empirical study: Experimental results and insights into PSFs, PSAM 9, 2008.

Bust P.D., NARA (Nuclear Action Reliability Assessment) further development of a data based HRA tool, Contemporary ergonomics, 2008.

Cacciabue P.C., Guide to applying human factor methods: Human error and accident management in safety critical systems, 1st edition, Springer-Verlag, London, 2004.

Carvalho E., Rixey R.A., Shepley J.P., Gomes J.O., Guerlain S., Design of a nuclear power plant supervisory control system, IEEE, 2006.

Carvalho P.V.R, Dos Santos I.L, Gomes J.O., Da Silva Borges M.R, Huber G.J., The role of nuclear power plant operators' communications in providing resilience and stability in system operation, 2008.

Carvalho P.V.R., Dos Santos I. L., Vidal M. C. R., Nuclear power plant shift supervisor's decision making during micro-incidents, International journal of industrial ergonomics, 2005.

Carvalho P.V.R., Ergonomic field studies in a NPP control room, Progress in nuclear energy, 2006.

Chang Y. H. J., Mosleh A., Cognitive modeling and dynamic probabilistic simulation of operating crew response to complex system accidents. Part 1-5, Reliability Engineering & System Safety, 2007.

Chang Y.H.J, Cognitive modeling and dynamic probabilistic simulation of operating crew response to complex system accidents (ADS-IDACrew), PhD Dissertation, Technical research report, University of Maryland at college park, 1999.

Coyne K., A predictive model of nuclear power plant crew decision making and performance in a dynamic simulation environment, PhD Dissertation, University of Maryland at college park, 2009.

Dawson P.E., Evaluation of human error probabilities for post-initiating events, Masters of science Dissertation, MIT, 2007.

Dietrich R., Childress T.M., Group interaction in high risk environment, Ashgate publishing company, 2004.

Druckman D., Bjork R.A., In the mind's eye: Enhancing human performance, National academy press, Washington, D.C., 1991.

Embrey D.E., Humphreys E.A., Kirwan B., Rea K., SLIM-MAUD: An Approach to assess human error probabilities using structured expert judgment, NUREG/CR-3518, Brookhaven national laboratory for the U.S. Nuclear regulatory commission, Washington, DC, 1984.

Entin E. E. , Entin E. B., Measures for evaluation of team processes and performance in experiments and exercises, Proceedings of the 6th International Command and Control Research and Technology Symposium, 2001.

Essens P., Military command team effectiveness: Model and instrument for assessment and improvement, Technical report for Research and Technology Organization, 2005.

Firth-cozens J., Why communication fails in the operating room, Quality & safety in health care, 2004.

Flin R., Crichton M.T., Identifying and training nontechnical skills of nuclear emergency response teams, Annuals on Nuclear Energy, 2004.

Flin R., Goeters K.M, Hörmann J., Martin L.A, Generic structure of Non-Technical skills for Training and Assessment, 23rd Conference of the European Association for Aviation Psychology, 1998.

Flin R., O'Connor P., Mearns K., Crew resource management: Improving safety in high reliability industries. Team performance management, 2002.

Flin R., O'Connor P., Crichton M., Safety at the Sharp End: A guide to non-technical skills, Ashgate, 2008.

Furuta K., Shimada T., Kondo S., Behavioral simulation of a nuclear power plant operator crew for human–machine system design, Nuclear engineering and design, 1999.

Gertman D. I., Hallbert B. P., Prawdzik D., Blackman H. S., Kramer J., Persensky J. J., and Trager E. A., Human performance characterization in the reactor oversight process, PSAM 6, 2002.

Gibson W. H., Kirwan B., Kennedy R., Edmunds J., and Umberes I., NARA (Nuclear Action Reliability Assessment): Further development of a data based HRA tool, International Conference Contemporary Ergonomics, 2008.

Groth K. M., Mosleh A., A data informed model of PSFs and their interdependence for use in human reliability analysis, ESREL, 2009.

Harrington D.K., Kello J.E., Systematic evaluation of nuclear operator team skills training: a progress report, IEEE Fifth Conference on human factors and Power Plants, 1992.

Health and Safety Executive of Great Britain, Top ten human factors of major hazard sites in the chemical and allied industries, Energy institute, UK, 2005.

Helmreich R.L., Foushee H.C., Why Crew Resource Management? Empirical and theoretical bases of human factors training in aviation, Cockpit Resource Management, San Diego, CA: Academic Press, 1993.

Helmreich R.L., Merritt A.C., Wilhelm J.A., The evolution of Crew Resource Management training in commercial aviation, International Journal of Aviation Psychology, 1999.

Hendrickson S.M.L,Whaley A.M, Boring R.L., ChangY.H.J, Shen S.H, Mosleh A., Oxstrand J.H., Forester J.A., Kelly D.A., A mid-layer model for human reliability analysis: understanding the cognitive causes of human failure events, Idaho national laboratory, PSAM10, 2010

Hirotsu Y., Suzuki K., Kojima M., Takano K., Multivariate analysis of human error incidents occurring at nuclear power plants: Several occurrence patterns of observed human errors, Cognition, Technology, & Work, 2001.

