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Cognitive Task Analysis Framework for Modeling Complex System

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ABSTRACT

This thesis reports a framework for modeling complex system using Cognitive Task Analysis (CTA). Complexity is largely caused by the human operators in the system. Assuming that human behavior is guided by limited goals, system complexity can be modeled by breaking down the decision-making process. This assumption works better for a constrained environment where tasks are structured and there is little room for personal preference.

The proposed framework was developed from a review of research performed by two schools of thoughts: an empirical approach as used in Naturalistic Decision Making (NDM); and a formative approach in Cognitive Work Analysis (CWA). There are similarities in the way CTA was performed. The review concluded that CTA can be conducted using a five-stage framework: (1) Bootstrapping, (2) Knowledge Acquisition, (3) Data Analysis, (4) Knowledge Representation, and (5) Knowledge Validation.

The review also revealed that NDM has developed into a strong method for knowledge acquisition while CWA has developed into a strong method for knowledge representation. The strengths of the two schools were combined in the derived CTA framework and applied in a study that modeled operator's fault diagnosis in petroleum refining.

In the process of developing and using these methods, there were difficulties in transforming the acquired knowledge to the desired representation. A new method, Applied Work Domain Analysis (AWDA), was devised to bridge the gap at the Data Analysis stage. The AWDA representations turned out to do more than crunching the data. It is a good tool for knowledge elicitation and has the potential to be developed into a decision-support and training system.

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LIST OF ACRONYMS

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ACRONYM	CONCEPT	METHOD	MODELS	REPRESENTATIONS
ACTA	Applied Cognitive Task Analysis	X		
ADH	Abstraction Decomposition Hierarchy			X
AH	Abstraction Hierarchy			X
ASM	Abnormal Situation Management			
AWDA	Applied Work Domain Analysis	X		
CDM	Critical Decision Method	X		
CDT	Cognitive Demands Table			X
COCOM	Contextual Control Model		X	
CTA	Cognitive Task Analysis	X		
CWA	Cognitive Work Analysis	X		
DURESS II	Dual Reservoir System Simulator			
JCS	Joint Cognitive System		X	
LRCCU	Long Run Catalytic Cracking Unit			
MES	Motivation-Expectation Space			X
NDM	Naturalistic Decision Making	X		
PFD	Process Fault Diagnosis			
SME	Subject-Matter Expert			
SQA	Systematic Question Asking	X		
SRK	Skill-, Rule-, Knowledge-based behavior		X	
WDA	Work Domain Analysis	X		

1. INTRODUCTION

1.1 BACKGROUND

A system is made up of many elements (Cilliers, 2004). From a social perspective, these elements can be the workers and the leaders; from a technical perspective, they can be the machineries and equipment (Vicente, 1999). When there are many elements, the system may become complex. This condition is necessary but not sufficient to label a system complex. To make it complex, the elements need to interact, and this interaction is often rich, non-linear, fairly short ranged and is recurrent (Cilliers, 2004). *Rich* means that the element must be influencing or be influenced by other elements. *Non-linear* refers to the situation where the outcome of the interaction between the elements is not proportional to the size of the interaction. A small change can have a large impact and vice versa. *Short-range* means that information to an element is received only from immediate neighbors, and each element is ignorant to the behavior of the whole system. *Recurrent* means that elements receive feedback through the interaction with other elements.

In addition to the interaction, there are three other characteristics of a complex system (Cilliers, 2004). First, the system is open. This means that the system interacts with its environment. A closed system is not a complex system, but a complicated system. Second, a system operates under conditions, which are far from equilibrium. There is a constant flow of activity which results in feedback to keep the system stable. Lastly, the system has a history that characterized its current behavior.

There is plenty of complexity around us. Eating an apple is no longer as simple as plucking the fruit from the tree and biting it. Apples are now collected by farmers, who send them to factories. The factories sort, label and pack the apples. A truck comes along and transports the apples to the airport. When the apples reach their destination, they are sent to the warehouse before being transferred to the supermarket. At the supermarket, they are tagged. The consumer goes to the supermarket, picks up the apple, and pays at the cashier. The journey of the apple has probably much more details than my quick description. This example illustrates that

complexity is ubiquitous and the complexity is beyond the ability of anyone to gain a complete understanding. Still, that should not stop you from buying your next apple.

To understand complexity, scientists have formulated models. Unfortunately, modeling complexity is, in itself, a paradox. In modeling, complexity is simplified by removing redundancy. But this is not mathematically possible for a complex system where the interactions are non-linear. In order to simplify, some information has to be lost. In this way, the model is distorted and not a true representation of the complexity.

Should this stop us from modeling complexity? Cilliers (2004) stated that:

"...it is impossible to have a perfect model of a complex system. This is not because of some inadequacy in our modeling techniques, but a result of the meaning of the notions "model" and "complex". There will always be a gap between the two. This gap should serve as a creative impulse that continually challenges us to transform our models, not as a reason to give up." (p. 25)

From an ergonomics perspective, system complexity is largely due to the dynamic thought processes of the human mind and the range of activities in the social system. The variability in the technical system is relatively insignificant. Automation can assume only a few states, and it is easy to map out its possible actions. However, with a human operator in the system, the possibilities increase tremendously. The human is more adaptive than the technical system. He can generate a range of solutions for the same problem. He can make errors that may or may not be predictable, and he can correct errors.

Fortunately, the complexity of the human mind is not random. The variations in human behavior and action are guided by a finite number of high-level goals, and the variability is often a result of the complexity in the environment. The complexity, as explained earlier, is caused by the interaction of the elements in the system and the characteristics of the system. Such goal-oriented behavior was described succinctly by Nobel laureate Herbert Simon in his parable of the ant on the beach (Simon, 1981): "The complex path of the ant as it traverses the sand is a reflection of the complexity of the environment and not the ant."

This led scientists to analyze cognition and goal-formulation rather than the varied behavior of the human. Scientists moved from performing Task Analysis to Cognitive Task Analysis (CTA). Woods & Hollnagel (1987) stated that CTA was used to derive a description of the cognitive demands imposed by a task. Roth (1989) employed CTA as an approach to Knowledge Acquisition. Klein (1995) identified CTA as the attempt to describe how experts were performing tasks, rather than what steps they were carrying out. Vicente (1995) utilized CTA to account for the variability in behaviors caused by differences in knowledge and cognitive strategies. Despite their differences in defining and performing CTA, their methodologies were developed with one primary interest: to account for the dynamics of human thought processes.

Within the CTA community, there were differing views on what CTA is, how it is conducted, and what it is used for. The differences and similarities between the methods and the practical benefits of conducting CTA were discussed at a Human Factors and Ergonomics Society symposium (Vicente, 1995). Roth & Mumaw (1995) differentiated CTA in three dimensions: empirical approach, formative approach and computer modeling. The empirical approach elicited expert's knowledge in a naturalistic environment to discover implicit knowledge and skills needed for performing the task (Klein, 1995). The formative approach structured both technological and organizational parameters to aid the user's cognitive demands (Vicente, 1995). Finally, computer modeling mimicked human problem-solving heuristics for analyzing familiar events (Frank, 1990; Yow, Walters, Plott, Laughery, & Persensky, 2005), as well as first-of-a-kind events (Lintern & Miller, 2003; Woods & Hollnagel, 1987) and hazardous systems (Cacciabue, 1997).

In this project, the empirical and formative approaches were compared. A review of the literature found that the steps in conducting the empirical and formative studies were similar though there were differences in focus. These steps were summarized in a five-stage framework and applied on modeling diagnostics tasks performed by petroleum refining operators.

1.2 OBJECTIVES

The objective of the project was to formulate a CTA framework for modeling complex system. This entailed three phases:

1. Compare current CTA techniques and their methodology.
2. Establish a CTA framework based on the existing CTA techniques. The author identified five phases for the framework.
3. Apply the framework on a complex system. The complex system is petroleum refining, which involves the interaction of many sub-processes to maximize the yield.

1.3 REPORT OUTLINE

This chapter introduces the difficulties in modeling complexity and argues that complexity is attributed by the variability in human behavior. The varied behavior is believed to be guided by a set of goals. Thus, complexity can be understood through the study of human cognition. Two complementing Cognitive Task Analysis (CTA) approaches were put together in a single framework. This report presents the derivation and application of the framework.

The chapters are divided into three sections.

Section I has three chapters that describe how the framework is derived. *Chapters 2 and 3* describe the literature of the two approaches: (1) Cognitive Work Analysis and (2) Naturalistic Decision Making. They introduce the basic concepts, previous applications, radical contributions of the approaches to CTA, and steps for conducting the CTA.

Chapter 4 explains the proposed framework for modeling complex system. The author tapped on the methodology from the two approaches and concluded that there are five stages for conducting CTA: (1) Bootstrapping, (2) Knowledge Acquisition, (3) Data Analysis, (4) Knowledge Representation, and (5) Knowledge Validation.

Section II shows how the framework can be applied. There are five chapters; one for each of the five stages. The objective of the case study was to model the fault diagnosis of operators as they troubleshoot problems in the petroleum refinery.

Chapter 5 introduces the background by analyzing the context, purpose, constraints and boundary, and suitability. A review of human factors and process control is also presented. **Chapter 6** describes where and how data was collected and the lessons learnt.

Chapter 7 demonstrates the data crunching process by using three intermediate representations. The *Cognitive Demands Table (CDT)* was used to organize and store the data collected before formulating the *Abstraction Decomposition Hierarchy (ADH)*. However, it was difficult to analyze because the formulation of the ADH involves many rules. To overcome the problem, the author devised the *Motivation Expectation Space (MES)* to translate the CDT to ADH. The ADH revealed three functions in operator's reasoning: (1) purpose, (2) cause, and (3) strategies.

Chapter 8 discusses the representation for each function. The ADH was a sufficient representation for the purpose function. The cause and strategies functions were elaborated by studying repeated themes. Five independent cause function themes were identified. The strategies function themes were placed in a Process Fault Diagnosis model.

Chapter 9 presents the validation study for the three functions. The validation study was conducted differently for the function. Only the validation for the strategies function was elaborated.

Section III consists of two chapters to conclude the study of CTA. **Chapter 10** presents the discussion and future research for the CTA framework. It also revisits AWDA and its representation, Motivation-Expectation Space (MES). AWDA was compared with the Work Domain Analysis while the value of MES was elaborated. **Chapter 11** concludes the report.

Section I – Formulation of the CTA Framework

2. REVIEW OF NATURALISTIC DECISION MAKING

The empirical approach elicits experts' knowledge in their naturalistic environment to discover implicit knowledge and skills needed for performing a task (Klein et al., 1989). It attempts to understand experts' thought processes as they perform their task in the actual work environment. The focus is on eliciting and articulating tacit knowledge including the nature of the tasks they undertake, the cues they look at, and understanding their experience (Orasanu & Connolly, 1993). This approach created a new class of decision-making theories referred to as Naturalistic Decision Making (NDM). NDM is used generically for the research efforts that take an empirical approach.

Before the development of NDM, decision making was studied in laboratories. These studies identified many selection strategies including: the maximization of expected value; addition of utilities; and elimination by aspect (Zsombok, Beach, & Klein, 1992). However, decision-makers do not spontaneously or naturally use these strategies (Rouse, 1983; Zsombok, Beach, & Klein, 1992). The studies were limited to simulations and were therefore not as varied and dynamic as studies in the natural settings (Diaper, 2002; Hollnagel & Woods, 2005). Though these strategies formed good theoretical bases for decision making at the micro level, they had no robust theories to aid decision-making at the macro level. These strategies are good for the computers, which are good at logics and computation. Humans have limited capacity to perform tedious calculations and do not generate as many options. As such, the decision-making found in the laboratory setting was different from that in an operational setting (Orasanu & Connolly, 1993).

The challenge in NDM is to understand work in its operational setting. It is difficult to predict the outcome of a study. The analyst should not be speculating about the outcome of the study. Instead, the analyst should be receptive to new ideas and assimilate into the environment. At the same time, the analyst has to be objective and clear about goals of the study, which will shape the analysis and reporting.

NDM had been studied in many research projects. These include studies of manual work including: ditch digging (Shalin & Verdille, 2003), and car cosmetic repair

(Tan, Seva, & Helander, 2006). NDM research also analyzed decision activities including: observations of air crew, incident reports, and accident investigation in aviation (Orasanu, 1995), protocol analysis in process operations (Bainbridge, 1974), decision analysis (Fischhoff, 1989), conceptual graph analysis in forest management (Gordon, 1995), and interviews in air traffic control tasks (Seamster, Redding, Cannon, Ryder, & Purcell, 1993).

2.1 NDM STRENGTH

Two important techniques derived from these NDM studies are the Critical Decision Method (CDM) (Klein, Calderwood, & MacGregor, 1989) and Applied Cognitive Task Analysis (ACTA) (Militello & Hutton, 1998). Both are retrospective interviewing techniques. Talking with experts was found to be an efficient way to understand work in its natural setting. Unlike observations and data logging, the analyst can guide the process. Past events are discussed and analyst can choose significant events that are relevant to meet the objectives of the study. These techniques are elaborated in the following sub-sections.

2.1.1 CRITICAL DECISION METHOD

Critical Decision Method (CDM) is a retrospective interview technique that is used to identify cognitive elements in expert's decision-making as they narrate actual non-routine tasks (Klein, Calderwood, & MacGregor, 1989). To explain how things work, people often tell stories. Instead of citing the underlying principles and causal relationship, the expert narrates a scenario of actions and explains the rationale of these actions (Carroll, Mack, Robertson, & Rosson, 1994). These stories are expressions of the operator's expertise.

CDM is a method with a strong theoretical basis. It has been repeatedly used to prove the Recognition-Primed Decision Making model (Hoffman, Crandall, & Shadbolt, 1998). The methodology was developed from Flanagan's Critical Incident Technique (CIT) (Flanagan, 1954; Klein, 1989). CIT describes a set of operations for observing human behavior systematically. The output can be used to solve practical problems

such as assessing lack of training and educational gaps (Twelker, 2003). CDM was greatly influenced by CIT. It was modified and improved from CIT.

Table 2-1 Critical Decision Method (Klein, Calderwood, & MacGregor, 1989)

<p>Sweep 1: Incident identification and selection</p> <p>Ask: Can you think of a time when you were (type of incident) and your skills were really challenged? Tell me about the last time you....</p> <p>Can you think of a time when your skills really made a difference - maybe things would have gone differently if you weren't them?</p> <p>Listen for: An incident that fits your study goals, and where your participant played a key role</p> <p>Sweep 2: Timeline verification and decision point identification</p> <p>Ask: Will you give me a quick run through of the Incident?</p> <p>Listen for: Decision points, shifts in situation assessment, places to probe, gaps in the story, gaps in the timeline, conceptual leaps, violated expectancies, errors, ambiguous cues, Individual differences</p> <p>Flags: I just knew... it felt right ... I guessed...It was just a gut feeling... Something felt wrong.... I've seen it before... It depends...</p> <p>Sweep 3: Progressive Deepening</p> <p>Ask: About Situation Assessment, Cues, Goals</p> <p>Listen for: Critical decisions, cues and their implications, ambiguous cues, strategies, violated expectancies</p> <p>Sweep 4: What if queries, expert-novice differences, errors</p> <p>Ask: Did you consider other alternatives? Might someone else in the same position have done it differently? Could you have reasonably taken any other action? Would you have made the same decision at an earlier point in your career? Would this Incident have turned out differently if you or someone with your level of skill experience had not been there?</p> <p>Listen for: Other possible courses of action, other potential interpretations, expert-novice differences, potential errors.</p>
--

The CDM comprises of a series of probes for eliciting cognitive elements considered by Subject Matter Expert (SME), see Table 2-1. CDM elicits knowledge in four “sweeps” (Crandall, Klein, & Hoffman, 2006). In Sweep 1, the SME selects a challenging incident that had happened recently. He describes the chronological sequence of the incident in Sweep 2 and progressively deepens the story in Sweep 3. Finally, the SME discusses the expert-novice difference in Sweep 4.

CDM is semi-structured and the investigator can therefore side-track during the questioning. The elicitor must be clear of the goals of the study to keep him on track (Klein, Calderwood, & MacGregor, 1989). In addition, the elicitor can consider asking the questions systematically.

Systematic Question Asking (SQA) is a method for focusing on each of the statements that an informant makes about the problem domain (Carroll, Mack, Robertson, & Rosson, 1994). The elicitor focuses on each event systematically and uses the events as “entry points” in probing the cognitive aspects in the incident, see Figure 2-1.

Figure 2-1 Steps in the Systematic Question Asking method for knowledge acquisition in CDM

In deepening the story, the analyst can make use of the additional probes in Table 2-2 (Crandall, Klein, & Hoffman, 2006). The analyst can listen for points where decisions have been made and probe the expert using the questions listed along the 11 probe types. As an example, an analyst can ask about other courses of actions

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which had been considered or available to the SME. As the SME explains his rationale of selection, the elicitor can note down the cues and strategies used by SME.

**Table 2-2 Critical Decision Method (CDM) interview probes
(Crandall, Klein, & Hoffman, 2006)**

PROBE TYPE	PROBE CONTENT
Cues	What were you seeing, hearing, smelling....?
Knowledge	What information did you use in making this decision, and how was it obtained?
Analogues	Were you reminded of any previous experience?
Standard Operating Procedures	Does this case fit a standard or typical scenario? Does it fit a scenario you were trained to deal with?
Goals	What were your specified goals and objectives at the time?
Options	What other courses of actions were considered by or available to you?
Basis	How were this option selected/other options rejected? Was there a rule that was being followed?
Experience	What specified training or experience was necessary or helpful in making this decision? What training, knowledge, or information might have helped?
Decision Making	How much time pressure was involved in making this decision? How long did it take actually to make this decision?
Aiding	If the decision was not the best, what training, knowledge, or information could have helped?
Situation Assessment	Imagine that you were asked to described the situation to someone else at this point, how would you summarized the situation?
Errors	What mistakes are likely at this point? Did you acknowledge if your situation assessment or option selection were incorrect? How might a novice have behaved differently?
Hypothetical	If a key feature of the situation had been different, what difference would it have made in your decision

What-if scenarios and expert-novice differences can provide a holistic overview and a basis for assessment of the work scenario for the SME. The SME can reflect and share the significance of the knowledge he has acquired over the years. It is a characteristic of expert to notice relevant and subtle features (Bransford, Franks, Vye,

& Sherwood, 1989). However, these inherent features will not come to the mind of the SME unless there are alternatives to compare with. Bransford et al. (1989) asked subjects to identify features that led to the success of a “general and a fortress” story. Subjects were unable to correctly identify the cause of a victory until a contrasting story was told. Similarly, when experts are asked about the incapability of a novice, they compare the knowledge that they have acquired over the years with that of a novice. This highlights their expertise and makes it easy for them to verbalize the knowledge. They can also compare their knowledge to their knowledge in the past, as well as the current knowledge of their colleagues.

A point to note is that story tellers are good at summarizing, whilst story understanders are good at reverse-engineering stories to create complex details of the actual event (Carroll, Mack, Robertson, & Rosson, 1994). The data collected from such studies is subjective and may therefore have to be validated. Subjective interpretation of the data is inevitable. Though it is almost impossible to gather perfect and complete data, Hoffman (1998) argued that CDM is reliable (test, retest, and intercoder reliability with $p > 0.8$), adaptable, efficient, possesses sound quality (validity of verbal report, reasoning bias, content validity, differential access), and is helpful in decision aiding, and formulating satisficing decisions.

Before one decides to conduct a CDM, one should consider the timeframe for the study, the cost-effectiveness of conducting the CDM, the packaging of the results, and the level of training of the analysts (Klein, Calderwood, & MacGregor, 1989).

CDM has been used in a wide range of domains including understanding the work of: intelligence analysis (Hutchins, Pirolli, & Card, 2004), white water rafting guides (O'Hare, Wiggins, Williams, & Wong, 1998), air traffic controllers (Seamster, Redding, Cannon, Ryder, & Purcell, 1993), fireground commanders (Klein, 1998), tank platoon leaders (Klein, Calderwood, & MacGregor, 1989), design engineers (Crandall, Klein, & Hoffman, 2006), neonatal sepsis (Hoffman, Crandall, & Shadbolt, 1998), and ambulance dispatch management (Wong & Blandford, 2001).

2.1.2 APPLIED COGNITIVE TASK ANALYSIS

Applied Cognitive Task Analysis (ACTA) is a three-staged interviewing technique (Militello & Hutton, 1998). The first stage is the Task Diagram interview. SMEs are asked for a broad overview of their daily task. This is analogous to the timeline identification in CDM. It serves as a roadmap to identify cognitively complex elements of the job. The second stage is a Knowledge Audit. It is an interview to extract details and examples of expert's knowledge. In the third stage, Simulation Interview, the analyst uses a challenging simulation where the SME narrates his cognitive processes within the context of the simulation.

Instead of focusing on just one incident, ACTA covers eight aspects in cognition: past and future, big picture, noticing, job smarts, opportunities/improvising, self-monitoring, abnormalities, equipment difficulties, see Table 2-3. These questions survey a broad spectrum of cognitive activities. Instead of one story, SMEs share an incident for each area. Like CDM, cues, strategies and expert-novice differences are the primary concern. However, the coverage of each story is less in-depth than a CDM.

The advantage of the technique is that the questions are phrased in layman's terms. Expertise is tacit and difficult to verbalize explicitly (Polanyi, 1983). Experts are very skilled and develop automatic responses in their work, and thus, are unable to express and share their experiences (Rasmussen, 1983). They have the skills to resolve situations, but it is difficult to express tacit skills in words. The ACTA probes are able to elicit tacit expertise as the questions are easy to understand and will probe individuals to conceptualize answers in an interview.

**Table 2-3 Applied Cognitive Task Analysis - Knowledge Audit
(Militello & Hutton, 1998)**

<p>Past and Future</p> <p>Is there a time when you walked into the middle of a situation and knew exactly how things got there and where they were headed?</p> <p>Big Picture</p> <p>Can you give me an example of what is important about the Big Picture for this task? What are the major elements you have to know and keep track of?</p> <p>Noticing</p> <p>Have you had experiences where part of a situation just “popped” out at you; where you noticed things going on that others didn’t catch? What is an example?</p> <p>Job Smart</p> <p>When you do this task are there ways of working smart, or accomplishing more with less, that you have found especially useful?</p> <p>Opportunities/Improvising</p> <p>What are some examples when you have improvised in this task, or noticed an opportunity to do something more quickly or better, and followed up on it?</p> <p>Self-Monitoring</p> <p>Can you think of a time when you realized that you would need to change the way you were performing the job in order to get the job done?</p> <p>Anomalies</p> <p>Can you describe an instance when you spotted a deviation from the norm, or knew something was amiss?</p> <p>Equipment Difficulties</p> <p>Have there been times when the equipment pointed in one direction, but your own judgment told you to do something else? Or when you had to rely on experience to avoid being led astray by the equipment?</p>
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The strength of the NDM approach lies in its interviewing techniques. These techniques have been applied in various contexts. Interviewing is one of the many activities when conducting a NDM study. The next section details the NDM method.

2.2 NDM METHODOLOGY

Typically, there are four main steps in performing NDM research: Bootstrapping, Knowledge Acquisition, Data Analysis and Knowledge Representation (Crandall, Klein, & Hoffman, 2006), see Table 2-4.

Table 2-4 Review of Cognitive Task Analysis (CTA) methodology in Naturalistic Decision Making (NDM) (Crandall, Klein, & Hoffman, 2006)

CTA FRAMEWORK	NATURALISTIC DECISION MAKING
Bootstrapping	What issues do you plan to address? What aspects of expertise or types of cognition do you need to know about? Who do you talk to? What are the most informative types of situations? What will you deliver?
Knowledge Acquisition	Critical Decision Method Applied Cognitive Task Analysis Concept Mapping Observation Self-Report Automated Capture
Data Analysis	Structured Approach Emergent Theme Approach (Wong, 2004)
Knowledge Representation	Narratives Graphics Flow diagram Relationship diagram Illustration Code Syntax Cognitive Demands Table

BOOTSTRAPPING

Bootstrapping is a preparatory stage at the start of the study. It is done to identify the purpose of the CTA and consider how the CTA results will be used before conducting it. The following points can be considered (Crandall, Klein, & Hoffman, 2006):

- What issues do you plan to address?
- What aspects of expertise or types of cognition do you need to know about?
- Who do you talk to?
- What are the most informative types of situations?
- What will you deliver?

Analyst can start by understanding the context. This is easier if the analyst is already familiar with the context. However, such is often not the case. The analyst needs to identify what the context entails and gain familiarity with the technical terms or colloquialisms used in the domain. This can be done by reading training manuals, procedures, reference books, and performing web search of the technical terms in the proposal.

KNOWLEDGE ACQUISITION

As mentioned, NDM has developed many knowledge acquisition techniques. Common useful techniques include: Critical Decision Method (Klein, Calderwood, & MacGregor, 1989), Applied Cognitive Task Analysis (Militello & Hutton, 1998), Concept Mapping, Observation, Self-Report, and Automated Capture (Crandall, Klein, & Hoffman, 2006). These techniques require the elicitor to interact with the Subject Matter Expert (SME). The elicitor has to convince the SME to participate in the study. The SME may be required to log his daily activities, be interviewed, and/or observed. Some SME may feel that their privacy has been intruded.

Recurring themes emerge as patterns, and they can be used to structure and reduce the data. These patterns provide the structure to guide the next round of coding. This is repeated until the analyst is satisfied that results are converging with a reasonable structure. The final representation structure is supported and explained with data in the transcript.

FIG. 16.6. Overview of the emergent themes approach.

Figure 2-3 Critical Decision Method Data Analysis - Emergent Approach (Wong, 2004)

KNOWLEDGE REPRESENTATION

Knowledge representation is needed to communicate findings. Being explorative, NDM does not define the representation. The analyst can decide on a representation that best suits her findings. It can be in the form of narratives, graphics, flow diagrams, relationship diagrams, illustrations, code syntax, and tables (Crandall, Klein, & Hoffman, 2006).

The most primitive of these representations is the Cognitive Demands Table (CDT). The analyst chooses appropriate aspects and logs the interview notes in a tabular form. To ensure that all necessary data has been asked and recorded, this is best done after data collection. The distinction between CDT and other tables is that the first column records sections of stories. The section ends with a decision point where important decisions are made. In the other columns, the analyst records supplementary information such as cues that explain the decision, the difficulty in reaching this decision, and prior experience. In this way, the study remains explorative, yet focused. At the end of the study, the analyst has an information rich table.

3. REVIEW OF COGNITIVE WORK ANALYSIS

The formative approach attempts to identify the technological and organizational requirements that need to be satisfied, so that the technology can support the user's cognitive demands (Rasmussen, 1986; Vicente, 1999). This approach is commonly referred to as Cognitive Work Analysis (CWA). It is a framework for studying human work based on concepts of behavior-shaping constraints (Vicente, 1999).

CWA identifies technological and organizational requirements for supporting unanticipated variability using a single integrated framework. There are five concepts: (1) Work Domain, (2) Control Tasks, (3) Strategies, (4) Social-Organizational and Cooperation, and (5) Worker Competencies. The five concepts are ordered so that there is a gradual transition from ecological to cognitive considerations (Vicente, 1999). These considerations include behavior-shaping constraints which are defined from the tasks, the environment in which tasks are carried out, as well as the attributes of the people who do the task.

Figure 3-1 Transition of consideration from Ecological to Cognitive in the five concepts of CWA (Vicente, 1999). Work Domain Analysis is at the ecological end and Worker Competencies at the cognitive end. The degree of freedom decreases from the Work Domain Analysis to the Worker Competencies. The tapering in the figure reflects the reduction in the degrees of freedom with each concept.

The Work Domain Analysis generates a map that shows all the actions that are possible in a system (Vicente, 1999). With the map, a Control Task Analysis selects specific events from the domain to identify requirements for supporting expert's behavior. A Strategies Analysis identifies the various possible ways of performing activities identified in the Control Task Analysis. The Social-Organizational and

Cooperation analysis is concerned with how people and automation can be organized and governed to facilitate communication, cooperation, and ultimately improve system performance. This last stage of the CWA, Worker Competencies Analysis summarizes the requirements derived from the first five stages to design a coherent system that complement human capabilities and limitations. There is no strict rule that all the concepts have to be applied for a particular problem; a researcher can select only the concepts which are appropriate for his study.

CWA, like NDM, has been used in many studies to understand complex system. This includes the petrochemical industry (Burns, Garrison, & Dinadis, 2003), virtual private network (Kuo & Burns, 2000), design of product accounting equipment for retail chain shop (Rasmussen, 1990), hydro scheme control (Sanderson, Wong, Choudhury, & Memisevic, 2003), Navy Surface Combatant (Bisantz et al., 2003), and bookhouse design (Pejtersen & Rasmussen, 1997). Most of these studies utilized the first method, i.e. Work Domain Analysis (WDA).

3.1 CWA STRENGTH

The strongest feature of CWA lies in its modeling tools. Table 3-1 presents the tools and the design interventions that can be utilized in the analysis of each concept. Here, the three prominent tools are briefly discussed: Abstraction-Decomposition Hierarchy, Ladder Diagram and Skill-, Rule- And Knowledge-Based Taxonomy.

Table 3-1 Cognitive Work Analysis Framework (Vicente, 1999)

CONCEPTS	MODELING TOOLS
Work Domain	Abstraction-Decomposition
Control Tasks	Decision Ladder
Strategies	Information Flow Map
Social-Organizational	All of the above
Worker Competencies	Skills, Rules, Knowledge

3.1.1 ABSTRACTION DECOMPOSITION HIERARCHY

The Abstraction-Decomposition Hierarchy breaks the work domain into small, manageable parts and relates the system to its sub-system in two dimensions: decomposition and functional. The Decomposition Hierarchy, on the horizontal dimension, represents the structural physical relationship. The Abstraction Hierarchy, on the vertical dimension, represents the means-end functional relationship. Figure 3-2 shows an example of an Abstraction-Decomposition Hierarchy at a coarse level of detailing used in a Dual Reservoir System Simulation, DURESS II (Bisantz & Vicente, 1994).

Figure 3-2 DURESS II Abstraction-Decomposition Hierarchy (ADH) (Bisantz & Vicente, 1994). Vertically, components are arranged based on their functional qualities. Horizontally, components are arranged based on their physical terminology.

3.1.2 LADDER DIAGRAM

The ladder diagram maps cognitive activities and the knowledge states of the operators using a ladder, see Figure 3-3. Novices need to traverse the ladder from Detect to Evaluate. Experts, on the other hand, know about the system. They have learnt to take shortcuts and need not evaluate the top goals.

Figure 3-3 Decision ladder diagram (Rasmussen, Pejtersen, & Goodstein, 1994) shows the decision-making process. Shortcuts are often taken when a novice becomes an expert.

3.1.3 SKILL-, RULE-, KNOWLEDGE-BASED TAXONOMY

The ladder diagram was generalized into a skill-, rule- and knowledge-based (SRK) taxonomy (Rasmussen, 1983). The SRK model organizes the decision-making process in a form that facilitates system designs, see Figure 3-4. There is a distinction between three levels of human performance: skill-based behavior, rule-based behavior, and knowledge-based behavior. This allows the differentiation of the skills needed and thus, tasks can be modeled based on the different skill set.

Figure 3-4 Skill-Based, Rule-Based, Knowledge-Based Behavior (Rasmussen, 1983)

3.2 CWA METHODOLOGY

CWA has a strong theoretical foundation, but there is relatively little literature on how CWA can be carried out. The most comprehensible review was written by Naikar, Hopcroft, & Moylan (2005). This is based on CWA's Work Domain Analysis (WDA). As a result, the framework can only be based on the WDA stage, and the other stages are assumed to follow after a WDA. Nine steps were identified and they are mapped against the proposed CTA framework in Table 3-2.

Table 3-2 Review of Cognitive Task Analysis (CTA) method in Work Domain Analysis (WDA) (Naikar, Hopcroft, & Moylan, 2005)

CTA FRAMEWORK	WORK DOMAIN ANALYSIS
Bootstrapping	1. Establish the purpose 2. Identify the project constraints 3. Determine the boundaries of the Work Domain Analysis 4. Identify the nature of constraints
Knowledge Acquisition	5. Identify the potential sources of information
Knowledge Representation	6. Construct preliminary Abstraction-Decomposition Hierarchy 7. Construct Abstraction-Decomposition Hierarchy – 2nd iteration 8. Construct Abstraction-Decomposition Hierarchy – 3rd iteration
Knowledge Validation	9. Validate the Abstraction-Decomposition Hierarchy

BOOTSTRAPPING

The first four stages are classified under bootstrapping. They include identifying the purpose, constraints, boundaries, nature of constraints, and source of information.

First, it is necessary to set a clear purpose and explain how the purpose can be achieved, so that one does not waste effort unnecessarily (Naikar, Hopcroft, & Moylan, 2005). This is especially true for a complex context, where there are many

parameters and possibilities of representing them. As such, the Abstraction Decomposition Hierarchy can be represented in many forms. A clear objective can help to clarify the knowledge acquisition and knowledge representation. It will also guide the subsequent steps and decisions in conducting the CTA.

After stating the purpose, the next step is to identify the constraints. There are two major project constraints. First, there are constraints related to the resources available for performing the CTA. A CTA study is resource intensive and analyst should assess the use of CTA over other methods. Second, there are constraints within the system for the study. An example is when the management of the system has inadequate resources for change. Hence, applications derived from the CTA study might have to be incremental rather revolutionary. In this case, the purpose needs to be altered to fit the constraints. Both constraints are concerned with available resources and scheduling.

It was mentioned in Chapter 1 that complex systems are open system. The third step is to determine the boundary of the Work Domain Analysis. It is necessary to frame the system so that elements in the Abstraction Decomposition Hierarchy (ADH) address the needs of the study, see Section 3.1.1. This is despite the fact that the model will be distorted as compared to the actual system. The discarded elements may be related to the elements in the system. Nevertheless, it is necessary to frame and model the work domain to gain an understanding of the complexity. One common way is to frame the work domain such that elements within the work domain have stronger interaction compared to their interaction with the elements outside the work domain, which are weaker and less important.

Finally, the analyst should analyze if the ADH will be an appropriate representation. This can be checked by identifying where the work-domain lies in the causal-intentional continuum (Rasmussen, Pejtersen, & Goodstein, 1994). ADH is suitable only if the work domain falls on the causal end of the continuum. A work domain at the causal end is more regulated than a work domain at the intentional end. It is hence tightly coupled, highly structured and constrained by its technical equipment. If the work domain is at the causal end, the human operator serves the system and

works towards the system goal. Activities happen as designed and there is little room for creativity in the work domain.

At the intentional end, humans can be creative in carrying out the activities. Users have their preference and personal goals. There are fewer constraints, and the work domain supports the goals of the users. A work system at the intentional end is more flexible, and it will be difficult to represent the work domain using the Abstract Decomposition Hierarchy. The analyst should look for other representations.

KNOWLEDGE ACQUISITION

In Knowledge Acquisition, the analyst should look for the most efficient situations for uncovering suitable data. These can be derived by concentrating on specific tasks or expert areas (Crandall, Klein, & Hoffman, 2006). There are three sources of data: documents, observations and interview.

The analyst should be familiar with existing documents. Relevant documents may be found in similar research areas. It can also be on-site documents such as engineering and technical manuals, company reports, commercial brochures, operating procedures, policy documents, training manuals, accident and incident reports, site maps, architectural drawings, concept papers, feasibility studies, and system requirements and specifications.

The analyst can also observe meetings and training sessions. However, it may be difficult for the analyst to catch up with the discussion. Another way is to observe the expert working at his workstation, and ask questions at appropriate times.

The last method is to interview the operators and/or conduct walkthroughs, talkthroughs, or tabletop analysis. This is a more effective than observations because the analyst can ask the interviewee questions about the job, as well as his thought process.

KNOWLEDGE REPRESENTATION

The Abstraction Decomposition Hierarchy is the representation for a Work Domain Analysis, see Table 3-1. It generates field descriptors that are necessary to describe a system. This description is independent of the actors, events, tasks, goals and interfaces (Hajdukiewicz & Vicente, 2004; Vicente, 1999). With a comprehensive representation of the system, multiple relations can be analyzed, and a user can get a quick overview of the system. This can help the analyst to identify the intrinsic properties of the work (Eggleston, 2003), decide what to display to the operators and how displays can be improved (Reising & Sanderson, 2002). It is also a helpful tool to identify scenarios for simulating new systems (Lintern & Miller, 2003), set criteria for selecting designs (Naikar & Sanderson, 2001), and for design of training systems (Naikar, Sanderson, & Lintern, 1999).

The reason is that the hierarchy breaks the work domain into small, manageable parts and relates the system to its sub-system in two dimensions: structural and functional, see Figure 3-2. The Decomposition Hierarchy (horizontal) represents the structural physical relationship, while the Abstraction Hierarchy (AH) represents the means-end functional relationship.

Figure 3-5 shows the details of a Decomposition Hierarchy in the same Abstraction-Decomposition Hierarchy. Individual components in the system form the reservoir, which is a sub-system of the DURESS II system. As illustrated, flow A1 and B1 are the components of Heat and Water Input 1. Similar relations between other sub-systems and its components can be drawn. This part-whole hierarchy decomposes the system physically along the horizontal axis. The fine details of individual components are located on the right end, and the coarse description on the left. Using a forest metaphor, moving to the left is analogous to the seeing the big picture – the forest, but moving to the right zooms in at the details – the trees.

Figure 3-6 shows how an abstraction hierarchy can be derived for DURESS II. Following the topographical link up, the goal of “Mass Source 1” is to “Supply Demand 1”. Moving down, “Mass Source 1” can be achieved with “Heat and Water

Input 1". The AH belongs to a class of stratified hierarchy with the following properties (Mesarovic, Macko, & Takahara, 1970):

- Each stratum discusses the same system but with a different interest.
- Each stratum has its unique set of terms, concepts, and principles. The most commonly used levels are functional purpose, abstract function, generalized function, physical function, and physical form. Functional purpose describes the overall system goals. Abstract function refers to physical laws that bound the system. Generalized function corresponds to the everyday working functions. Physical function describes the state of the components. Lastly, physical form describes the appearance, condition, location, and anatomical configurations.
- The design of the stratum depends on the knowledge and interest of the analyst. Hence, a designer may or may not choose all the five levels. He may also select a different set from the abstraction hierarchy.
- The higher levels in the stratum set constraints for the lower level, whilst changes in the lower level affect the higher levels.
- Understanding of the system increases by traversing levels. By moving up in the hierarchy, a person can understand the goals that determine the design of the system.

The AH enables diagnosis to be performed both top-down and bottom-up. Relationships between nodes are easily comprehended with a why-what-how mental model. Traversing up the ladder, the user can understand the goal or "why" of the "what". Traversing down the ladder, user knows "how" to resolve "what". The functions to solve the problem can then be uncovered through the link.

COGNITIVE TASK ANALYSIS FRAMEWORK FOR MODELING COMPLEX SYSTEM
REVIEW OF COGNITIVE WORK ANALYSIS

Figure 3-5 Part-whole links in DURESS II Abstraction Hierarchy (Bisantz & Vicente, 1994) related the physical aspects of the system.

COGNITIVE TASK ANALYSIS FRAMEWORK FOR MODELING COMPLEX SYSTEM
REVIEW OF COGNITIVE WORK ANALYSIS

Figure 3-6 Portion of means-ends links in DURESS II Abstraction Hierarchy (Bisantz & Vicente, 1994) relates the functional aspects of the system.

KNOWLEDGE VALIDATION

For knowledge validation, the analyst can refer to scenarios that test the operator’s reasoning skills (Burns & Hajdukiewicz, 2004; Naikar, Hopcroft, & Moylan, 2005). Useful scenarios include records of past incidents, training materials, walkthrough tasks.

The objective is to explore if the links in the Abstraction Decomposition Hierarchy can support the operator’s reasoning in the work domain. The analyst can construct the reasoning space of the operators. There are alternative methods such as studying multiple operators’ reasoning for the same scenario or engaging single operator in different scenarios.

4. FRAMEWORK DERIVATION

The review revealed that there are similarities and differences in the two approaches. The stages employed in both the Naturalistic Decision Making (NDM) and Cognitive Work Analysis (CWA) are compared in Table 4-1.

Table 4-1 Similarities between the Cognitive Task Analysis (CTA) methods: Naturalistic Decision Making (NDM) and Cognitive Work Analysis (CWA).

CTA FRAMEWORK		NATURALISTIC DECISION MAKING	COGNITIVE WORK ANALYSIS
1	Bootstrapping	What issues do you plan to address? What aspects of expertise or types of cognition do you need to know about? Who do you talk to? What are the most informative types of situations? What will you deliver?	Establish the purpose Identify the project constraints Determine the boundaries of the WDA Identify the nature of constraints Identify the potential sources of information
2	Knowledge Acquisition	Critical Decision Method Applied Cognitive Task Analysis Concept Mapping Observation Self-Report Automated Capture	Interview Observation Document Walkthrough/Talkthrough Table Top Analysis
3	Data Analysis	Structured Approach Emergent Theme Approach	
4	Knowledge Representation	Narratives Graphics Flow diagram Relationship diagram Illustration Code Syntax Cognitive Demands Table	Abstraction-Decomposition Hierarchy Ladder Diagram Skill-, Rule-, Knowledge- based taxonomy
5	Knowledge Validation		Validate the Abstraction-Decomposition Hierarchy

Both approaches undertake the research process of Bootstrapping, Knowledge Acquisition, and Knowledge Representation. Data analysis in Cognitive Work Analysis is not explicit although defining the properties of each level in the hierarchy can be considered a form of data structuring. Similarly, there is limited literature on knowledge validation for Naturalistic Decision Making. Nevertheless, these five

stages: (1) Bootstrapping, (2) Knowledge Acquisition, (3) Data Analysis, (4) Knowledge Representation, and (5) Knowledge Validation can guide the CTA process based on these two approaches. The author proposes that the five stages can define the framework for conducting CTA. Analysts employing CTA should choose and/or devise methods along these five stages to completely model their system.