Hoegl M., Gemuenden H. G., Teamwork quality and the success of innovative projects: a theoretical concept and empirical evidence, Organization science, 2001.

Hulin C.L., Ilgen D., Introduction to computational modeling in organizations: the good that modeling does. In computational modeling of behavior in organizations: The third scientific discipline, Washington, DC, Psychol. Assoc, 2000.

Ilgen D. R., Hollenbeck J. R., Johnson M., Jundt D., Teams in organizations: from input-process-output models to IMOI models, Annual Review of Psychology, 2004.

International Nuclear Safety Advisory Group, Summary report on the post-accident review meeting on the Chernobyl accident, International Atomic Energy Authority, Vienna, 1986.

International HRA Empirical Study – Phase 1 Report (NUREG/IA-0216, Volume 1, 2), 2009.

Juhasz M., Soos J. K., Impact of nontechnical skills on NPP teams performance, IEEE 8th conference on human factors and power plants and the HPRCT 13th Annual Meeting, 2007.

Juhász M., Soós J.K., Human aspects of NPP operator teamwork, Nuclear Power - Control, Reliability and Human Factors, Dr. Pavel Tsvetkov (Ed.), InTech, 2011.

Kaplan S., Haimes Y.Y., Garrick B.J., Fitting hierarchical holographic modeling into the theory of scenario structuring and a resulting refinement to the quantitative definition of risk, Risk Analysis, 2001.

Kanki, Helmreich, Anca, Crew Resource Management, 2010.

Kim J.W., Jung W., A taxonomy of performance influencing factors for human reliability analysis of emergency tasks, Journal of loss prevention in the process industries, 2003.

Kim A.R, Park J., Lee W.S., Jang I., Kang H.G, Development of new taxonomy of inappropriate communication and its application to operating teams in NPPs, Nuclear engineering and technology, 2011.

Kirwan B., A guide to practical human reliability assessment, Taylor & Francis, 1994.

Klein K.J., Kozlowski S.W.J., Multilevel theory, research, and methods in organizations: foundations, extensions, and new directions. San Francisco, CA: JosseyBass, 2000.

Klein G., Ross K. G., Moon B. M., Klein D. E., Hoffman R. R., Hollnagel E, Macrocognition, IEEE Intelligent Systems, 2003.

Klein J. T., A taxonomy of inter-disciplinarity, Oxford Handbook of Inter-disciplinarity, Oxford, UK: Oxford University Press, 2010.

Kolbe M., Künzle B., Zala-Mezö E., Wacker J., Grote G., Measuring coordination behavior in anesthesia teams during inductions of general anesthetics, Safer surgery: Analyzing behavior in the operating theatre Aldershot: Ashgate,2009.

Kozlowski S.W.J., Gully S.M., Nason E.R., Smith E.M., Developing adaptive teams: a theory of compilation and performance across levels and time, The Changing Nature of Performance, San Francisco, CA: Jossey-Bass,1999.

Lang A. W., Roth E. M., Bladh K., Hine, R., Using a benchmark-referenced approach for validating a power plant control room: Results of the baseline study, Human factors and ergonomics society 46th annual meeting, Santa Monica, 2001.

Lee S.M., Su Ha J., Hyun Seong P., CREAM-based communication error analysis method (CEAM) for nuclear power plant operators' communication, Journal of Loss Prevention in the Process Industries, 2011.

Letsky M., Warner N., Fiore S. M., Rosen M. A., Salas E., Macrocognition in Complex Team Problem Solving, 12th ICCRTS, June 2007.

Levi, Group dynamics for teams, 2nd edition, Sage publications, 2007.

Losada M., The complex dynamics of high performing teams, 1999.

Mao M., Peng C., Chen L., Multi-granularity object oriented software estimation model and tools, International conference on computer science and software engineering, 2008.

Marks M.A., Mathieu J.E., Zaccaro S.J., A temporally based framework and taxonomy of team processes, Acad. Manage, 2001.

McGrath J.E., Hollingshead A.B., Groups interacting with technology; ideas, evidence, issues, and agenda, Sage publications, 1994.

Mengzhuo Y., Jia G., Bingqun Z., Xiangrui H., Zupei S., Study of operator reliability in nuclear power plants, Chinese Science Bulletin, 1997.

Mosleh A., Chang Y.H.J, Model-based human reliability analysis: prospects and requirements, Reliability engineering & system Safety, 2004.

Mullen B., Copper C., The relation between group cohesiveness and performance: an integration, Psychological bulletin, 1994.

Mumaw R. j., Roth E.M, Vicente K.J, Burns C.M, There is more to monitoring a nuclear power plant than meets the eye, Human factors, 2000.

O’Hara J., Higgins J., Human factors engineering plan for reviewing nuclear plant modernization programs, Brookhaven national laboratory, Environmental and systems engineering division, 2004.