Bootstrapping is done similarly in both approaches. Both models describe the need to establish a purpose for the study and gather literature through reading manual, procedure, etc.

For the remaining four steps, there are slight differences. NDM is more structured in the Knowledge Acquisition stage, while CWA is more structured in Knowledge Representation. In Knowledge Acquisition, NDM has developed strong interviewing methods including the Critical Decision Method and the Applied Cognitive Task Analysis. CWA only explores a range of general techniques, such as interviews and observation.

In Knowledge Representation, CWA has established useful representations such as the Abstraction-Decomposition Hierarchy, the Ladder Diagram, and the Skill-, Rule-, Knowledge-based taxonomy. However, the representations in NDM, such as narratives, were adopted from other research area.

The differences between the methods are due to the opposing direction in the approaches taken by each school, see Figure 4-1. Cognitive Work Analysis (CWA) takes a formative top-down approach while Naturalistic Decision Making (NDM) uses an exploratory bottom-up approach. The CWA approach arranges information in a systematic fashion to aid the design process. On the other hand, the NDM approach tries to understand the mechanics of existing complex system and use the findings to redesign. The differences result in better acquisition techniques for NDM and stronger representations for CWA.

Figure 4-1 Opposing research direction of CWA and NDM. In CWA, knowledge is structured before approaching the user. For NDM, the theoretical structure is built from the interview.

Although NDM and CWA approach problem definition and problem solving from two opposing directions, there are several commonalities. This is illustrated in the Venn Diagram, which classifies the knowledge gathered from CWA and NDM, see Figure 4-2. Three pieces of knowledge acquired in NDM (goals, expert-novice differences, and strategies) can be useful data for the CWA representations (Work Domain Analysis, Control Task Analysis, and Strategies Analysis).

Figure 4-2 Venn diagram depicting the knowledge gathered from Naturalistic Decision Making and Cognitive Work Analysis.

The synergy between NDM and CWA can be demonstrated with an example of a NDM study in ambulance coordination (Wong & Blandford, 2001). In the study, decision criteria for ambulance dispatch were developed to support five goal states, namely: (1) notification of emergencies, (2) maintaining situation awareness, (3) planning resource-to-task compatibility, (4) speedy response, and (5) maintaining history of development. These goals were not independent and a Work Domain

Analysis can be used to relate the goals. For example, to achieve a “speedy response” (ends), one may send a “notification of emergencies” (means).

To summarize, CWA representation provides a better way of representing data as compared to NDM. However, this is only true for the Work Domain Analysis and Control Task Analysis. Strategies Analysis is different; the versatility of NDM in representing data seems to work better for a Strategies Analysis. CWA is generally weak in analyzing strategies (Burns, Kuo, & Ng, 2003; Vicente, 1999) and few (e.g. Riera, 2001). On the other hand, strategies can be derived and employed more effectively from NDM studies. One example is the study of the work of intelligence analysts (Hutchins, Pirolli, & Card, 2004), see Figure 4-3. A neat description and schema of how the analyst worked and divided the work into several parts including data mining, data correlation and human judgment was presented graphically. Critical Decision Method representations were able to provide a context for the strategies undertaken by the intelligence analyst, which made them more comprehensible.

COGNITIVE TASK ANALYSIS FRAMEWORK FOR MODELING COMPLEX SYSTEM
FRAMEWORK DERIVATION

Figure 4-3 Mental Model of an intelligence analyst and the strategies he took to accomplish his task (Hutchins, Pirolli, & Card, 2004).

Section II – Exemplification of the CTA Framework

This section presents a study using the proposed framework. The objective is to demonstrate the use of the framework that is derived from in the earlier section. As mentioned, application of CTA requires several methods at the different stages. Table 4-2 is a summary of the methods used in the study.

Table 4-2 Methods adopted for this thesis for each of the five stage in the CTA framework.

FRAMEWORK		WHAT IS COVERED
1	Bootstrapping	Context, Purpose, Constraints, Boundary, Suitability, Literature
2	Knowledge Acquisition	Observation, Documents, Interviews: Critical Decision Method, Applied Cognitive Task Analysis
3	Data Analysis	Cognitive Demands Table, Applied Work Domain Analysis
4	Knowledge Representation	Purpose Function: Abstraction-Decomposition Hierarchy Cause Function Strategies Function: Process Fault Diagnosis Model
5	Knowledge Validation	Purpose Function: Expert Review Cause Function: Card Sorting Strategies Function: Simulation Interview

First, bootstrapping was performed to understand the context, purpose, constraints and boundary of the study, as well as the suitability of the Abstraction-Decomposition Hierarchy (ADH). Researches and findings from a review of literature were also documented. Next, the observations made in plant visits, documents reviewed, and interviews conducted are described.

In data analysis, a Cognitive Demands Table organizes the data before composing the ADH. However, the abstract rules for ADH hindered the analysis. The author devised a new method, called the Applied Work Domain Analysis as a solution to transform data collected from the Knowledge Acquisition stage into an ADH (Tan & Helander, 2006).

The ADH consists of three functions: purpose, cause, and strategies. The purpose function was validated by asking experts. The cause function was validated using data from a study of experts sorting cards with descriptions of malfunctions. The strategies function was expanded in the Process Fault Diagnosis model and validated with a Simulation Interview.

5. BOOTSTRAPPING

5.1 CONTEXT

Proper handling of materials in a petroleum refinery is of concern for managing efficiency and safety. Occasionally, there are severe disturbances that require a plant to shut down. Such instances can result in economic and reputation loss for the company. As the chemicals are highly explosive, the consequences of mishandling are undesirable and may lead to disasters resulting in loss of human lives such as the disaster in Bhopal and the recent explosion at a BP refinery in Texas.

Over the past twenty years, automation has driven changes in the process industry. Sensing technology and control logics have changed the operator's tasks. Processing plants are now highly dynamic with multiple technologies working concurrently. In order to run the plant safely, rules and standard operating procedures have been designed to guide the operation. Rules and working patterns constantly change, and these changes are brought about by people, machines and technology. This dynamism creates rooms for errors. Hence, there is a need to constantly monitor trends and patterns in the plants to deter accident and improve efficiency.

Figure 5-1 Changes in the physical layout of the control room. Left: in the 1970s, the displays and controls span across a wide area. Right: Presently, the controls and displays are centrally located on LCD displays. This brings about both benefits and disadvantages.

The control room is the heart of the operations. Decisions, concerning the process flow, are made by operators in the control room. These decisions can either help to optimize the process, but they might also result in accidents.

In this computer era, humans are no longer the sole players in operating the processing plants. Designers utilize the speed and reliability of computers to try to improve the efficiency of the process. For speedy identification, sensors are often installed to monitor and display common process parameters such as flow, pressure and temperature. The human operator is “aided” by such information to diagnose faults.

However, due to the increased automation, the work of the operators has actually become more demanding. Operators’ information needs are now more complex than the operators of the past. With the high interconnectivity of the processes, many of the sensors are coupled. Being the decision-makers in the running of the processing plant, they need to monitor the processes, as well as the decisions taken by automation. To perform their task, operators need additional information (e.g., the logics that control the automation). The operator’s performance is critical and contributes to the variability of the system. Their decisions directly affect plant performance, as well as plant safety (Tyror, 1990). Therefore, it is important to identify and understand operators’ skills.

The knowledge and skills possessed by experienced operators are acquired gradually over many years. A highly experienced operator knows almost everything about the plant - from chemical processes to control logics. When there is an upset in the plant, they are able to visualize and integrate information that is necessary for problem solving. In addition, some experienced operators were engaged in the design of the plant. Hence, they have an excellent understanding of the internal workings of the plant. They can foresee potential problems and handle difficult situations. Their thought processes are streamlined and they can make decisions in a shorter timeframe. It takes a long time for novice operators to acquire these skills, and some never do.

5.2 PURPOSE

The purpose of this study was to understand how operators use existing displays to diagnose faults in the oil refinery. This is known as Process Fault Diagnosis (PFD) (Venkatasubramanian, Rengaswamy, Yin, & Kavuri, 2003). The CTA will be used to:

- Provide the designers with an understanding of the operator's line of thought
- Guide designers in designing displays that assist operators in fault diagnosis

5.3 CONSTRAINTS AND BOUNDARY

One of the difficulties in the study was to get access to the operators. One representative control room was studied. This was a good control room since much of the technology was new, and the processes were complex. Two processes were handled by the operators: the Long Run Catalytic Cracking Unit (LRCCU) and the Platformer. The LRCCU breaks the chemical bonds of the gas oil, while the Platformer reforms naphtha into aromatics.

Figure 5-2 Task Analysis – the dotted line marks the work domain of the operators.

In the control room, the operators' tasks are generally to start up, monitor and shut-down the plants, see Figure 5-2. There are standard operating procedures written for plant start-up and shut-down. However, there are often faults that upset the process. Operators perform a Process Fault Diagnosis (PFD) to identify causes and determine the corrective actions needed (Parasuraman, Sheridan, & Wickens, 2000). These faults are more frequent for new plants. Over time, operators correct and learn from previous faults and are able to diagnose these faults quickly.

Plants are also scheduled for maintenance. Operators are responsible for shutting down the plant. Later, they hand over the maintenance task to engineers. The dotted line in Figure 2-1 is the work domain of the operators. This marks the boundary of the study; only the operator's tasks were studied. The maintenance of equipment in the plant was not covered.

5.4 SUITABILITY

Petroleum refinery is undertaken in a chemical plant. The environment is essentially the same as what was used for the original formulations of the Abstraction Decomposition Hierarchy (ADH) (Rasmussen, Pejtersen, & Goodstein, 1994). The nature of constraints is causal and the ADH is well-suited to this environment. There were many automated systems, and technical equipment that supported the functioning of the system. Human activities were constrained by these automated systems and also by various natural phenomena, operating procedures and system goals. There was limited room for personal preference and goals.

5.5 LITERATURE

The framework in Figure 5-3 shows a conceptualization of the operations in a process control system. It organizes the system variables using Helander's (1997) systems approach to ergonomics. This framework served as a roadmap to guide thoughts and discussions for comprehending the complexity in a petroleum refinery. In the framework, the mechanism of the human mind was more detailed than other areas in the framework; the amount of details in this framework reflected the primary interest of the study: Operator's Process Fault Diagnosis (PFD) skills (Venkatasubramanian, Rengaswamy, Yin, & Kavuri, 2003).

The system is divided into three broad categories: operator, machine and socio-technical. The contents under "operator" are elaborated below, as the objective of the study was to understand operator's PFD skills. It is also necessary to provide more details on the automation since PFD is closely related and dependent on the level of automation. Though social-technical aspects were not a primary concern in the study, they nevertheless affect the operator and were hence included in the framework. The following subsection discusses each categories and their interaction in details.

Figure 5-3 System map of variables affecting the refining operations. There are three main aspects: operator, machine and social-technical.

5.5.1 OPERATOR

To understand the operator's PFD skills, the primary concern is the decision-making process. Many factors that affect the operator's decision were identified. He perceives visual and auditory signals from process equipment, as well as cues and signs from his supervisors and colleagues to make decisions for the operation. When a decision has been made, he controls the process through the keyboard, mouse, trackball and walkie-talkie (Wickens & Hollands, 2000). Many modulating variables also affect how the operator performs his job. Operator's needs, attitude, competence, motivation, experience and gender impact how he perceives, decides and controls the process. In addition, the information he perceives, his mental processes, and the amount of control he has, can induce stress. Stress can also come from time and information constraints, noise and other factors. The influence of operator's stress on performance is a vicious cycle. Stress can demean performance and lead to more stress. However, the effects of stress on decision-making are only partially understood (Sheridan, 2002).

Decision-making is the primary area of interest in this study. The framework suggested a concept where operators has many percepts, impulses and experiences which they synthesized and uses as a basis for problem-solving. This comprised of a diagnostic stage before a decision was made. In the diagnostic process, the operator performs pattern matching using long term memory and logical deduction with his working memory. The thought processes also synthesize patterns drawn from the long term memory. However, the strategies involved in the synthesis of these patterns and the creation of new solutions were not well unleashed.

One particular strategy undertaken by operators was documented in Riera's (2001) proposal for specifications of an Advanced Human-Adapted Supervisory System. It was a strategy on the initial stages of the Process Fault Diagnosis, see Figure 5-4. When an operator first detects a fault, he determines if the fault will affect the process. Some disturbances are caused by faulty instruments such as the pressure gauge. These instruments are used for taking measurements, and their failure need not necessarily have a direct impact on the process. Assuming such circumstances,

the process parameters are not affected. On the other hand, if the process parameters were affected by a fault, operators will judge if the parameters will be stabilized by the automation. Further diagnosis is required if the operator foresees that the process will not reach a steady state. Hence, the operator's task is not just to diagnose and correct the process, but also to understand if the automation can successfully take over his task. This introduces a sensitive dual-task operation.

Figure 5-4 Strategy undertaken by process operators as they diagnosed process fault (Riera, 2001)

5.5.2 MACHINE

Figure 5-5 Important Processes in the Petroleum Refinery. This is a simplified diagram of the complex system. In the actual plant, there are more processes involved. In addition, the operators need to know the architecture, mechanism and algorithms in the control system (Thomson, 2005).

Figure 5-5 is a simplified illustration of important processes in the petroleum refinery. Petroleum refinery is the process of transforming crude oil into usable products. At the distillation tower, crude oil is physically separated into many cuts: residual, gas oil, kerosene, naphtha, LPG, and gasoline vapour. Depending on the demands, heavy cuts can be further broken down in the cracking unit. The alkylation unit, on the other hand, combines the light cuts chemically. To meet the fuel demand, naphtha can be reformed into gasoline. The coker improves the maintenance process by collecting carbon deposits, rather than transporting it to hard-to-reach corners. These processes are constantly improved and re-invented to enhance the technology. Operators will have to keep up with the changes.

As illustrated in Figure 5-3, most parts of the processing plants are run by automation. The operator controls the mechanics of the process through a computer. The machine provides the operator with information. At the same time, the operator may instruct the computer thereby controlling the task.

The behavior of the automation can be modeled analogous to a human information processing model. There are four stages in Human Information Processing model: sensory perception, perception, decision-making, and response selection (Wickens & Hollands, 2000). Similarly, there are four broad classes of functions for the automation: information acquisition, information analysis, decision and action selection, and action implementation (Parasuraman, Sheridan, & Wickens, 2000), see Figure 5-6. The computer receives instruction from the operators to activate pumps, valves, heaters and other device. It analyzes the information, decides on an action and implements the action (Ivergård, 1989; Sheridan, 2002). One of the actions would be to update and display the sensor readings of pressure, temperature, flow and vibration readings.

Table 5-1 Stages in Human Information Processing and Automation Functions

HUMAN INFORMATION PROCESSING	AUTOMATION FUNCTIONS
Sensory perception	Information acquisition
Perception/working memory	Information analysis
Decision-making	Deciding action
Response selection	Action implementation

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Figure 5-6 Variables in the Automation Functions (Parasuraman, Sheridan, & Wickens, 2000)

Sheridan coined the concept of Supervisory Control (Sheridan, 2002) and identified five major roles of the human supervisor: (1) plan, (2) teach, (3) monitor, (4) intervene, and (5) learn, see Figure 5-7. In planning, the operator has to know the physical elements to be controlled, understand the process, and understand the performance goals and how the goals can be traded off against each other and against constraints. Second, he has to “teach” the computer by translating the plan into a formal computer command language. Third, he has to formulate a strategy for monitoring. This affects the frequency of checking, and the allocation of attention to urgent, important and resource-heavy tasks. Fourth, he has to intervene when there are problems. Based on his diagnosis of the system response, he decides if there is a need to abort the task, or engage recovery actions. After the intervention, he might decide to program the machine to take a similar action in the identified situation. Lastly, the supervisor has to learn and update his mental model of the task. The model could affect the initial plans and he might have to revise the plan.

Figure 5-7 Five roles of the Human Supervisor (Sheridan, 2002)

More than supervising, the human can teach automation to make decision. Hollnagel advocates the concept of a Joint Cognitive System, which is a cognitive system comprising of both man and machine (Hollnagel & Woods, 2005). A cognitive system (CS) refers to any system that demonstrates an orderly conduct of goal oriented actions. Hence, a machine can be a CS if its behavior is directed towards a goal. Automation can self-regulate by interpreting the readings and actuating the devices based on rules and logics written in the computer. This reduces the workload of the operators. Ironically, the operators will need to learn the mechanics behind the computer-aided decisions (Bainbridge, 1983).

The responses in automation, like in human cognition, can be guided by both feedback and feedforward activities as illustrated in the Contextual Control Model (COCOM) (Hollnagel & Woods, 2005), see Figure 5-8. Feedback reactions are error-controlled. The CS records an error/event and responds appropriately to the error/event. The feedback performance is displayed in the outer loop: events/feedback - modifies - CS's construct/mental model - determines - actions. On the other hand, feedforward actions are cause-controlled (inner loop in Figure 5-8). A CS anticipates a deviation and responds to the prediction before it actually takes place.

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Figure 5-8 Contextual Control Model (COCOM) (Hollnagel & Woods, 2005)

COCOM is guided by three main concepts: competence, construct and control. Competence refers to the set of possible actions or responses that the CS can possess. This sets the constraints to the events that can take place. This is similar to the concepts in the Work Domain Analysis and the Abstraction Decomposition Hierarchy.

Based on the system's limitation, the CS can predict and anticipate the outcome of its action. The "construct" is the mental model the CS possesses. It is how the CS perceives the situation at a particular time. It is constantly updated and modified as the CS re-interprets the information.

Lastly, "Control" describes the orderliness of performance. There are various patterns for control: scrambled, opportunistic, tactical, and strategic. Table 5-2 provides a description of the four control modes and their characteristics and Figure 5-9 is a graph showing the continuum of when the control modes are active.

Opportunistic control is typically for Process Fault Diagnosis. Performance is almost always dictated by a procedure or rule. There are one to two goals, and actions are selected by habits and association. The belief is that information display and

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automation can be improved to bring the operator’s control model from an Opportunistic to a Tactical mode. Operators can observe trends and predict faults at an earlier stage. Automation can compare trends with known patterns to detect faults.

Table 5-2 Control Mode Characteristics (Hollnagel, 1993)

CONTROL MODE	DESCRIPTION	NO. OF GOALS	SUBJECTIVELY AVAILABLE TIME	EVALUATION OF OUTCOME	BASIS FOR SELECTION OF ACTION
Strategic	choice of next action is basically irrational or random	Several	Abundant	Elaborated	Models/predictions
Tactical	salient features of the current context determine the next action	Several (limited)	Adequate	Detailed	Plans/experience
Opportunistic	performance follow a known procedure or rule	One or two (competing)	Just adequate	Concrete	Habits/association
Scrambled	System can look ahead at higher level goals.	One	Inadequate	Rudimentary	Random

Figure 5-9 Control Modes (Hollnagel et al., 2005)

If a machine can do what the human can do and vice versa, functions can be allocated to humans and/or to machines. However, if there are automation failures, operators can lose their trust in the automation aids especially if the task is easy

(Madhavan, Weigmann, & Lacson, 2003). In assigning, control can be given to human or automation in varying degree. Figure 5-10 illustrates five control systems with varying degree of automation (Sheridan, 1997).

Figure 5-10 Five control systems with varying degrees of automation (Sheridan, 1997). From the leftmost: (1) There is no computer; (2) The computer offers no assistance; the human must do it all, (3) The computer selects one way to do the task and allows the human a restricted time to veto before automatic execution; (4) The computer selects one way to do the task and executes automatically, then necessarily inform the human; (5) The computer selects one way to do the task and execute automatically, then informs the human only if asked

In the model, the degree of automation was based on four criteria: (1) generation of alternatives, (2) selection of options, (3) approval of selection, and (4) information provided for the human, see flowchart in Figure 5-11. From manual control to fully automatic control, seven degrees were identified:

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Figure 5-11 Flowchart for degree of automation

5.5.3 SOCIO-TECHNICAL

Socio-technical variables affect the system at a macro level. Organizations impose work roles and responsibilities. In a petroleum refining plant, the primary responsibility of the operator is to monitor the production of gas and oil to meet the demands defined by the marketing department. Their responsibilities are shared with the automation system. Many of the monitoring and regulating tasks are programmed to alleviate the work of the operators. With the decrease in work, the operations can be supported with fewer operators.

Communication plays an important role in sustaining the task composition. Tasks flow from one department to another. As mentioned, operators would communicate with the marketing on how much to produce. The scale of the production is huge and complex and the output from one control room is often fed to another control room.

At the test site, there are four main control rooms. Sometimes, one control room may accidentally shut off the supply and this affects the operations in the next control room. Communication is important in alleviating differences between the departments.

In petroleum refining plant, the feed is highly flammable and safety is an important issue. It is the organization's responsibilities to provide adequate tools to ensure the safety of the production. Many safety rules and emergency shut-down procedures are in place, and the operators are trained to exercise safety as they make decisions in the operations.

Environmental conditions such as illumination, noise, temperature and motion also affect the operating conditions (Cacciabue, 1998). The control room is air-conditioned and explosion-proof. The air-conditioning is adjusted to a cold temperature to protect the computers from failing. The explosion-proof feature protects the operators should there be an explosion.

5.5.4 CONCLUSION

The literature review generated an overview of the factors that affect Operator's Process Fault Diagnosis (PFD) task. Figure 5-3 shows a system diagram with relationships between the various factors. Notable concepts were presented: Automation Function (Parasuraman, Sheridan, & Wickens, 2000), Supervisory Control (Sheridan, 1992), COCOM (Hollnagel & Woods, 2005), and degree of automation (Sheridan, 1997).

6. KNOWLEDGE ACQUISITION

There were three major tools for acquiring knowledge: observations, documents and interviews. Below, we describe how knowledge was acquired in the study.

6.1 OBSERVATIONS

Observations were done in three site visits at Chevrans, Exxonmobil, and Sinopec (Shanghai). These observations were near silent, so that the analyst would not disturb the work of the operators. Occasionally, the analyst asked the operators to explain their work, and the operators singled out the cues they looked for on the console. Experiences in these site visits built a foundation for the study. Through observing, there is a clearer understanding of the context. The knowledge gained was particularly beneficial when analyzing the data and constructing the representations. The observations are recorded in Appendix A - C.

6.2 DOCUMENTS

The emergency procedures for Shell were reviewed. These emergency procedures are documented and updated by both engineers and operators to handle emergency cases. In reviewing the procedures, many useful keywords and their relationship were identified, and these were later used for constructing the Motivation-Expectation Space. One problem with the procedures was the repetition of knowledge. This makes it difficult to extract information when emergency arises.

6.3 INTERVIEWS

Interviews are often more efficient in the data gathering. As accidents are rare, it does not make sense for the analyst to wait for an accident to gather data. Even if it happened and there were a few occasions, the analyst might not be able to focus on the important aspects. Moreover, interrupting an emergency would be intrusive. Interview is, therefore, a better option.

The analyst alternated between probes suggested in the Critical Decision Method (CDM) and the Applied Cognitive Task Analysis (ACTA) to elicit knowledge from thirteen operators in two refineries. During the interview, operators recalled earlier incidents, and the analyst probed for his cognitive responses to the event. These techniques are explained in Chapter 2. Thirteen operators were interviewed. Five were from Sinopec (Shanghai) and eight from Shell.

FIRST INTERVIEW SESSION - SINOPEC

In the first round of interviews in Sinopec (Shanghai), there were five participants. The five interviewees comprised of two console operators, one process engineer, one computer engineer and one instrument engineer. Of the five interviews conducted, only the interview with the process engineer and one of the console operators were useful for analysis.

Data from the other three operators was not so rich for a couple of reasons.

First, one of the operators was interviewed at his workstation in the presence of other operators. He appeared to be reluctant to share his experience. This could be due to peer pressure. The lesson learnt was to talk to operators individually.

Second, the computer engineer was happy and willing to share her experience. However, her work had little to do with the handling of alarms in the console. The lesson learnt was to set criteria on the selection of interviewee.

Third, it was almost time for dinner when the instrument engineer was interviewed. The instrument engineer was distracted since he wanted to catch the bus. It was difficult to sustain his attention. Two lessons were learnt here: do not pack too many interviews in a day, and do not schedule interviews before breaks and dismissal times.

SECOND INTERVIEW SESSION - SHELL

With these lessons learnt, the second round of interviews achieved better results. Out of the eight interviews conducted in Shell, three were considered unsuccessful interviews. One of the interviews was unsuccessful because the interviewee was not working on the task of interest. It is important to find interviewees with relevant experience. The analyst had to communicate her interest precisely to her sponsor and get the sponsor to recommend interviewees. One mistake was the assumption that all sites operated similarly. In reality, the assignment of responsibilities varied from site to site. In Sinopec, the Process Control Engineer worked on the console and was able to narrate incidents that were relevant to the investigation. The Process Control Engineers in Shell had a different job responsibility and could not describe incidents of relevance to the study.

It was also important that the interviewee was actively engaged in the task of interest at the time of the interview. One interviewee was a trainer with previous experience as a console operator. However, he had stopped working on the console and was unable to narrate the cues and strategies. As a trainer, he had other priorities and was unable to provide useful data for the study.

The last unsuccessful case was with an operator who was very reserved and reluctant to comment. This is difficult to predict and prevent. Eloquence of interviewee can be improved by arranging interviews with people who are more forthcoming. This can be done by asking interviewees to recommend potential candidates. If all measures have been taken, and the interviewee is still reserved, the analyst can be opportunistic and use the time to clarify technical difficulties. These can be technical gaps in other stories - such as the reason for gas starving.

7. DATA ANALYSIS

The interview notes were first recorded onto the Cognitive Demands Table (Crandall, Klein, & Hoffman, 2006) and later translated onto the Abstraction Decomposition Hierarchy (ADH) (Rasmussen, Pejtersen, & Goodstein, 1994). There were difficulties with the translation. Thus, a new method, Applied Work Domain Analysis (AWDA) (Tan & Helander, 2006), was devised. This chapter discusses the basic concepts of AWDA and how the ADH was finally derived. The ADH revealed three functions, which were further analyzed using the Emergent Theme Approach (Wong, 2004).

7.1 COGNITIVE DEMANDS TABLE

The data from the interviews was systematically arranged in a Cognitive Demands Table (CDT) (Crandall, Klein, & Hoffman, 2006). This table, by itself, can be a good way for Knowledge Representation. However, it can be lengthy. In this study, the CDT was used as a data storage tool for the interview data.

In this section, only three of the stories are reported, see Table 7-1. A full set of the data can be found in Appendix D. These three stories were related and were used together to develop the ADH.

In Story 1, the locking of the recycle compressor was faulty. The storyline documented the decisions made by the expert, see Table 7-1. The expert noted how he was able to resolve the issue using a temporary solution. This kept the plant running for a few more days. A permanent solution was to be handled by the engineers and would have taken several months.

The same fault resurfaced for the expert in Story 2. This time, the expert pinpointed the exact cause of the fault. He re-used the same temporary solution. In Story 3, a novice in the shift missed a procedure and a second fault arose at the downstream of the recycle compressor. Despite the already confused situation, the expert was able to diagnose the problem.

Other than the interesting decisions recorded under the storyline, four other aspects were recorded in the CDT for the purpose of understanding Process Fault Diagnosis, namely: (1) cues and strategies, (2) difficult cognitive demands, (3) common errors, and (4) expert-novice differences.

Cues and Strategies refer to strategies adopted by the subject matter expert (SME) and the cues he looked for as he planned and adopted strategies. *Difficult Cognitive Demands* refers to the difficulty in making the decision. *Common Errors* are mistakes that operators might fall into. They could be mistakes which the operator had made, or which he had observed other people making. *Novice-Expert Differences* refers to what an expert would do and see which a novice would have difficulties in observing and/or performing.

Table 7-1 Cognitive Demands Table. In the first story, the failure surfaced in the middle of the night. The operator narrated how the team of operators worked together to contain the fault. In the second story, the failure happened again and the exact cause was identified. This happened in the day and visibility was better. In the last story, there was another failure on the downstream of the first failure. It depicted how a novice was unable to comprehend an expert's instruction which encompassed many sub-instructions.

STORY 1: RECYCLE GAS COMPRESSOR FAILURE

STORYLINE	CUES & STRATEGIES	DIFFICULE COGNITIVE DEMANDS	COMMON ERRORS/EXPERT-NOVICE DIFFERENCES
There were many alarms. The shift controller checked the panel and quickly identified that the airflow in Gas Compressor K6801 had tripped.	<p>There were two main reasons for focusing on K6801.</p> <p>First, K6801 was in the upstream of the process. A trip in the compressor K6801 would cause the feed and furnace to trip. The shift controller understood the domino effects in the process. When the compressor trips, there would be insufficient hydrogen to transport the feed. Hence, there is an in-built safeguarding system that trips the feed. When there is no flow in the furnace, heat in the furnace would not be channeled away. Hence, the furnace has been programmed to prevent overheating.</p> <p>Second, the shift controller understood the severity of a compressor trip. It was easier for him to restore the feed and furnace rather than the compressor, which might need to be repaired. Hence, the compressor was his primary concern and he checked it first.</p>	<p>When a unit trips, there are usually 20-30 alarms. The locations of the alarms on screen are identified. E.g. Platformer unit is denoted by 68, so the alarm might be 68T000. 'T' denotes temperature (other parameters include: P for pressure, Q for Quality (% of impurities, e.g. S), L for level, R for ratio, F for airflow). The last 3 digits denote the instrument.</p> <p>With a large number of alarms and information, it is difficult to step into the situation and get a good grasp of the situation.</p>	<p>Due to the complexity of the plant, novices need to learn many things. They need to know the tag number, colour and location of every pipe and piece of equipment in the plant. In addition, they have to understand the functions and limitations of the equipment. It takes a novice 2 years to learn the basics. The novice starts by tracing the lines in the field. Gradually, they learn to associate the physical line with the schematics in the panel. The shift controller, on the other hand, focuses on how the plant functions. Recalling the numbers has become a skill to him. This may or may not be easy for the novice. The effect of the memory association is also known for stressful situations.</p>
When the shift controller identified that the Gas Compressor K6801 had tripped, he immediately dispatched his unit men to close 36 related valves.	<p>The furnaces would be over-rich with fuel. All available men had to go and shut the 36 valves of the furnaces manually.</p>	<p>This is part of the Emergency Procedures. There are many scenarios and actions in the Emergency Procedures. Operators will need to know the appropriate actions for the situation.</p>	<p>Novices may face difficulties in recalling the procedures.</p>

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STORYLINE	CUES & STRATEGIES	DIFFICULE COGNITIVE DEMANDS	COMMON ERRORS/EXPERT-NOVICE DIFFERENCES
The shift controller also informed the duty manager, who was in charge of the facility, about the severity of the problem. The facility comprised of the operation of three other control rooms.	The shift controller understood that the breakdown of the system would cut production of H2 in the Platformer. As Platformer supplies H2 to other units in the facility, the breakdown would mean a shortage of H2 at the other units. He informed the duty manager so that he could disseminate the information and make the necessary adjustments.	The shift controller has to gauge the magnitude and severity of the abnormality.	A novice will not be able to understand the impact of the breakdown on other units. As the plant is highly integrated, the shift controller has to know the relationship between the various units. He has to know how the inputs and outputs are linked.
The duty team leader led the technicians to restart the compressor. However, it was still not working. He instructed a unit man to go to the field to take a look. The unit man cannot find the problem. The shift controller suspected it was a mechanical rather than electronic problem. So he asked for the standby (it was a night shift) instrument engineer to look for mechanical problems. They found that the Governor valve had disengaged with the steam valve.	The practice is to try to restart the system when it breaks down. However, that did not work. The shift controller suspected a mechanical problem and contacted the instrument engineer.	The primary responsibilities of the shift controller are to run the plant and consult engineers and managers when needed. The design and repair of the equipment are handled by the Engineers. In this situation, the shift controller knows the functionality, internal construction of the compressor. He was able to make the right diagnosis and consult the relevant engineers.	
However, they had no spare valves. The shift controller ordered for a decrease in the production level to reduce the internal consumption of hydrogen.	It was not possible to restart the compressor. Rather than shutting down and starting up the plant, the shift controller put the production on idle	It takes a lot of effort and many days to start up the plant. This is unlike other system (e.g. computer) where restarting is easy.	

STORY 2: SHEARED GOVERNOR VALVE IN RECYCLE COMPRESSOR

STORYLINE	CUES & STRATEGIES	DIFFICULE COGNITIVE DEMANDS	COMMON ERRORS/EXPERT-NOVICE DIFFERENCES
<p>During a shift briefing, the platformer tripped. The alarm summary page was flooded with alarms. A team leader tried to find the root of the trip. However, new alarms keeps seeping in, hindering his search. The operator looked at the Summary of Events (SOE).</p> <p>SOE was a newly installed system to aid fault diagnosis. It captured events at the separation of 0.001 seconds. Hence, operators were able to identify the first alarm.</p>	<p>Whilst the shift controller was certain that his duty team leader was trying to put the plant to a safe operating condition, the shift controller was trying to find the root of the problem.</p> <p>The alarm summary was useful in alerting operators of upsets and a useful tool for diagnosing minor upsets. The operator knew how bad the system would be flooded when the scale of the upset was great. Hence, he turned to the new technology, SOE, hoping that it would facilitate his diagnosis</p>	<p>Some operators would not have tried the new system in an abnormal situation.</p>	
<p>However, the information on the SOE was too complicated. Shortly, he gave up on the SOE</p>	<p>There might be some cues in the SOE that prompted the shift controller the SOE is not functional.</p>	<p>There were indeed problems with the SOE. After the incident, the shift controller checked with the technologies and found that the SOE was not working ideally.</p>	<p>Some operators may trust the new technology, and missed the big picture. They may not see that there are inherent problems with the SOE and insist on using the system, despite its difficulties.</p>
<p>The Shift controller decided that attempts to use the panel were futile. Instead, he got his unit man to check the governor valve for compressor K6801.</p>	<p>The shift controller knew that the compressor had tripped previously and the solution to the trip was a temporary first-aid solution. The replacement for the governor valve would only arrive in a few months. Hence, it was likely that the first-aid solution was not working.</p>	<p>The shift controller was able to link the trip to a past trip that happened days ago.</p>	

COGNITIVE TASK ANALYSIS FRAMEWORK FOR MODELING COMPLEX SYSTEM DATA ANALYSIS

STORYLINE	CUES & STRATEGIES	DIFFICULE COGNITIVE DEMANDS	COMMON ERRORS/EXPERT-NOVICE DIFFERENCES
<p>He went out to the field to see the condition of the valve.</p> <p>The Shift controller was determined to trace the problem with the governor valve. It had tripped previously in the night shift, it was reported that the locking was sheared. However, the X-ray of the locking showed otherwise. They were also speculation that there might be loop-oil failure or speed pickup failure but nothing was proven.</p> <p>In his investigation, he found that the screw thread on the locking had worn off.</p>	<p>In the tripped state, the linkage looked normal. The actuator and link were both retracted, see Appendix D. The shear that was reported cannot be seen from the outside of the linkage.</p> <p>The shift controller, with the help of his operators, actuated the governor valve and observed its behavior. He observed that the link was floating. When the actuator unscrew, the link did not move outward as expected. He suspected that the screw thread, which was the actuating mechanism, had worn off. He checked the screw thread and found faint traces of the thread. This confirmed his reasoning.</p> <p>Previously, the actuator was screwed in for one round. He was hoping that the two rounds can work for two weeks as they sourced for a better solution.</p>	<p>The shift controller had to understand the mechanism and operating behavior of the governor link to identify the problem. Under normal operation, when a signal was sent to open the valve, it would unscrew the connection between the actuator and the link to the governor valve. The link would response by moving outwards, see Appendix D. When the governor valve was tripped, it shut the valve by retracting both the actuator and the link.</p> <p>There has to be good lighting for the shift controller to identify the movement and the wear-off threads.</p>	<p>Others might not have used such a strategy to test the failure.</p> <p>In addition, timing played a critical role in the diagnosis. Previously, the fault had happened at night where visibility was poor.</p> <p>After the problem was rectified with the first-aid solution, engineers were unable to perform further testing. They can only make use of X-rays to test the suspected failure: shearing.</p>
<p>The Shift controller ordered his operators to screw in the actuator for two rounds.</p>			

STORY 3: HYDROTREATER TRIP

STORYLINE	CUES & STRATEGIES	DIFFICULT COGNITIVE DEMANDS	COMMON ERRORS/EXPERT-NOVICE DIFFERENCES
<p>The platformer tripped.</p> <p>The shift controller ordered a novice operator to put the hydrotreater HDS4 to a full recycle.</p>	<p>The platformer produced a large quantity of H2 for downstream processes. The H2 was stored in vessel before it was transferred to the downstream processes. A cut in the H2 supply would deplete the store of H2. Consequently, the downstream processes would trip.</p> <p>The shift controller wanted to arrest these effects before they happened. Hence, HDS4, which consumed the largest quantity of H2 (2/3 of the production), was put to recycle.</p>	<p>The operator was able to visualize the effects of the trip on the processes downstream.</p> <p>He judged that the supply of H2 was sufficient support the smaller H2 consuming processes.</p>	
<p>Despite the preventive measure, HDS4 tripped. The shift controller flipped through the graphics and found that there was an alarm indicating that the flow of H2 in HDS4 was low.</p>	<p>Three highly probable causes were feed, furnace and H2 supply. The shift controller searched all three to identify the cause of the trip.</p>		<p>The novice operator may overlook the H2 flow as he had operated on it not too long ago.</p>
<p>The shift controller checked the flow in the recycle hydrogen supply and found that the compressor was operating at 50% instead of 100%.</p>	<p>The shift controller suspected that the novice operator had not increase the compressor of the recycled H2 from 50% to 100%.</p> <p>The H2 supply came from two lines: the fresh H2 supply from the vessel and the recycle H2 within HDS4, see Appendix D. These two operations should add to 100%</p>		<p>The novice operator was unable to see the relationship between the two supplies. When he was asked to put HDS4 to recycle, it meant unloading the fresh H2 compressor from 50% to 0%, as well as, loading recycle H2 compressor from 50% to 100%. However, he missed the loading and thus, there was insufficient flow of hydrogen in HDS4.</p>

7.2 APPLIED WORK DOMAIN ANALYSIS

As mentioned, the CDT is lengthy and unstructured. A more structured representation would be the Abstraction Decomposition Hierarchy (ADH). However, the construction of an ADH has many rules and was thus difficult to apply to this scenario. To overcome the problems, the Applied Work Domain Analysis was formalized (Tan & Helander, 2006). This was achieved by using two intermediate representations for conceptualizing elicited knowledge and translating the knowledge into levels in the ADH, see Figure 7-1. These representations are first described and explained before their applications are illustrated.

Figure 7-1 Applied Work Domain Analysis (AWDA) framework. AWDA uses a Venn diagram and Motivation-Expectation Space (MES) to translate data from interviews, protocols, and procedures onto the Work Domain Analysis' Abstraction-Decomposition Hierarchy (ADH).

7.2.1 CONCEPTS

The first is the Motivation-Expectation Space (MES), where cause-effect relationships are included and coupled with means-ends relationships. The MES is an orthogonal representation of the links in the abstraction hierarchy, which is concrete and comprehensible.

The second concept is a Venn diagram, which is used to illustrate the physical decomposition. The resulting decomposition hierarchy is used to capture the dependencies between the descriptors in the system. As the AWDA is conducted, the analyst updates both diagrams simultaneously.

MOTIVATION-EXPECTATION SPACE

Figure 7-2 shows the basic block for constructing the MES. A new dimension, the cause-effect link was introduced. Operators often consider the effects of a failure. These effects are not guided by any purpose and thus do not fit in a means-ends relationship. A cause-effect link represents the operator’s belief of what was taking place. Such causal reasoning was termed “cognitive orientation” and the means-ends characteristics “motivational orientation”(Ford & Hegarty, 1984).

Figure 7-2 Motivation-Expectation Space basic block. Moving left explains the cause of an event; moving right states the effect of this event; moving up explains the rationale for having the event; and, moving down states the solution to the event.

If the operator’s beliefs are formulated as established rules, the cause-effect dimension is effectively the “Abstract Function” or “causal or intentional constraint” in the ADH (Lin & Zhang, 2004). Cause-effect phenomena have been used in many other contexts including: cognitive maps, cause maps, information maps and belief nets (Boland, Maheshwari, Te’eni, Schwartz, & Tenkasi, 1992).

In ADH, the two dimensions for classifying data are the abstraction level and decomposition level. Navigating vertically provides the why-what-how, forming a causal explanation of the functionality of the system, while navigating horizontally displays the spatial relationship between objects in the systems: system to sub-system to components, see Figure 3-2.