O'Connor P., O'Dea A., Flin R., Belton S., Identifying the team skills required by NPP operations personnel, Industrial ergonomics, 2008.

Orasanu J., Human and organizational risk management, DOD Human factors engineering technical advisory group meeting, 2003.

Paris C., Salas E., Cannon-Bowers J., Teamwork in multi-person systems: a review and analysis, Ergonomics, 2000.

Park J., The use of a social network analysis technique to investigate the characteristics of crew communications in nuclear power plants - A feasibility study, Reliability Eng. & System Safety, 2011.

Pascual R.G., Mills M.C., Henderson S.M., Supporting control room teamwork, People in Control: Human factors in control room design, London, U.K, IEE Press, 2001.

Passino K.M, Michel A.N., Antsaklis P.J., Lyapunov stability of a class of discrete event systems, Automatic control, IEEE Transactions, 1994.

Patrick J., Belton S., What's going on?, Nuclear engineering international, 2003.

Patrick J., James N., Ahmed A., and Halliday P., Observational assessment of situation awareness, team differences and training implications, Ergonomics, 2006.

Pattron B.R., Downs T.M., Decision making group interaction, achieving quality, 4th edition, Allyn & Bacon Inc., 2002.

Pattron B.R., Downs T.M., Decision making group interaction, achieving quality, 4th edition, Allyn & Bacon Inc., 2002.

Petkov G., Todorov V., Takov T., Petrov V., Stoychev K., Vladimirov V., and Chukov I., Safety investigation of team performance in accidents, Journal of hazardous material, 2004.

Pew R.W., Mavor A.S., Human system integration in the system development process, committee in human design support for changing technology, Natural research console of the national academies, 2007.

Pew R.W., Mavor A.S., Modeling human and organizational behavior: Applications to military simulations. Washington, DC, National academy press, 1998.

Rasker P., van Vliet T., van Den Broek H., Essens, P., Team effectiveness factors: A literature review. TNO Technical report No.: TM-01-B007, 2001.

Reason J., Managing the risks of organizational accidents, 1st edition, Ashgate Publishing Company, 1997.

Roth E., Mumaw R.J., Lewis P.M. , An empirical investigation of operator performance in cognitive demanding simulated emergencies. NUREG/CR-6208, Westinghouse science and technology center, Report prepared for Nuclear Regulatory Commission, 1994.

Rumbaugh J., Blaha M., Lorensen W., Eddy F., Premerlani W., Object-Oriented Modeling and Design, Prentice-Hall, UK, 1991.

Sasangohar F., Thornburg K., Cummings M. L., and D'Agostino A., Mapping complexity sources in NPP domains, Human factors and ergonomics society annual meeting, 2010.

Sasou K., Reason J., Team errors: Definition and taxonomy. Reliability engineering & system safety, 1999.

Sebok A., Team performance in process control: Influences of interface design and staffing levels, Ergonomics, 2000.

Shanahan P., Mapping team performance shaping factors, QinetiQ, Fort Halstead, 2001.

Shlaer S., Mellor S.J., Object lifecycles: modeling the world in states, Prentice-Hall, UK, 1992.

Smidts C., Mosleh A., The IDA cognitive model for the analysis of nuclear power plant operator response under accident conditions. Part I: problem solving and decision making model Reliability Engineering & System Safety, 1997.

Smith E., Borgvall J., Lif P., Team and collective performance measurement, technical report for Defence science and technology lab Bedfordshire, UK, 2007.

Stachowski A. A., Kaplan S. A., Waller M. J., The benefits of flexible team interaction during crisis, Applied psychology, 2009.

Strater O., Bubb H., Assessment of human reliability based on evaluation of plant experience: requirements and implementation, Reliability engineering and system safety, 1999.

Strater O., Group interaction in high risk environments, communication in NPP, GRS report, GRS: Cologne, 2002.

Sully P., Modeling the world with objects, Prentice-Hall, UK, 1993.

Takano K., Sunaoshi W., Suzuki K., Total simulation of operator team behavior in emergencies at nuclear power plants, Aviation, space and environmental medicine, 2000.

US Department of Commerce, Three Mile Island Special Inquiry Group, Human factors evaluation of control room design and operator performance at Three Mile Island-2, Final report NUREG/CR-1270-V-1, Washington, DC, 1980.

Vicente K. J., Roth E. M., Mumaw R. J., How do operators monitor a complex, dynamic work domain? The impact of control room technology, International journal of human-computer studies, 2001.

Vicente K.J., Mumaw R.J., Roth E.M., More about operator monitoring under normal operations: The role of workload regulation and the impact of control room technology, Human factors and ergonomics society annual meeting proceedings, Cognitive engineering and decision making, 1998.

Waern Y., Analysis of a generic dynamic situation, cooperative process management, cognition and information technology, Routledge, 1998.

Waller M., Gupta N., Giambatista R., Effects of adaptive behaviors and shared mental models on control crew performance, Management science, 2004.

Zhao F., Ou J., Du W., Simulation Modeling of Nuclear Steam Generator Water Level Process: A Case Study, ISA transactions, 2000.