In the MES, the up-down navigation is similar to the abstraction level in ADH, see Figure 7-2. Moving up explains “why” something is happening while moving down explains “how” it can be resolved. The left-right navigation presents the operator’s view of cause-effect. Moving left explains the cause of “what” is happening and moving right explains the effect of “what” is happening.

It is hence important to differentiate cause-effect from means-ends relation. The cause-effect relationship is driven by expectations and the means-ends relationship by purposes. A joint representation of the operator's purpose or motivation and the behavior of the technological system is formed. Operator's reactions are guided by the goal for the task, as well as the technological progression and state of the system.

VENN DIAGRAM

In the ADH, physical decomposition is represented using the means-ends hierarchy. In the MES, the physical descriptors can be studied using a Venn diagram, where various kinds of relationships and descriptors can be organized.

In the ADH, only hierarchical relationships between components are modeled – a component is a part of a sub-system and a sub-system is a part of a system, see Figure 7-3. For example, in a catalytic cracker, there is a reactor. In the reactor, there are a few valves. The valves are components of the reactor, which is a sub-system of the catalytic cracker. Mathematically, the valve is a subset of the reactor, is a sub-set of the reactor. Such hierarchical relationship is captured by using different columns in a table in the ADH.

Figure 7-3 WDA Venn diagram of the hierarchical physical decomposition of a system.

A simple hierarchy for classifying physical objects does not always work. One example is the modeling of supplies. Bisantz and Vicente (1994) classified supplies under components in their ADH. However, supplies may enter the system at different decomposition levels and require different types of troubleshooting. These details cannot be captured in the ADH.

In AWDA, the relationships need not be constrained to hierarchical relationships. There may be similar types of components and they can be clustered using different graphical representation, see Figure 7-4.

Figure 7-4 AWDA Venn diagram that illustrates other important relationship such as flow and independence between element.

It is desirable to establish the relationship between all descriptors for two reasons. First, it can be used as a semantic analysis to achieve independence between descriptors. Descriptors with similar meanings can be identified and combined. For example, “notify” and “inform” share the same meaning. We can replace occurrences of “inform” with “notify”. Second, the descriptors can be ordered to fit the requirements of the context that is investigated.

7.2.2 EXAMPLE OF AWDA

This section describes how Applied Work Domain Analysis (AWDA) was performed using data from the Emergency Procedures and Cognitive Demands Table, see Appendix D. There were three steps:

1. Constructing the Venn diagram
2. Constructing the Motivation-Expectation Space (MES)
3. Translating MES into the Abstraction-Decomposition Hierarchy (ADH)

VENN DIAGRAM – GATHERING THE DESCRIPTORS

AWDA utilizes Venn diagrams to organize descriptors that are used in the MES. Five independent categories were identified and put into the TEAMS structure: (1) *Technical*, (2) *Events*, (3) *Actions*, (4) *Measurement*, and (5) *Social*. The complete library of descriptors can be found in Appendix D.

Technical descriptors refer to the machines in the system. These descriptors can be sub-classified into supply, plant, system, equipment, and component. The relation between the sub-classification is depicted using a Venn Diagram, see Figure 7-5. The Venn diagram is organized so that components constitute a subset of a piece of equipment, which is a subset of the system. The system is in itself a subset of the plant (not shown in figure). Finally, the supply flows through the system.

Events describe what happens. Many of these are the nouns of the descriptors in the action type. They can be described as a sub-class similar to the technical descriptors and they are placed with the Technical descriptors in the Venn Diagram.

There are three actors in the Action Venn Diagram: human, nature, and automation. The Venn diagram in Figure 7-5 shows the possible actions that each actor could perform and the actions that all three could do. Each box in the Motivation-Expectation Space consists of a descriptor from the Technical or Event type and it is followed by a descriptor from the Action type, e.g. pump affected.

Measurements are the readings taken in the technical system. They are typically followed by a technical descriptor, describing the measurement taken.

Social descriptors refer to the people in the system. They can be co-workers as well as leaders. Social descriptors can be used in place of the Technical and Event descriptors. Use of the social descriptors is rare. If its usage is rampant, operators are spending a large proportion of time in communication. This would often imply that there is a deficiency in the system.

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Figure 7-5 Venn diagram of descriptors in the MES for troubleshooting faults in a platformer unit. The Venn diagram helps to structure and eliminate descriptors with similar meaning. The descriptors are ordered in the TEAMS structure: *Technical, Events, Action, Measurement, and Social*. This list helps to standardize the order of describing a point in the MES.

MOTIVATION-EXPECTATION SPACE

The Motivation-Expectation Space uses the descriptors in the Venn diagram to describe a point. Moving left from point to point in Figure 7-6 describes the causal constraints while moving down describes the means for resolution. In Figure 7-6, starting from the top right corner, the effect of a compressor trip is illustrated: (1) there will be no pressure difference to circulate the hydrogen; (2) when the hydrogen is not supplied, chemical bonding cannot take place; (3) the reactor will be saturated with the hydrocarbon feed, and excessive coke will be deposited on the reactor (coking). These links describe a natural course, since they take place without an actor.

If too much coke is deposited on the reactor, the reactor will not provide the ideal condition for reforming. Major maintenance will have to be scheduled. To avoid the coking and maintenance, designers have programmed the hydrocarbon feed to trip when the compressor trips. In the vertical dimension, one can move downwards and find the actors (human or automation) and actions needed to counter the predictions (actions by nature). If one starts from the prediction that coking will take place, the problem can be resolved by preventing the coking and subsequently by tripping the feed.

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Figure 7-6 Motivation-Expectation Space of a case in a petrochemical plant. The horizontal dimension shows the operator’s belief of the system while the vertical shows his behavior to counter his predictions. The triangles show the missing gaps where further knowledge needs to be recorded. The actions with the double dotted outline are actions taken by automation, while the ones with the double outline are actions taken by the operators.

The MES can also be formulated by combining several scenarios. The MES in Figure 7-7 was developed by combining the three stories in Section 7.1. This could be achieved, since the three stories had the same cause, that is, a shear in the governor valve. Gaps in the stories were filled by reading the emergency procedures and asking experts. Thereby the remaining triangles in Figure 7-6 could be removed.

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Figure 7-7 Completed Motivation Expectation Space for a recycle compressor trip in a platformer.

TRANSLATING MOTIVATION-EXPECTATION SPACE INTO ABSTRACTION DECOMPOSITION HIERARCHY

Below, we describe how the Motivation-Expectation Space can be dissected and arranged into an Abstraction-Decomposition Hierarchy. There are three steps for the mapping the MES onto the ADH. First, the vertical ladders in the MES were extracted and classified under three hierarchies, see Figure 7-8. The first row describes the Cause Function (Why) in the vertical chain. The second row refers to the Strategies Function (What), and the last row represents the Action Function (How) in the system. When put together, the three rows form an Abstraction Hierarchy.

Next, points were moved with reference to the relationship set in the Venn diagram, see Figure 7-9. This was done to represent the decomposition of the system. “Social” and “Supply” were placed to the left in the figure. There is no hierarchical relationship in the decomposition, and hence supported the earlier argument that the Venn diagrams in Figure 7-5 is a better representation of the relationship. Nevertheless, this provides a simplistic overview of the system and forms an almost completed ADH.

Finally, two higher level functions were added to explain the purpose-directed behavior of the operators, see Figure 7-10. The MES was able to represent the lower level goals of the operators. These lower level goals were guided from higher level goals, which were elicited from the interviews. At the highest level is the purpose function. In this case study, the goals of the operators, when handling an abnormal situation, was the integration of the system, safety and loss minimizing. At the next level is a general function that groups and classify the strategies. This represented the completed ADH.

Abstraction Hierarchy

Figure 7-8 Abstraction Space depicting the means-ends relationship. For simplicity, these ladders were formulated from the rudimentary Motivation-Expectation Space in Figure 7-6.

Abstraction-Decomposition Hierarchy

Figure 7-9 Abstraction-Decomposition Hierarchy depicting the means-ends and physical relationship.

Abstraction-Decomposition Hierarchy (higher level goals)

Figure 7-10 Abstraction-Decomposition Hierarchy with higher level goals.

8. KNOWLEDGE REPRESENTATION

Knowledge regarding the functionality of a processing plant was represented in the Abstraction Decomposition Hierarchy (ADH), see Figure 7-10. The ADH focuses on problem solving and diagnosis when there is a plant upset. Five abstraction levels were identified: (1) Purpose, (2) Classification, (3) Cause, (4) Strategy, and (5) Action.

Of particular interest is the Strategy Function, which represents the decision taken in order to minimize the problem with the upset. The ADH reveals that there are two ends to the strategy function. The strategy taken depends on the Cause Function (what has happened) and Purpose/Classification Function (top goal of the operators).

The top goals are described succinctly in the ADH. There are three primary purposes: (1) integration, (2) loss minimizing, and (3) safety.

The cause and strategy functions are further elaborated below.

8.1 CAUSE FUNCTION

Eight causes were identified from the ADH. The Cognitive Demands Table in Appendix D was revisited to identify common themes of causes (Crandall, Klein, & Hoffman, 2006; Wong, 2004).

Five themes emerged:

1. Loss of utilities supplies
2. Equipment failure
3. Undesirable condition for reaction
4. Undesirable set-up for operations
5. Problematic display

These themes are not independent, and a validation study was conducted to explore how operators would group malfunctions under these themes, see Section 9.1.

8.2 STRATEGIES FUNCTION

The Emergent Theme Approach was again applied to identify Process Fault Diagnosing strategies by reviewing the CDT, ADH and Emergency procedures. The flow map in Figure 8-1 depicts the major steps taken when operators diagnose process faults. There are four major steps: (1) detect fault; (2) isolate fault; (3) diagnose cause; and (4) devise solution. The data in the CDT that was used to formulate the themes is presented in Table 8-1. Each of the steps is explained below with examples from the stories in the CDT.

Table 8-1 Emerging themes from stories in the Cognitive Demands Table. In each story, operators detected, isolated, diagnosed, devised and implemented. There were different cues as they detected the fault. They isolated by either looking for the first trip or screening pertinent equipment. They diagnosed by listing possible causes and systematically checked the process flow and history. They also considered the cause and effect as they diagnosed the fault and devised a solution. Finally they implemented the solution.

STORY	DETECT	ISOLATE		DIAGNOSE		DEVISE
		FIRST TRIP	PERTINENT EQUIPMENT	LIST POSSIBLE CAUSE	BACKWARD SEQUENTIAL CHECK	CAUSE AND EFFECT
1	Many alarms		compressor	Mechanical /electronic faults		idle
2	Big Flare		compressor		2-stage compressor	backflow
3	Deafening ‘pop’ and ‘hissing’	Shut valves			H2 smell	Possible explosion
6	Many alarms	First alarm		Loop-oil/speed pick-up/screw thread worn-off	Check fault earlier	More rounds

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Figure 8-1 Process Fault Diagnosing model.

DETECT FAULT

In handling a fault, the first stage was detecting the fault. Many cues were elicited from the stories. There were visual cues such as many alarms, fire, bigger flare, thicker smoke and observing a sudden drop in the flow from the console. There were also auditory cues such as a loud ‘pop’ followed with a violent ‘hissing’ sound and olfactory cues such as the smell of oil or rotten eggs in the air. Sometimes, there were even tactile cues such as when the structure shook violently. These cues were captured selectively by the operator’s senses and this selection was based on a comparison of the abnormal events with normal events. The operators perceived these cues and would suspect that something was wrong.

ISOLATE FAULT

The process control plant is highly integrated, and one abnormal event will often lead to another event. Isolating a fault is typically a rule-based behavior for experts (Rasmussen, 1983), meaning that an expert will perform this task instinctively, and not necessarily reflect on how he concluded that there was a fault. When they detect an abnormality, it is important to identify the affected area and isolate the fault. For some faults, isolation is straightforward. For example, in Story 3, the expert was re-commissioning a compressor when he heard a loud “pop”. He quickly undid his previous actions to isolate the fault. For other faults, the expert might need to devise a new solution. This situation is more challenging and sometimes requires the operator to think hard about options –what Rasmussen (1983) referred to as knowledge-based level.

To isolate the fault, there were two main strategies. The expert either looked for the first trip alarm or a pertinent piece of equipment. This is illustrated in Story 1 and 6 in Appendix A. In both stories, the recycle compressor was faulty. Unfortunately, there were no replacement parts and the experts had to use a makeshift solution.

The expert in Story 1 detected the fault by screening the major pieces of equipment and understanding the relationship between the compressor, the feed, and the furnace. The compressor is programmed to trip when the feed and furnace trip. If there is no feed flowing in, the compressor continues running but the furnace will trip. When the furnace trips, the compressor and feed will not be affected. His main concern was the status of the major equipment, especially the compressor. Hence, he checked that first. When he identified that the compressor has failed, he immediately ordered 36 valves to be shut off, thereby isolating the fault.

The expert in Story 6 looked for the first alarm on the screen. Unfortunately, the navigation scheme in the panel was not user-friendly. He eventually gave up and based on his knowledge of previous incident, checked the compressor. When he had confirmed the fault, he ordered for the downstream hydrotreater to be isolated. In both stories, the experts looked for the affected area and isolated the area from the system. The first expert looked at the major equipment, while the second expert looked for the first cause.

DIAGNOSE CAUSE

Diagnosing a cause is typically a knowledge-based activity. Operators list first the possible causes, which can range from one to many causes. After hypothesizing the causes, they look for evidence to either confirm and/or disconfirm their hypotheses. In Story 7, the hydrotreater tripped. The expert listed three probable causes: feed, furnace and hydrogen supply. He found a piece of confirming evidence in an alarm that indicated a low flow in the hydrogen supply.

Frequently, operators run a backward sequential check (BSC). BSC can be performed in two modes – time and process. In the terms of time, the expert looks at what happen prior to the event. One example was in Story 2 when the expert

remembered that the compressor was faulty a few days ago. This can also be an operation that was performed earlier.

In the process mode, operators referred to the process line in the analysis. The operators termed this “line tracing”. The flow of diagnosis usually takes a path in the opposite direction of the process flow. For example, in Story 3, a pipe was dislodged. After the expert found the location of the dislodged pipe, he gathered his teammates to backtrack the process to find the valve that must be closed in order to stop the leakage.

DEVISE SOLUTION

In devising a solution, operators simulate the cause and effect of each action. This is either a rule-based or knowledge-based activity, see Section 3.1.3. The operator might have recognized a familiar fault and performed the common procedure or rule for the operation. Alternatively, it can be a fault that the operator had not encountered before.

In Story 8, the expert described how he generated a solution for an unfamiliar scenario. The expert had to decide whether to put the catalyst regeneration on standby in order to repair a valve or to continue running the regenerator. The expert mentally simulated the case where the catalyst continues with the regeneration. If this happened, the catalyst would be diverted to a storage tank where the repair was taking place. The pressure in the reactor would drop, and corrosive gas would flow to other parts of the system and damage some equipment. Considering this bad outcome, the decision was taken to put the regenerator on standby.

9. KNOWLEDGE VALIDATION

Three validations were conducted: (1) purpose function, (2) cause function, and (3) strategies function. This section first describes the relationship between the three. Next, the validations of the purpose and cause functions are briefly discussed. Since they are not directly related to the purpose of the case study, they are not described in detail. The validation of the strategies function is then described.

The cause of a fault determines the operator's goals and the ensuing actions. In the ADH, the cause function hardly interacted with the purpose function (The classification function was taken to be part of the purpose function). Their interaction was mediated by the strategy function. The findings suggested that the strategies employed by the operators were dependent on the operator's goals, as well as the cause of the fault.

The ADH presents the operator's top goals: (1) to ensure safety, (2) minimize loss and, (3) support the plant integration. The purpose function was validated by asking experts about their top goals. The validation for the cause function is briefly presented while that of the strategies function is elaborated.

9.1 CAUSE FUNCTION VALIDATION

Five themes were identified in Section 8.1: (1) loss of utilities, (2) equipment failure, (3) undesirable condition for reaction, (4) undesirable set-up for operation, and (5) problematic display. Unfortunately, these themes were coupled. A fault can fall under more than one theme. This was not informative for classifying fault. A validation study was conducted to gain a better understanding on how the faults can likely affect the diagnostic process.

In the validation study, 24 operators were tasked to sort 28 faults under one of the six headings – the five themes and “others”. It was found that the initial set of themes were not independent; one fault can fall under more than one theme. Studying the patterns of the proportion of cards placed in each stack revealed that there were generally four categories of faults: (1) loss of supply, (2) equipment failure, (3) control valve failure, and (4) transmitter failure (Tan, Helander, & Ho, 2007).

9.2 STRATEGIES FUNCTION VALIDATION

To validate the Strategies function, represented by the Process Fault Diagnosis model, a simulation interview was conducted. Though the model addresses operator’s behavior both at the console and in the field, this validation was limited to the Process Fault Diagnosis at the console. The study was done on the Envision training simulator. The process tested was the Long Run Catalytic Cracking Unit (LRCCU).

PARTICIPANTS

Twenty-six operators participated in the study. Sixteen operators were process technicians, six were team leaders, two were shift controllers and two were formerly trainers. Five had less than 10 years of experience; ten had 10-19 years of experience; seven had 20-29 years of experience; and four had more than 30 years of experience.

Results from four of the operators were not used for the statistical analysis. Three of these operators were pilot subjects and received instructions that were slightly

different from the other operators. One operator had difficulties with the simulator and underperformed. Hence, data collected from 22 operators were used.

EQUIPMENT

The simulator is a training tool for the operators. As part of their reoccurring training, operators were required to practice on the simulator on a regular schedule. The screen pages available on the simulator closely replicated the pages in the real plant. There were six different screens in the simulator where operators could search for information:

- Alarm Summary
- Historical Trends
- Instrument Group
- Graphics
- Stream Summary
- Instrument Faceplate

The Stream Summary page was displayed at the start of each experiment. This page was chosen, because there were no alerts on this page. In the interview, some operators reported that they did not have access to this page in their normal routine. This was only available in the shift controller's office.

The Instrument Faceplate, unlike the other pages, was a pop-up window. It can be accessed from the Alarm Summary, Historical Trends, and Graphics page by double-clicking the parameter. Once opened, operators can control the parameter.

The Alarm Summary, Historical Trends, Instrument Group and Graphics were the four main pages of interest in the study. The information on these pages was similar but it appeared in different formats. Figure 9-1 shows how the pieces of information were related. Information was either presented in a chronological or topological order. Operators were able to control the system using the console. The pages can display one or more of the following: chronological information, topological information and control. A thick line in the diagram means that the page provides

strong information of that particular type of information. Table 9-2 details the strength of the links.

Figure 9-1 Information and control provided in each of the four pages of interest. Chronological order furnishes operator with information related to time. Topological order presented the information based on the spatial and functional relationship between the parameters. Control means that the page allows operators to control parameters in the plant. Bolder line means that the page provides stronger aspects of the information type. This is elaborated in Table 9-1 and Table 9-2.

Table 9-1 Details of chronological information, topological information and control provided in each of the four pages of interest.

PAGES IN THE SIMULATOR	PROVIDE INFORMATION		PROVIDE CONTROL
	CHRONOLOGICAL	TOPOLOGICAL	
Alarm Summary	Yes	No	Yes. Instrument faceplate
Historical Trends	Yes. Limited events	Yes. Limited.	Yes. Instrument faceplate
Instrument Group	Yes. One event	Yes. Limited.	Yes
Graphics	No	Yes	Yes. Instrument faceplate

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Table 9-2 Description of the four pages of interest.

The Alarm Summary page provided important chronological information and also allowed control. In the Alarm Summary page, alarms were presented according to the time it occurred. This explains the strong chronological link. A faceplate can be called up by double-clicking and the operator can change the parameter. Hence, there was slight control from the Alarm Summary page, see Table 9-1.

The Historical Trends page showed a set of graphs. There are approximately eight graphs on each page. Instead of showing all the events chronologically, operators can only see limited events. The set of eight graphs were put together based on their spatial and functional relationship. Hence, there was limited topological information. Again, there was slight control using the instrument faceplate.

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The Instrument Group page showed sets of controls. Again, there were eight on each page. In terms of chronological information, only one graph was shown each time. Hence, there was less chronological information on this page than the Historical Trends page. Similar to the Historical Trends page, each set of eight graphs were selected based on their spatial and functional relationship and there was limited topological information. There were eight controls. Hence, this page provided more control than the other pages.

The Graphics page provided strong topological information. This page displayed the schematics of the plant. There was basically no information that showed the change in the plant condition over time. Again, there was slight control from using the instrument faceplate.

DESIGN

In the Simulation Interview, operators were tasked to diagnose four faults using the Envision training simulator: one fault from each of the four failure types in the Cause Function analysis. The faults were embedded in the LRCCU model that closely replicated the real plant. The operators did not operate on the simulator. Instead, they browsed the simulator and answered the following questions:

- What do you think has happened?
- What is the cause of the upset?
- What do you think will happen next?
- What are your corrective actions if you are the panel man for the shift?
- What is most difficult about this task?

Five hypotheses in the model were tested, see Figure 9-2:

1. Operators perform fault isolation.
2. Operators isolate fault by looking at the first trip more than the pertinent equipment.
3. Operators list the possible causes.
4. Operators perform backward sequential check.
5. Operators consider the cause and effect of decisions.

All hypotheses, except for hypothesis two, were tested by counting the number of operators who exercised the described behavior in the simulation interview.

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Figure 9-2 Pages of interest in the simulator that supported the Process Fault Handling.

Hypothesis 2 was tested by reviewing the screens used by the operators in the task. Having the Process Fault Handling model and knowing what kind of support the interface provides for the operator, the former is linked to the latter to map the actions of the operators. Figure 9-2 illustrates the links.

To isolate the fault, operators looked at the chronological-ordered display to examine the first trip. The Alarm Summary and Historical Trends pages provided stronger chronological information than the Instrument Group pages. There was no chronological information on the Graphics pages. To isolate based on the pertinent equipment, operators looked at the topological-ordered displays. The Graphics pages were the strongest in providing topological information. The Historical Trends and Instrument Group pages provided topological information when the functionally-related information, which is usually physically close in proximity, was grouped and presented on the same page. If operators reviewed the Graphics pages, they were typically checking pertinent equipment. If they reviewed the Alarm Summary and Historical Trends pages, they were looking for the first trip.

RESULTS

Table 9-3 Results - Percentage of operators performing activities in the Process Fault Handling model as they were troubleshooting faults in the simulator.

HYPOTHESIS		% OPERATORS
1	Operators considered fault isolation.	64%
2a	Operators looked for the first trip.	65%
2b	Operators looked at the pertinent equipment.	35%
3	Operators listed the possible causes.	73%
4	Operators performed backward sequential check.	82%
5	Operators considered cause and effect.	95%

The results showed that 64% of the operators considered fault isolation as they worked on the troubleshooting task at the simulator, see Table 9-3. More operators looked for the first trip (65%) rather than pertinent equipment (35%).

Seventy-three percent of the operators listed possible causes as they diagnosed the problem. Eighty-two percent performed backward sequential checks. Ninety-five percent considered the cause and effects in the scenario.

CONCLUSION & DISCUSSION

This section concludes the study with a discussion of the implications of the findings.

Five hypotheses related to the model formulated:

1. Operators perform fault isolation.
2. Operators isolate fault by looking at the first trip more than the pertinent equipment.
3. Operators list the possible causes.
4. Operators perform backward sequential check.
5. Operators consider the cause and effect of decisions.

The validation study found that operators indeed performed the activities that they mentioned during the interviews. At least 64% of the operators demonstrated performance of the hypothesized activities. These activities included fault isolation,

cause listing, backward sequential checking and cause-and-effect considerations. For fault isolation, it was found that more operators looked for the first trip (65%) rather than traversed through pertinent equipment (35%).

The results suggest that chronological information was what operators looked for in their diagnosis. The topological information was learned and stored in their memory. Specific experts used this strategy more because of their experience with the facility. General experts and novice were able to recognize blocks of process set-ups based on the order of the numbers. There were two numbers. One was the equipment number and another was the system where the equipment was embedded. With this information, some novices were able to better relate to the topology of the equipments.

Implication 1: Topological information on the Graphics pages was etched in the operator's memory. Experienced and better-trained operators were able to understand the scenario by associating the numbers. This can possibly be a good means to bring across topological information without actually providing the plant schematics. Further studies can be conducted to understand operator's ability to associate with numbers, and how they use numbers to understand the blocks of processes.

Implication 2: With the technique to associate the numbers, operators can be efficient in reading alarms. Surprisingly, more alarms (approximately 45) were found to be more useful than fewer alarms (approximately 7) when operators diagnosed in the simulation interview. This is contrary to the popular notion of alarm flooding. The study found that fewer alarms led to limited clues for solving the fault. Increased redundancy actually aided operators in cross-checking the fault. This suggested that the optimum operating condition will be one where redundancy is controlled. It need not be one where redundancy is at a minimum.

Implication 3: Emphasis should be placed on helping operators visualize chronological information such as that in the Alarm Summary and Historical Trends pages. Many operators use the Alarm Summary as a tool to monitor plant health and as a tool to diagnose problems. One concern with the Alarm Summary was operator's dependency on the alarms to inform them of faults. Operator's reliance on

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the Alarm Summary will limit situation awareness of the plant. The operator who relies on the Alarm Summary screen is reacting to abnormal situations as they occur rather than being preventative. A better way is to monitor the process using trends. Operators can then track changes and project upcoming trends. Unfortunately, most operators seemed to face difficulties comprehending the trend information. More studies should be conducted to understand how trends are used and how interface can be improved to support operator's comprehension of trends.

Section III Concluding chapters

10. DISCUSSION & FUTURE RESEARCH

This study proposed a five-stage framework for conducting Cognitive Task Analysis: (1) Bootstrapping, (2) Knowledge Acquisition, (3) Data Analysis, (4) Knowledge Representation, and (5) Knowledge Validation. A case study was conducted to demonstrate the application of the framework and some benefits and drawbacks were discovered. These are discussed in the following sections.

10.1 CTA FRAMEWORK

Cognitive Task Analysis (CTA) had been used for about 30 years. However, the definition of CTA was unclear. Most literature discusses the theoretical aspect of CTA, but there have been few descriptions of how CTA should be applied. Only recently, the methods for conducting Work Domain Analysis (Naikar, Hopcroft, & Moylan, 2005) and Cognitive Task Analysis (Crandall, Klein, & Hoffman, 2006), more specifically Critical Decision Method, have been published. There are slight differences in how the analyses are conducted. This framework pulls the two methods together through understanding the procedures involved in each method. These issues are covered in Chapter 2 – Chapter 4. The benefits of having the framework are discussed next.

BENEFITS

The framework categorized the steps in an easy-to-remember format. Conducting CTA is different from that of other experimental procedures. Like all Human Factors or Psychology experiments, the descriptors used in CTA are different from hard sciences such as physics and biology. In Psychology experiment, terms like “subjects”, “between subject differences” and “within subject differences” are commonly used. These terms are adopted from Psychology, and scientists in other fields of studies are foreign to such description. Nevertheless, this did not deny the fact that Human Factors and Psychological were part of science. Gibson explained that a Human Factors was the science of ecology and there should be an ecological approach to designs (Gibson, 1986).

In CTA, there are several new terms such as bootstrapping and knowledge acquisition, representation and validation. The five stages identified in this study are compared with regular types of research reports in other sciences in Table 10-1. Traditional research report starts with an introduction where the author brings in a problem, and literature are examined. This is followed by the objectives and scope of the project. This part is similar to CTA's Bootstrapping where the analyst presents findings on the purpose of the project and the context of the study.

Table 10-1 Comparing the framework with traditional research.

CTA FRAMEWORK		REGULAR RESEARCH
1	Bootstrapping	Introduction Literature Review
2	Knowledge Acquisition	Method
3	Data Analysis	Result
4	Knowledge Representation	Result
5	Knowledge Validation	Method + Result

In the traditional research regime, a literature review is conducted to find out what other scientists have done for similar context. This is similar to the construction of a preliminary representation at the Bootstrapping stage. The rationale of both approaches is the same: to document the state-of-the-art, which serve as a basis for the current works.

The Knowledge Acquisition stage is similar to the Methods section in traditional research and serves to identify and document method for data collection. In the CTA framework, this refers to the techniques used for extracting the data from subject-matter experts.

The Data Analysis and Knowledge Representation stages of the framework are analogous to the Results section in traditional research. Sometimes, Data Analysis, which requires extensive computing capabilities, is performed by software. The software used is reported in the Methods section. Unfortunately, most CTA data requires the analyst to analyze the data. If the analyses are very lengthy, an excerpt can be reported and the remaining information can be placed in an appendix.

Finally, the data needs to be validated in the Knowledge Validation stage. This stage is different from traditional research. A CTA study can be quite subjective and difficult to prove. Separate testing is often required and designed to ensure that the results can be applied in a different situation. The design of a validation study can be as simple as verifying with experts. It can also be a tedious experiment such as the simulation interview reported in Section 9.2.

This comparison has shown that CTA follows closely the process of regular research regime. This classification helps CTA practitioners remember the steps for conducting CTA. This is particularly useful for the novice CTA practitioner who has been actively engaged in other forms of scientific research.

ISSUES & FUTURE RESEARCH

In using the CTA framework, it was found that the distinction between the Data Analysis and the Knowledge Representations stages is fuzzy and sometimes difficult to separate. In this report, the Cognitive Demands Table and the Motivation Expectation Space were useful representations by themselves. However, since they were part of the process to achieve the Abstraction-Decomposition Hierarchy, they were presented under Data Analysis.

There are two ways to determine where the representation should be located. First, the analyst can track the order of constructing the representations. Second, the analyst can identify the representations which are comprehensible to the audience. The latter criteria should precede the first. This means that the representations which can communicate the findings to the readers should be placed under Knowledge Representation. All others can fall under Data Analysis in a chronological order.

10.2 ADDITIONAL CONTRIBUTIONS

10.2.1 APPLIED WORK DOMAIN ANALYSIS

Work Domain Analysis (WDA) has been widely accepted as an approach for modeling complex system. However, there are too many rules in setting up a WDA and the method is difficult to apply. The intention of Applied Work Domain Analysis (AWDA) is to aid the translation of data onto the WDA Abstraction-Decomposition Hierarchy.

WDA is a refined representation of the AWDA. WDA provides the overview, while AWDA gives the detailed information. Table 10-2 lists some differences between AWDA and WDA.

Table 10-2 Difference between Work Domain Analysis and Applied Work Domain Analysis

CHARACTERISTICS	WORK DOMAIN ANALYSIS	APPLIED WORK DOMAIN ANALYSIS
USERS	Scientist, researchers	Human factors engineers Designers
REPRESENTATION	Means-ends decomposition Physical decomposition	Venn diagram Means-ends decomposition Cause-effect
INFORMATION STRUCTURE	Hierarchy	Network with embedded Hierarchy
BOUNDARIES	Bounded	Unbounded
	Event independent	Event dependent
PURPOSES	At the top as ends to the external environment	Embedded in the network

AWDA helps to structure information for formulating a WDA. The Abstraction-Decomposition Hierarchy (ADH) is a highly conceptual model. In conceptualizing a WDA there are many rules. Users need to have a strong theoretical foundation of the concepts before they can apply a WDA and generate the ADH. The proposed AWDA utilizes several of the concepts in WDA, it is however formulated so that it is easier to use.

AWDA representations retain more information than WDA-ADH. WDA categorizes information and presents them hierarchically. While this is good for generalizing behavior, it does not preserve the integrity of the information as well as AWDA's network of information. With the current state-of-the-art computing system, users can use a search engine to identify their interest and quickly identify the causes, effects, means, and ends of a situation. With more details, it is easier for designers and engineers to utilize the data. The AWDA allows designers and engineers to get a good overview of the task.

Like WDA, AWDA can only be applied in a structured work environment, where the causality of events and actions are clear. This means that one event can be predicted from another event. Operator's behavior is guided by procedures and operators exercise minimal personal preference and intention.

10.2.2 MOTIVATION EXPECTATION SPACE

A Motivation-Expectation Space (MES) was developed based on the strong themes of means-ends and cause-effect extracted from the interview notes. Operator's actions are guided by the system goals and what happens around them. If there is a goal but there are no activities, operators do not need to react. If there are activities but there are no goals, operator's reaction will be unpredictable and coordination will be hindered. The MES can be used to elicit knowledge from the operator. The knowledge can later be used to support operator's decision making.

A why and how space can be created by considering why operators make decisions and how they react to situations. When the furnace is overheated, operators would shut the pilot gas supply. This action is guided by the goal to maintain safety. Such considerations form the basis of the motivation dimension.

An extensive discussion on the cause and effect of the processes during the interview led to the development of the "Expectation" dimension. Operator's reasoning is almost always guided by the cause and effect of their surrounding environment. This can be the cause and effect of the process such as a temperature increase or the rules of the automation that support a function such as a furnace trip. It can also be his

expectation of his co-workers' reaction. These events are what the operators expect the system to behave. An expectation dimension can hence be formulated.

The motivation and expectation dimensions was combined in the two dimensional orthogonal Motivation-Expectation Space (Tan & Helander, 2006). The MES has a basic block for representation information, see Figure 7-2. The up-down navigation represented the means and ends of operator's action. Moving up explains "why" an event takes place while moving down explains how the event can be resolved. The left-right navigation presents the operator's view of cause-effect. Moving left will explain the cause of "what" is happening and moving right explain the effect of "what" is happening.

BENEFITS

Similar to the ADH, one advantage of the MES is that the reader can start from any point and still get useful data. A person starting from "Feed trip" can move up the ladder and understand that the feed is tripped to prevent coking, see Figure 7-6. He can also move right and understand that the effect of the trip is an overheating of the furnace and a stop of hydrogen production. An individual, who possesses knowledge of the AWDA building blocks in Figure 7-2, will be able to navigate and understand the MES.

The MES can be used as a knowledge elicitation tool. A researcher can use the MES map to identify areas of interests that require further explanation and elaboration. Expert operators often formulate short-cuts, which can be difficult to verbalize. The actions they take have become automatic, and it is difficult to explain this knowledge (Rasmussen, 1983). These situations leave gaps in their story. With the MES, these gaps can be flagged with triangles as in Figure 7-6. To address these gaps, researcher can teach the operators the basic block and have him explain the gaps. In one email exchange, an expert was presented the MES and these questions were asked:

- What are the possible causes for a compressor trip?
- How do operators restart the compressor? Are there many steps? How many? I supposed it is so clear to them that they don't need to refer to procedures.

- What happens when a furnace overheat? Can I put "furnace damaged" as an effect to furnace overheat?
- Lastly, what's the rationale for decreasing the feed when there is low hydrogen supply? Is it "hydrogenation affected"?

With the MES, the expert took approximately 20 minutes to answer these questions. The MES had provided a useful context for the expert. This would otherwise take much description. The MES facilitated sharing of the big picture between the investigator and the expert. The expert was able to structure his line of thoughts quickly and filled in the gaps. In the MES, there are less rules and the expert has less difficulty understanding the MES and answering these questions as compared to the Abstraction-Decomposition Hierarchy.

ISSUES & FUTURE RESEARCH

Future research can explore the application of the Motivation-Expectation Space (MES). It is believed that the representation can be useful as a basis for developing training programs and decision-support system.

Before the training and decision-support can take place, the MES needs to be populated with information. One possible means of formulating the MES is the use of the wiki technology to fill the cells, see Figure 10-1. This is termed "WikiMES" - a collaborative concept where team members can easily add, remove or edit the MES. It is almost like the MES is living and responding to the current affairs. To streamline the construction of the WikiMES, a few things have to be done. First, rules for constructing the MES can be set and taught to the operators. Second, existing emergency procedures can be used to seed the database. With the above infrastructure, operators can expand MES by using these seeds. To improve the integrity of the information, co-workers can rank and edit the knowledge in the MES.

Figure 10-1 WikiMES - use of the Wiki technology to populate the Motivation-Expectation Space.

The MES is now ready for use in training. Novices can be shown the representation and be asked to tell a story using the representation. MES will facilitate them to mentally walk through the scenario. With this information, it is possible to predict if an operator can quickly generate possible events when these representations are used as a decision aid. The effectiveness of different representations can also be compared. The analysts can ask the operators to develop and peer-compare their MES. The consistency in generating the representations across operators can then be investigated. Also, the analyst can check if there are expert-novice differences in generating these representations.

After these tests have been completed and the analyst is sure that the operators can read the representations proficiently, the next step will be to design a decision support system with the MES. This can be incorporated into the existing alarm summary, and operators can quickly access the representations from an alarm as they troubleshoot faults in the plant. One proposed solution is to show the ends and cause to the operators before showing them the means and effect. In this way, there would be a representation of “knowledge in the world” to help the operators make a diagnosis (Norman, 2002). Operators are presented with decision alternatives and make better decisions.

11. CONCLUSION

The CTA framework consists of five stages: (1) Bootstrapping, (2) Knowledge Acquisition, (3) Data Analysis, (4) Knowledge Representation, and (5) Knowledge Validation.

These steps were derived from two schools of thoughts: Cognitive Work Analysis (CWA) and Naturalistic Decision Making (NDM). CWA can analyze and break down a complex system using a top-down approach, while NDM uses a bottom-up approach. CWA systematically break down the complexity into smaller bits in five stages. Although there were five stages available, in our case only the first stage, Work Domain Analysis (WDA), was developed in detail. Thus, only the WDA was adopted in this study. NDM, on the other hand, builds up system complexity from the smaller bits of information. This gave rise to opportunities in devising techniques for eliciting knowledge.

Despite the differences in approach, the procedures for conducting the analysis were similar. In both CWA and NDM, the practitioner had to define the problem (bootstrapping), gather data (knowledge acquisition), analyze the data (data analysis), present the data in usable form (knowledge representation), and validate the representation (data validation).

The framework was applied to model the work of a petroleum refining operator. Knowledge acquisition was performed using NDM interview techniques, and the knowledge was represented using CWA's Abstraction-Decomposition Hierarchy. Thereby the analysis could draw from the strengths of both schools of thoughts. In doing so, there was a gap in transforming the acquired knowledge for use onto the representation. To overcome this problem, the Applied Work Domain Analysis was devised.

The study was designed to document operator's thought processes, which can help designers to design displays that aid operators in fault diagnosis. The Abstraction Decomposition Hierarchy was helpful. It structured the stories into four primary levels: (1) purpose, (2) cause, (3) strategy, and (4) action. These sub-tasks guided the

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design of the validation study and facilitated the evaluation of the information structure in the currently used displays. The strategy function was developed into the PFD model, which formed a good basis for guiding design.

All five stages were conducted in two of the refining processes. The belief was that the finding from this study was similar across processes and the learning can be transferred. The initial finding, stories in the Cognitive Demands Table, was specific to the task. Themes in the stories were categorized and a generic Process Fault Diagnosis (PFD) model was developed and validated.

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Report on Site Visit

Chevrons Oronite

24 August 2004

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Observations

Chevrons Oronite is a batch processing plant. Each batch takes approximately 18 to 20 hours and the important parameters for batch processing are temperature and pressure. Approximately 30 components are used for producing thousands of products.

Running of Plant

The plant has approximately 300 workers in various departments. The Planning department decides what to produce, based on the market, and issue DO (Delivery order?) to the engineering department, who will process the production. The production team held meeting every morning where the operators will be brief on the plans and any changes for the next few days. The DO slip will also be sent to operators for them to work on.

The batch processing plant shut down for cleaning, maintenance or when changes are made. Lube oil is used for cleaning when the next batch is of the same product as the previous batch. Such cleaning usually last approximately an hour. Cleaning will take half a day if a different product is produced as it has to be more thorough. Field equipment is shutdown weekly for maintenance. Over the five years of operations, the plant has stabilized and equipment database face little changes.

Production Team

Four full-time process engineers assess the DO before the process. They are also in-charge of troubleshooting, as well as writing reports when things go wrong.

There are a total of 6 remote operators and 4 field operators. The distribution of responsibilities over 4 consoles is shown in Table 1.

Table 1 Distribution of Responsibilities

Console	Reactors	Remote Operators	Field Operators
Utilities		1	1
Manufacturing 1	6	2	1
Manufacturing 2	6	2	1
Blending		1	1

Utilities cover the supply of hot oil, tin, air, nitrogen. Manufacturing produces components in 6 reactors each. Remote operators refer to operators who control the valves for the flow of components remotely using Distributed Control System (DCS).

Running of Control Room

System

The original plant was designed by Honeywell. Chevrans have made many changes over the years.

There are many company policies for design, for example, red-tagged means interlock and operator cannot operate the valve,)

The application used for the batch processing is the Total Plant Batch (TPB) server. The system runs on a Local Control Network (LCN) and five Universal Control Network (UCN). The five UCN controls five different functions:

1. Blending and shipping
2. Manufacturing
3. Utility
4. Manufacturing
5. Manufacturing

The system also has a Process History Database (PIMS/PHD) that stores data of alarms and trends for 3 months. This allows process engineers to see trend of the parameter. Other logs includes the Laboratory Information Management (LIM) and the Golden Batch. The Golden Batch is a Perfect batch log, however, it is seldom utilized

Written procedures, known as CyberDoc, were digitized on a separated PC. DCS was used purely for controlling the plant Operating System (OS). The OS will be change from NT to win2000 soon. There is also an Emergency Shutdown System built in the DCS.

Each remote operator works on 4 monitors with two in the safe mode as shown in **Error! Reference source not found..**

Figure 1 Operator's Monitor Display

Operators

Four teams of operators worked in 12 hour shifts, excluding 10 to 20 minutes of handover time. Operators were recruited based on qualifications (Polytechnic), as well as a test. Once accepted, operators undergo on-job-training with an experience operator.

Remote operators had Supervisory Access to the master list and activity log. More robust Engineering Access were limited to the supervisors of the shift. (term doesn't sound right) Operator keeps written log books and undergoes DCS training annually.

Field operators collect samples from the storage tanks for the Laboratory Information Management (LIM) to analyses the chemical contents. LIM will enter the component code into the LIM system. Remote operators will have to check that both codes tally before transferring components.

Alarms

In-house alarm system is used mainly for monitoring process to gather information in the process. It is displayed on two monitors, hung at a height of approximately 2.5m. Fixed point alarms and not rate of change alarms are used for the measurements. The alarm system reflects the status of the specified area in the plant. Three priority levels are set to indicate the criticality of the alarm: emergency, high low.

Appendix A

The alarms were not filtered to allow the operators to spot trends through the alarm channel. Start-up alarms were ignored as the process has not stabilized. Field operators will check on “flickering alarm”.

As of most plants, the number of false alarm has reduced from approximately 2000 to 800 over the years because of troubleshooting. This also means that the plant has stabilized over the years.

Conclusions

This study, being the first visit, was not too in-depth. Common problems, such as the crowding of the control room, were spotted. Training was not really well-understood and operator’s workload was still unclear. Being a batch processing plant, the worst production loss is the collapse of a batch and the consequences are less detrimental as compared to continuous processing plant. There seemed to be fewer problems in batch processing plant. It might not be a good idea to follow-up along this line.

Report on Site Visit

ExxonMobil Chemical

27 August 2004

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1.2	PROBLEMS WITH PRESENT LAYOUT	4
1.3	ORGANISATION STRUCTURE	5
1.4	TRAINING	5
1.5	OTHERS	6

Prepared by:
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1. Observations

1.1 Physical Layout

ExxonMobil Chemical has three business units. Production runs on six chemical plants with two consoles each. The consoles are remotely located at 2 to 3km away from the process. The heart of the console is placed nearer to the equipment at about 1 to 2km away from the process. Each console runs independently and operators communicate to field operator using walkie-talkie.

Five rooms are used for the remote operations:

1. Support consist of
 - Maintenance: contact and application engineers who help to analyze and enhance the plant
 - technical people who know the process
2. Application consist of
 - Troubleshooting and programming
 - Know the logic and control
 - Perform real-time optimization
3. System TDC assists the normal running of the plant. Access is tighter.
4. Operators
 - monitor and manage the process
 - control and manipulate the details
 - Support and operate 24 hours in a 2X12 hour shift
 - One operator is assigned to each console.
5. Office information system stores the plant data.

Appendix B

Figure 1 Layout of Consoles and Its Functions

Figure 1 shows the placement of the consoles and the functions these consoles operate on. It was noticed that the rooms are dimly lit. The three rooms are separated by huge (sliding/folding) door which permits easy access during normal condition. This provides the facility to open up for communication when the need arises.

ExxonMobil Chemical practices Operation Integration Management System (OIMS). In OIMS, document, risk assessment and safety procedures are filed. All changes must be well-documented under OIMS. OIMS focuses on safety, health and environment. The instruction manual is readily available to the operator online. The MPSS procedures which describe the operational instruction for each equipment can be viewed online from the computer behind the operator. A troubleshooting guide which contains the knowledge-base of all possible troubles can also be found.

Facilities located at the field include an Operator Shelter and a Remote Instrument Building. The Operator Shelter is constructed to house the field operators. Remote Instrument building has displays and controls to operate the plant. It serves as a back-up system when there is a total power failure in the main building.

1.2 Problems with present layout

The present layout of the operating room is based on a past criterion that operators should be isolated so that they can be more focused in their work. Figure 2 shows the present layout of a six-console arrangement. The aim was to increase difficulty of chatting among operators.

Figure 2 Present layout of the consoles

ExxonMobil Chemical is looking into new arrangements with their new criterion. The new layout should facilitate communication among operators as operators can help each other keep a look-out for abnormalities, as well as suggest troubleshooting methods. In addition, it should fence out unwelcome personnel, who distract operator's task of troubleshooting, especially during plant upsets. A possible design is shown in Figure 3.

Figure 3 Proposed new design

There is no one ideal design for all scenarios. A good practice would be to design for the most frequently used case.

1.3 Organisation Structure

1.4 Training

There are two types of training: with and without walkthrough. The certification, once obtained, is for life. There is no need to renew as concept, such as flow and operations structure, once understood, stays with the operator. However, names and acronym can be forgotten. These can be picked up with practice.

ExxonMobil Chemical has a training room to conduct training remotely. The room helps to differentiate training from work. Operator works on live plant in the operating room but trains on simulation in the training room. The change is location and setting helps to minimize confusion in the state of mind.

Appendix B

The training room is also use to train new stuff as they join the company. Programme includes: familiarizing with keyboard and screen, startup and emergency shutdown.

Experienced operators observed that operators learn most during upset. Troubleshooting sets operators to think and hence enhance learning. Operators become more skillful with practice. However, the pressure and criticality in live plant does not permit operator the luxury of time. Operators need to be prepared for abnormalities. The training rooms provide the facility to simulate pseudo abnormalities for operators to practice on. This helps to create “experience” for the operators and increase more “if...., then...” (Klein, 1999) scenarios for operators to retrieve when situation arises. With practice, operators will be better-equipped with the knowledge to handle more types of situation. However, practice is on a voluntarily basis and operators attend refresher training only for increment and promotion. It is no basic requirement to practice in the training room to improve troubleshooting skills.

1.5 Others

ExxonMobil Chemical is a continuous processing plant, i.e. productions do not change everyday.

Minor plant upset is about once in 6 months

For complicated plant, emergency shutdown can last 5 days

Operator’s concentration is poorer at night

Report on Site Visit

Sinopec

10 May 2005

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1. INTRODUCTION

The study served as a preliminary understanding, as well as a pilot testing for a bigger project “The Cognitive Operator”. In the project, the objective is to elicit knowledge from process control plant operators in order to design procedures and information displays that fit their expertise. Process control plant is an interesting context for studying cognition as there are complex automations which operators have to manned and troubleshoot. From another perspective, it is equally important to understand the cognition of the operators in the plant since human is one complex factor that contributes to the variability of the system.

By understanding how operators think and work, information can be systematically arranged to aid their task of diagnosing faults in the processing plant. Poor design needs to be compensated by additional effort, insofar as performance are degraded. On top of that, the superposition of many negative effects can lead to system failure.

The objective of the study is to apply Militello’s (1998) Applied Cognitive Task Analysis (ACTA) with Klein’s (1989) Critical Decision Method (CDM) to elicit strategies practiced in a processing plant. ACTA and CDM are retrospective interviewing technique where Subject-Matter Experts (SMEs) are probed for cues and thoughts as they narrate an incident. The strategies collected will be pooled with the data collected in “The Cognitive Operator” and represented in a Strategies Analysis (SA) described in Rasmussen’s (1994) Cognitive Work Analysis (CWA).

In the study, the interviewer utilizes two techniques, *ACTA* and *CDM*, in conducting the interview. The technique is a semi-structured interview where the interviewer can switch between the two techniques in the interview. The interviewer is interested to listen for cues and *strategies* adopted by the participants who are subject-matter-experts (SME) in manning the process plant.

2. FINDINGS

The findings were classified under five sub-chapters: communication flow, SME, cognitive demands table, backward sequential check and socio-technical. *Communication flow* and *SME* presented the physical workings of how the system is run and the apparent duties and goals of the SMEs. The *cognitive demands table* shows the difficult cognitive demands in the incidents narrated by the SME. More importantly, the cues and strategies were presented along with suggested improvements to the existing system. In addition, expert-novice differences were identifies. *Backward Sequential Check* is a detailed discussion of one promising strategy identified by the author. *Socio-technical* discusses the allocation of responsibilities and the trust of the automation. This section presents the author’s views and further studies need to be conducted to refine the arguments.

2.1 COMMUNICATION FLOW

From the interviews conducted, we derived the communication flow of the workers who are involved in the handling the process flow (See Figure 1). They consist of supervisor, process engineers, instrument engineers, console operators and field operators.

Figure 1 Communication Flow in the Process Plant under normal operations, and abnormal situation in the process flow

In the control room sits the supervisor and the console operators. With the close proximity, they are engaged in face-to-face interaction. However, responsibilities of each individual are defined. The supervisor oversees the process. Two console operators monitor two different stages of the process (reaction and separation) using **seven of the ten workstations** (verify with Jin), as shown in Figure 2. An experienced console operator stands-in for the two console operators when they needed to leave their workstation. In addition, there are six video displays that captures six important areas in the field (see Figure 2Error! Reference source not found.).

Figure 2 Workstation layout in the Control Room (adapted from Jin)

The console operators act as the heart of communication (refer to Figure 1). S/he monitors and controls the process through the automation system. S/he will inform the relevant personnel when s/he sees the need to. When s/he needs the field operator to manually control an instrument (e.g. valve and pump), s/he will call the field operators. Each of the field operators is assigned to an area in the plant and this determines who the console operator should call. When the problem is too difficult and beyond his/her means of diagnosis and control, s/he will approach the process engineers for help. S/he will contact the instrument engineers if there is equipment failure. Both process engineers and instrument engineers sit remotely in another building.

2.2 SUBJECT-MATTER EXPERTS

A total of five subjects were interviewed. They comprised of two console operators, one process engineer, one computer engineer and one instrument engineer. Of the five interviews conducted, only two interviews (one console operator and one process engineer) were relevant and useful for analysis.

Both SMEs have the same goal in running the process plant. They attempt to achieve high quality produce at the lowest cost. They speak of three means of achieving it: minimize process fluctuation; minimize energy intake, and use of low cost input materials. These findings were consistent with the first two abstraction levels in Bisantz's work (Bisantz & Vicente, 1994) (See Figure 3). However, the lower abstraction levels were not extracted from the operators as there were no plans to gather information for an abstraction hierarchy in this study.

Figure 3 DURESS II Abstraction Hierarchy (Bisantz & Vicente, 1994)

The first SME is a console operator (reserve). As a reserve, he has to be very experienced and must be able to handle any stage of operations. His daily duties include: attending briefing and debriefing, taking over operations when assigned operator is unavailable, monitoring situations and informing appropriate personnel of situation, changing basic PID parameters and updating the record book. This is to ensure that they have a history of the change and they can revert to the old parameters if the new one is not satisfactory. He was a field operator before he was promoted to a console operator. A field operator is promoted to a console operator only after he is conversant with the field operations of the process and passes a qualifying test. A novice console operator handles the preliminary stages of the process. As he gains more experience, he is promoted to handle the processes in the later stage. Only after he has mastered all stages of the process, is he capable to be a reserve.

The second SME is a process engineer. He is the bridge between the operators and the management. His responsibilities include setting SP limits of operations,

diagnosing situation applying appropriate actions, and preparing monthly report of operations: events, handling, cause, and time of event. He works from 8am to 4pm and his daily routine is to check what had happened when he was off duty and ensure that the production is running smoothly. The SME works for two years as a group leader before working as a process engineer two years ago.

Data from the other three SMEs were not so rich due to the following reasons:

- One of the operators was interviewed in his workstation in the presence of other operators. He appeared to be reluctant to share his experience. This could be due to peer pressure.
- The computer engineer was happy and willing to share her experience. However, her work had little to do with the handling of alarms in the console.
- It was almost time to knock off when the instrument engineer was interviewed. The interview was not in-depth.

There are a few lessons to be learnt here:

- Interviews should not be conducted at the console where operators are working in a team. The team tried to interview one operator at his console. However, he was uncomfortable in answering the questions. This could be due to his workload which was distracting to the interview (or, vice-versa). Another possible reason is that he was unwilling to speak as his colleagues were around. He might find some questions too simplistic to be answered.
- The expertise of a Computer Engineer is irrelevant to the study of the Cognitive Operator.
- It is not advisable to conduct the interview when the SME's attention is not with the interviewer. Instances where this happens include: prior to knock-off time, prior to lunch time or when the SME has other matters on hand. Hence, it is worthwhile to inform the SME about the interview at least one day in advance. This allows the SME to make necessary arrangements with his work.

Figure 4 Example of related parameters in a system

2.3 COGNITIVE DEMANDS TABLE

Example	Difficult Demands	Cognitive	Common Errors/Novice-expert difference	Cues & Strategies	Suggested improvements
	It is difficult to consider the cause and effect in the process		Novice will send outfield to take a look instead of visualizing the process.	View <u>alarm summary</u> to gather an overview. Look at the coding to identify <u>location of alarm</u> . Look at <u>PV</u> and <u>SP</u> values. Change SP if needed and monitor the situation.	Equipped operators with the necessary basic laws of physics.
	Wrong diagnosis that leads to a bad outcome (false alarm).		Like cycling, novices are afraid to operate and control the system.	Hands-on is very important. Even with theory and guidance from a master, fear in the novice cannot be removed until he starts to operate on the system. Only with practice will he be confident of operating the system.	Allow novice to practice on simulations
Pipe leakage	The air in the plant is slightly polluted as compared to other environment. Hence, it is difficult to differentiate even if there is an aberrant smell.		Novice might not be able to differentiate the smell.	<u>Smell of oil</u> in the air. Based on his previous experience, he can quickly identify that there is a leakage. Operator can <u>touch</u> the pipe to feel for the <u>temperature</u> . Logically, there would be a decrease in temperature if there is a leakage (pressure drops to atmospheric pressure).	Teach operators these cues in training

Appendix C

Example	Difficult Demands	Common Errors/Novice-expert difference	Cues & Strategies	Suggested improvements
From the video display, operators noticed smoke coming out from the tower.	Understanding of the process flow and channeling.	Novice focused only on the faulty equipment.	Use of a backward sequential check (See Strategy 2)	Improve information flow in the design of display
	The challenge is to come up with simple solutions for complex problems.	Novices cycle through more wrong causes before deriving the correct ones.	The causes that experts generate have two characteristics: high probability and simple. They cycle through the causes until they find the correct one. This strategy is similar to Klein's Recognition Primed Decision Making (Klein, 1989). However, they coined this strategy "elimination".	Have the system suggest list of possible causes.
Some parameters are coupled and they fluctuate in-phase. For example, valve A and B in Figure 4, are coupled and fluctuate in-phase as the flow (controlled by Pump C) varies.	Understanding of the physics of the system. Having a correct mental model of the relationship between the parameters.	Novices are unable see the relationship between the various values. Frequently, they tunnel at one caused and missed other related cues.	Look at other related display. If parameters, which are supposed to be in phase, are not changing concurrently, the readings are suspicious.	Reduce the coupling in the system. However, there should still be redundancies. Brainstorm for ideas to bring teach operators the use of these redundancies

Example	Difficult Demands	Cognitive	Common Errors/Novice-expert difference	Cues & Strategies	Suggested improvements
Equipment error			Novices are unaware of this technique. They will send the field operators to check.	To check if there are equipment errors, perform small adjustments and expect the display to change. If there are no changes, something is wrong.	Teach this technique in training
Electric supply trip. This is a rare incident. However, the area that was affected was large. All control points are affected. Some resume automatically while others require activation by operators.				Flicker in the lighting system, all alarms are active. There are around 60 alarms. We try to resume the major processes first. These include the operation of pumps, the stability of the fluid flow and temperature. All field operators will go out to check their assigned areas. We traverse screen after screen until all the parameters are back to normal.	Review procedures to handle these events periodically
Sudden rise in pressure reading	Understanding of physics	of		Experts understand that it is illogical to have an immediate rise in the pressure. In addition, experts are able to perform calculations to predict the situation.	Equipped operators with the necessary basic laws of physics.

2.4 BACKWARD SEQUENTIAL CHECK

A strategy adopted by SMEs, as they diagnose a situation, is to look back at what had happened prior to the occurrence of the situation. The author named this strategy as “Backward Sequential Check” or “BSC”. BSC can function in two modes – time and process. (Check: Cause-and-effect analysis) In the terms of time, the SMEs look at what had happened prior to the event. This can be the operations that were being performs on a particular device; has the device been changed recently? In the process mode, the operator refers to the process line in the analysis. The flow of diagnosis takes the opposite direction of the process flow (See Figure 5). In the example, the process flows from device A to D. When a fault occurs at device C, the operator first check device B, followed by device A. SME do not consider device D unless it is closely related to device C. When adopting this strategy, diagnosis takes a path that is opposing the process flow.

Figure 5 Backward Sequential Check - Process mode

Graphical timeline serve as a useful tool when BSC is conducted in time mode. SMEs analyze trends to understand what had happened prior to the incident. In addition, they look for previous faults that had happened to the device and the operations that had been performed. The existing system is able to aid the operators in these aspects. They found the timeline provided by the system useful. When asked if they refer to the paper recordings they made every two hourly, they exclaimed that the graphical plots in the electronic system are easier to analyze. However, there are still rooms for improvements in the history log of events.

In the process mode, graphical representation of the process is a useful aid for the operators. Presently, this is able to provide operators with strong “knowledge in the world”. They are able to refer to these drawings and utilize the information for analysis.

2.5 SOCIO-TECHNICAL

Figure 6 Monitoring vs. Decision-making in Process Control

In the monitoring vs. decision-making model drafted, responsibilities hop between human and computer. At the most primitive level, computer monitors points in the process plant. Computers are capable of handling the vast amount of information and are more consistent than human in monitoring the process. However, the mathematics for problem solving in the computer are set up by designers who are not capable of predicting new situations (Bainbridge, 1983). Hence, it is beyond the capacity of the computer system to generate new solutions. Ultimately, human are still needed to troubleshoot problems and optimize the process. With the data retrieved by the computer, they are able to derive new meanings and make decisions which are more robust. But, human has his/her limitations in making decisions (Wickens & Hollands, 2000). They might miss critical dangerous cues when they are under stress. Hence, the consistent assessment in the computer is needed to override the human's decision to keep the process within safety limits.

Process engineers set the limits for the alarms. They tend to set it within a conservative range such that the operators are informed of the situation at an early stage. Experts know these ranges and use it to facilitate their understanding of the situation for the timely identification of anomaly. Based on their experience, they understand that no actions need to be taken when these alarms sound. (Do they use Statistical Process Control Theories – warning limits?)

Maintaining the system is still based largely on human judgment. Sensors act as a “scout/pageboy/informant” to bring awareness to the team. Operators later monitor affected components closely and react appropriately to achieve their goal of sustaining and optimizing the system. Emergency shutdown system takes over the control when the team is unable to handle the situation.

Further studies: Why does the operator have less confidence in the monitoring of the trend (optimization) but so much confidence in the Emergency Shutdown System (safety)? Survey should be constantly conducted to find out the level of confidence operators have on the Emergency Shutdown System. Whilst there may be fewer possibilities in an emergency system as there are in optimizing operations, dangerous limits are still not al-predictable. Overdependence on system to adhere to safety limits can be dangerous. Operators should be clearly notified on the limits of machines and should be actively engaged in understanding these limits. If they possess a misconception that the ESS is able to predict all situations, there will come

a time when awareness of safety limit will be lost. We should be clear that what goes into the computer system is nevertheless derived from human.

3. PROBLEMS ENCOUNTERED IN INTERVIEWS

Subjects might be too eager to impress. E.g. Mention of Emergency Shutdown System. Are they really sure of the system? Has there been successful diagnosis? Interviewer should doubt these points and probe further. However, this also means that interviewer must be aware of the limits. At the point of interview, I had not considered these loopholes. Further detailed studies should be conducted.

A good way of interview is to have the simulation in the interviewing room. This facilitates understanding throughout the interview. An equally effective way is to have plenty of papers for explaining the systems, as well as cues.

To further understand the work of the operators, it is good to perform near-silent observations and note down the behavior of the operation. Occasionally, interviewer can conduct small interviews with operators to understand their rationale behind certain actions.

4. FUTURE DIRECTION

ACTA and CDM were proven to be effective tools to extract information for a SA. This is a positive prelude for “The Cognitive Operator” and the chances of meeting the goal of eliciting knowledge is high. However, the author sees the need to include a Work Domain Analysis (Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999) before conducting the interview. This allows the interviewer to have an overview of the system and thus, the interviewer will be able to probe for deeper thoughts.

As proposed, the statements derived from the interviews should be verified by having the SMEs rate the accuracy of the statements. The reason being that the data presented is heavily dependent on the interpretation of the researcher. Like most subject studies, there are many loopholes in the research methodology and the results might be controversial. Hence, a rating from the SMEs can prove the confidence of the data.

5. CONCLUSIONS

The study has led to an understanding of the process plant. Though the one day interview was unable to achieve an all-rounded understanding of the workplace, the information collected was a great leap forward. At the very least, the workings and operations of the plant were understood. In addition, the strategies practiced in the plants were extracted with ACTA and CDM. The methodology for “The Cognitive Operator” was analyzed and refined. Also, lessons were learnt and experience was gained.

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Findings from Interview
2005

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Cognitive Demands Table

Appendix D

Story ID: 1 Story Title: Recycle Gas Compressor failure			Expert ID	2	Job Title	Shift Controller
Storyline	Cues	Strategies	Difficult Cognitive Demands		Common Error/Expert Novice Difference	
There were many alarms. The shift controller checked the panel and quickly identified that the airflow in Gas Compressor K6801 had tripped.	There were two main reasons for focusing on K6801. First, K6801 was in the upstream of the process. A trip in the compressor K6801 would cause the feed and furnace to trip. The shift controller understood the domino effects in the process. When the compressor trips, there would be insufficient hydrogen to transport the feed. Hence, there is an in-built safeguarding system that trips the feed. When there is no flow in the furnace, heat in the furnace would not be channelled away. Hence, the furnace has been programmed to prevent overheating. Second, the shift controller understood the severity of a compressor trip. It was easier for him to restore the feed and furnace rather than the compressor, which might need to be repaired. Hence, the compressor was his primary concern and he checked it first.		When a unit trips, there are usually 20-30 alarms. The locations of the alarms on screen are identified. E.g. Platformer unit is denoted by 68, so the alarm might be 68T000. T denotes temperature (other parameters include: P for pressure, Q for Quality (% of impurities, e.g. S), L for level, R for ratio, F for airflow). The last 3 digits denote the instrument. With a large number of alarms and information, it is difficult to step into the situation and get a good grasp of the situation.		Due to the complexity of the plant, novices need to learn many things. They need to know the tag number, colour and location of every pipe and piece of equipment in the plant. In addition, they have to understand the functions and limitations of the equipment. It takes a novice 2 years to learn the basics. The novice starts by tracing the lines in the field. Gradually, they learn to associate the physical line with the schematics in the panel. The shift controller, on the other hand, focuses on how the plant functions. Recalling the numbers has become a skill to him. This may or may not be easy for the novice. The effect of the memory association is also known for stressful situations.	
When the shift controller identified that the Gas Compressor K6801 had tripped, he immediately dispatched his unit men to close 36 related valves	The furnaces would be over-rich with fuel. All available men had to go and shut the 36 valves of the furnaces manually.		This is part of the Emergency Procedures. There are many scenarios and actions in the Emergency Procedures. Operators will need to know the appropriate actions for the situation.		Novices may face difficulties in recalling the procedures.	
The shift controller also informed the duty manager, who was in charge of the facility, about the severity of the problem. The facility comprised of the operation of three other control rooms.	The shift controller understood that the breakdown of the system would cut production of H2 in the Platformer. As Platformer supplies H2 to other units in the facility, the breakdown would mean a shortage of H2 at the other units. He informed the duty manager so that he could disseminate the information and make the necessary adjustments.		The shift controller has to gauge the magnitude and severity of the abnormality.		A novice will not be able to understand the impact of the breakdown on other units. As the plant is highly integrated, the shift controller has to know the relationship between the various units. He has to know how the inputs and outputs are linked.	
The duty team leader led the technicians to restart the compressor. However, it was still not working. He instructed a unit man to go to the field to take a look. The unit man cannot find the problem. The shift controller suspected it was a mechanical rather than electronic problem. So he asked for the standby (it was a night shift) instrument engineer to look for mechanical problems. They found that the Governor valve had disengaged with the steam valve.	The practice is to try to restart the system when it breaks down. However, that did not work. The shift controller suspected a mechanical problem and contacted the instrument engineer.		The primary responsibilities of the shift controller are to run the plant and consult engineers and managers when needed. The design and repair of the equipment are handled by the Engineers. In this situation, the shift controller knows the functionality, internal construction of the compressor. He was able to make the right diagnosis and consult the relevant engineers.			

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Storyline	Cues	Strategies	Difficult Cognitive Demands	Common Error/Expert Novice Difference
However, they had no spare valves. The shift controller ordered for a decrease in the production level to reduce the internal consumption of hydrogen.	It was not possible to restart the compressor. Rather than shutting down and starting up the plant, the shift controller put the production on idle		It takes a lot of effort and many days to start up the plant. This is unlike other system (e.g. computer) where restarting is easy.	

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Story ID: 2 Story Title: Mis-programmed valve			
Expert ID		4 Job Title Team Leader	
Storyline	Cues Strategies	Difficult Cognitive Demands	Common Error/Expert Novice Difference
<p>When the Platformer unit was first started in 1994, many problems were anticipated. A 100% fool-proof check before the first start-up was not economical; it was impossible to predict all possible process. To master this situation, only experienced operators were engaged as panel men. In the first year of operating the Platformer, there was approximately one major fault per week.</p> <p>The expert was the panel man and he narrated one incident from those times. The alarm summary showed a trip in Booster Compressor K6831. The panel man looked at the live video of the flare system and saw that the flare was bigger than usual.</p>	<p>The panel man traced the process line in a direction opposing the process flow. He focused on the operation of various equipments rather than the faulty equipment. Knowing that the flaring system was on the immediate upstream of the compressor, he looked at the live video and noticed an abnormally large flare.</p> <p>The panel man suspected that there was excessive hydrogen fuelling the flare. This could be due to a back-flow in K6831.</p>	<p>To identify the equipment that was linked to K6831, the panel man needs to know the process flow.</p> <p>In addition, he had to know what a normal flare looked like. Being a completely new plant, he had to judge the abnormality based on his experience of other plants.</p>	<p>In troubleshooting, a novice may be too focused on the digital information and miss the image in the live video recording. The video display was located on a grid at some distance from the panel. The interaction between the operators and the video was single-directional. Information flowed from the video to the operator.</p> <p>Operator may be too engross in analyzing the controls and feedbacks in the panel. Though the live recordings displayed critical area which required higher surveillance, the operator may miss the isolated information in the midst of reading and controlling the panel.</p>
<p>The panel man turned to the K6831 schematic. The booster compressor had two stages of compression. In the first stage, the feed was compressed from 6bars to 18 bars. In the second stage, the feed was compressed from 18 bars to 30 bars.</p> <p>He checked the recirculation valves on the panel. The recirculation valves 68PC012A/B were used to ensure a normal feed by re-channeling the output of the compressor back as an input. This was achieved by opening the normally closed recirculating valves when the inlet pressure of K6831 was low.</p>	<p>To confirm his suspicion, he checked the hydrogen pressure at the outlet of K6831.</p> <p>The hydrogen pressure at the outlet of the second stage was indeed dropping quickly from the intended 30 bars towards 21 bars, a dangerous level.</p> <p>One highly probable cause of the hydrogen back-flow was that the recirculating valves were open.</p> <p>However, the panel reflected that the recirculating valves were closed at 0%. This validated his suspicion.</p>	<p>The panel man needed to know the internal construction of K6831 to know exactly which parameter to look at, in this case the hydrogen pressure.</p>	
<p>He sent his unit man to check the recirculation valves.</p>	<p>Nevertheless, the panel man was confident of his diagnosis of the fault. He sent a few unit men to check the two valves. The unit men found that the recirculating valves were indeed open.</p>	<p>The panel man needs to know which valves are to be open and which ones close.</p>	
<p>The panel man put the system under manual mode to override the logic in the recirculation valves. With the help of the unit man, the recirculating valves were closed and they started the compressor K6831.</p>	<p>The panel man adjusted the parameters (0% to 100%) of the recirculating valves to close the valves. The unit men manually judged the status of the recirculating valves. The team finally closed the first recirculating valve with a value of 100% and the second recirculating valve with a value of 50%. This did not conform to the conventional settings of close at 0% and fully open at 100%.</p>	<p>The mental effort needed to rationalize and identify the faulty cue.</p> <p>This is the case an a wrong configuration. To check, panel man perform small adjustments and note to change. If the change is not as expected, something is wrong.</p>	

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Appendix D

Story ID: 3 Story Title: Tracing a dislodged pipe			
Expert ID		4 Job Title Team Leader	
Storyline	Cues Strategies	Difficult Cognitive Demands	Common Error/Expert Novice Difference
Re-commissioning is the task of putting a piece of equipment back into the system after it has been repaired or sent for maintenance. The operator re-commissioned compressor K3551 in hydrotreater HDS together with two unit men. K3551 had been sent for maintenance. In K3551, H2 was the feed. During the maintenance, O2 was built up in as it was exposed to the atmosphere. Hence, the unit man had to get rid of the oxygen in the system (O2 free the system) and replace it by H2 in the re-commissioning. However, O2 and H2 can react. Hence, an inert N2 was used to flush the O2 out of the system before H2 was used to flush out the N2. While N2 is harmless, flushing out N2 relieves the system of needless pressure buildup. While they were increasing the pressure to flush N2 using H2, they heard a deafening 'pop' followed by a violent 'hissing' sound. The structure shook violently. They immediately isolated K3551 by shutting the 12 valves at the 3 inlets and 3 outlets of the compressor.	When problems arised, the first thing to do was to restore the set-up to its original form. Although it was dangerous to return, the risk of leaving was greater. The unit could explode and lives could be lost. Moreover, it was their duty to keep the unit safe. Another alternative was to shut down the unit. But, they do not think that this was a good decision. They had to find the leak and put the unit back to a safe level.	The unit man was fairly confident that H2 was in the air, because there was a faint smell of rotten egg, an indication of H2S. (is H2S an impurity in the H2 supply?) Knowing that H2 might ignite and cause an explosion, they decided to evacuate. Informing the control room was part of the procedures when problems arised. The unit man chose a safe place to do the reporting. Although it was dangerous to return, the risk of leaving was greater. The unit could explode and lives could be lost. Moreover, it was their duty to keep the unit safe. Another alternative was to shut down the unit. But, they do not think that this was a good decision. They had to find the leak and put the unit back to a safe level.	Novices are also trained to react in this manner. However, some novice may experience shock.
However the noise and the shaking persisted. They were fearful and ran down the staircase from the 2nd level to the ground level. On the ground level, they recomposed themselves. They informed the control room and more unit men were dispatched to assist them. The unit man assessed the risks and decided to go back to the leak to rectify the situation	The unit man knew the properties of H2. As H2 is colorless, identifying the leakage becomes a problem. In addition, H2 is explosive. With a large volume of H2 in the open air, an explosion may take place and they may lose their lives. The unit man knew that they had to go to a safe place to radio the control room. On the ground floor, without the 'earthquake' below their feet, they were more composed and communicating to the control room was more effective.		

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Storyline	Cues Strategies	Difficult Cognitive Demands	Common Error/Expert Novice Difference	
Each unit man searched a level.	They distributed the task and each unit man searched a different level.			
The unit man pulled his gloves halfway down so that they were dangling at his fingertips.	Since H2 is colorless, it cannot be detected through direct vision. It is also dangerous to feel with bare hands for the leak as a 50 bars jet can easily pierce through him. Auditory inspection did not work since the hissing noise was too loud. The unit man tried to use his gloves to find the leak. A leak would move the gloves. Hence, he could identify the leak.	In this incident, the unit man had used his gloves to identify leaks, he had also make use of other materials such as a sheet of paper in other incidents. There were also the other tricks he improvised to simplify inspection. Rather than walking over to check if a valve is open, he would visually inspect the distance between the wheels on the valve.		
The unit man found a ¼ inch stainless steel tubing pipe dislodged and vibrating vigorously. The pipe was located under the meshed floor that he was standing on.	The unit man felt a stronger vibration at one spot as compared to the surrounding area. He stopped and used his dangling gloves to probe for possible leaks. He searched from top to bottom. As he bent his knees, he saw a dislodged piping vibrating at a faster rate than other parts of the structure. He understood that this was the leak.			
The pipe was among a bundle of several pipes. The unit man shouted for his colleagues to come over.	The unit man knew that he had found the root cause of the danger. The next step was to gather the help of his colleagues to stop the leak.			
They quickly traced the source of the dislodged pipe and closed the valve to isolate the leak. The hissing and shaking stopped immediately.	Only one of the two ends of the rupture was vibrating. The calm end was a short route leading to the pressure gage and the pressure had been released. They traced the piping in one direction and found a valve. They shut the valve to stop the pressure from coming through.			

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Story ID: 4 Story Title: Followers needed				
		Expert ID	5	Job Title Team Leader
Storyline	Cues Strategies	Difficult Cognitive Demands		
	Common Error/Expert Novice Difference			
It was during a shift briefing when the platformer tripped. The operator was the unit man for the LRCCU. Hence, his main concern was the LRCCU. For the entire incident, he listened to the panel man and followed his instructions.				

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Story ID: 5 Story Title: Uncrackable feed				
		Expert ID	5	Job Title Team Leader
Storyline	Cues	Strategies	Difficult Cognitive Demands	
The discharge from the compressor dived from 500t/d to 450t/d. The panel man got the unit man to physically check the following: lube oil, noise, temperature, cooling water. The panel man reported to engineering. The panel man tried to shut the discharge valve, but the flow continues to drop. The cause of the dive was that a batch of "uncrackable feed" slipped into the LRCCU. This amounted to 30% of the feed and resulted in insufficient production of the light ends.			Common Error/Expert Novice Difference	

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Story ID: 6		Story Title: Sheared governor valve in recycle compressor		Expert ID	6	Job Title	Shift Controller
Storyline	Cues	Strategies	Difficult Cognitive Demands	Common Error/Expert Novice Difference			
During a shift briefing, the plantowner tripped. The alarm summary page was flooded with alarms. A team leader tried to find the root of the trip. However, new alarms keeps seeping in, hindering his search. The operator looked at the Summary of Events (SOE). SOE was a newly installed system to aid fault diagnosis. It captured events at the separation of 0.001 seconds. Hence, operators were able to identify the first alarm.	Whilst the shift controller was certain that his duty team leader was trying to put the plant to a safe operating condition, the shift controller was trying to find the root of the problem. The alarm summary was useful in alerting operators of upsets and a useful tool for diagnosing minor upsets. The operator knew how bad the system would be flooded when the scale of the upset was great. Hence, he turned to the new technology, SOE, hoping that it would facilitate his diagnosis		Some operators would not have tried the new system in an abnormal situation.				
However, the information on the SOE was too complicated. Shortly, he gave up on the SOE	There might be some cues in the SOE that prompted the shift controller the SOE is not functional.		There were indeed problems with the SOE. After the incident, the shift controller checked with the technologies and found that the SOE was not working ideally.	Some operators may trust the new technology, and missed the big picture. They may not see that there are inherent problems with the SOE and insist on using the system, despite its difficulties.			
The Shift controller decided that attempts to use the panel were futile. Instead, he got his unit man to check the governor valve for compressor K6801.	The shift controller knew that the compressor had tripped previously and the solution to the trip was a temporary first-aid solution. The replacement for the governor valve would only arrive in a few months. Hence, it was likely that the first-aid solution was not working.		The shift controller was able to link the trip to a past trip that happened days ago.				
He went out to the field to see the condition of the valve. The Shift controller was determined to trace the problem with the governor valve. It had tripped previously in the night shift, it was reported that the locking was sheared. However, the X-ray of the locking showed otherwise. They were also speculation that there might be loop-oil failure or speed pickup failure but nothing was proven. In his investigation, he found that the screw thread on the locking had worn off.	In the tripped state, the linkage looked normal. The actuator and link were both retracted (See Figure). The shear that was reported cannot be seen from the outside of the linkage. The shift controller, with the help of his operators, actuated the governor valve and observed its behavior. He observed that the link was floating. When the actuator unscrew, the link did not move outward as expected. He suspected that the screw thread, which was the actuating mechanism, had worn off. He checked the screw thread and found faint traces of the thread. This confirmed his reasoning.		The shift controller had to understand the mechanism and operating behavior of the governor link to identify the problem. Under normal operation, when a signal was sent to open the valve, it would unscrew the connection between the actuator and the link to the governor valve. The link would response by moving outwards (See Figure). When the governor valve was tripped, it shut the valve by retracting both the actuator and the link. There has to be good lighting for the shift controller to identify the movement and the wear-off threads.	Others might not have used such a strategy to test the failure. In addition, timing played a critical role in the diagnosis. Previously, the fault had happened at night where visibility was poor. After the problem was rectified with the first-aid solution, engineers were unable to perform further testing. They can only make use of X-rays to test the suspected failure: shearing.			
The Shift controller ordered his operators to screw in the actuator for two rounds.	Previously, the actuator was screwed in for one round. He was hoping that the two rounds can work for two weeks as they sourced for a better solution.						

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Story ID: 7 Story Title: Hydrotreater trip				Expert ID	6	Job Title	Shift Controller
Storyline	Cues	Strategies	Difficult Cognitive Demands	Common Error/Expert Novice Difference			
<p>The platformer tripped.</p> <p>The shift controller ordered a novice operator to put the hydrotreater HDS4 to a full recycle.</p>	<p>The platformer produced a large quantity of H2 for downstream processes. The H2 was stored in vessel before it was transferred to the downstream processes. A cut in the H2 supply would deplete the store of H2. Consequently, the downstream processes would trip.</p> <p>The shift controller wanted to arrest these effects before they happened. Hence, HDS4, which consumed the largest quantity of H2 (2/3 of the production), was put to recycle.</p>	<p>Three highly probable causes were feed, furnace and H2 supply. The shift controller searched all three to identify the cause of the trip.</p>	<p>The operator was able to visualize the effects of the trip on the processes downstream. He judged that the supply of H2 was sufficient support the smaller H2 consuming processes.</p>				
<p>Despite the preventive measure, HDS4 tripped. The shift controller flipped through the graphics and found that there was an alarm indicating that the flow of H2 in HDS4 was low.</p>				<p>The novice operator may overlook the H2 flow as he had operated on it not too long ago.</p>			
<p>The shift controller checked the flow in the recycle hydrogen supply and found that the compressor was operating at 50% instead of 100%.</p>		<p>The shift controller suspected that the novice operator had not increase the compressor of the recycled H2 from 50% to 100%. The H2 supply came from two lines: the fresh H2 supply from the vessel and the recycle H2 within HDS4 (See Figure 2). These two operations should add to 100%</p>		<p>The novice operator was unable to see the relationship between the two supplies. When he was asked to put HDS4 to recycle, it meant unloading the fresh H2 compressor from 50% to 0%, as well as, loading recycle H2 compressor from 50% to 100%. However, he missed the loading and thus, there was insufficient flow of hydrogen in HDS4.</p>			

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Story ID: 8 Story Title: Regenerator section momentum				Expert ID	7	Job Title	Team Leader
Storyline	Cues Strategies		Difficult Cognitive Demands	Common Error/Expert Novice Difference			
<p>A valve X575 at the flow control hopper was faulty. The flow control hopper, located below the regenerator R6851, controlled the flow of catalyst in the regenerator. R6851 regenerated spent catalyst from the platformer reactors R6801/02/03/04. (See figure) The operators decided that they would put the catalyst regeneration section on standby to repair X575.</p>	<p>The operator foresaw the consequent of the event. The regenerated catalyst would continue to flow. The level of catalyst in R6851 would build up and the pressure in R6851 would increase. Since fluid flowed from high pressure to low pressure, the untreated corrosive gas in R6851 would flow to other parts of the system and damage other equipment. To avoid the damage, a pressure difference safety alarm (PDZA) would be reported and the regeneration section would trip.</p> <p>The catalyst would continue to flow. When the flow of catalyst reached X575, it will be diverted to a storage vessel. However, this was not feasible. The catalyst in R6851 would deplete and the pressure in R6851 would drop. When the pressure dropped, the untreated corrosive gas in R6851 would flow to other parts of the system and damage other equipment.</p> <p>Repair of the valve was tedious. It would take a few days for it to be completed. It was unlikely that regeneration section would not be tripped.</p> <p>The regeneration section can be put on standby. All flow in the regeneration section would halt. Burning of the coke off the spent catalyst</p>		<p>The operator had to weigh the risk between damaging the equipment and decreasing the production. Since the operator had a primary goal of keeping the plant safe rather than production, the choice was obvious. The operator also understood the limitations of the problem. It was unlikely that R6851 would be able to sustain the duration needed for the repair of the valve.</p>				
<p>Isolating X575 required the catalyst in the pipelines to be unloaded. Contractors were engaged to unload the catalyst. The operator demanded and oversaw that the contractors labelled the storage drum and loaded it back in order.</p>	<p>The operator foresaw that there would be problems if the catalyst was not replaced in order.</p>		<p>The operator understood that the regeneration section had stabilized over the years. There was a momentum running in the system. Altering the supply of the catalyst might lead to unpredictable behavior in the start-up after the repair.</p>	<p>Novice operators would not have the experience to understand the momentum and the effect of the disturbance. They had not been in start-up teams where upsets were frequent and the system was unstable.</p>			
<p>When the catalyst was finally loaded, the operators were ready to start-up the regeneration section. Based on previous experience, this would take approximately 4 days. They would have to observe the air flow, temperature profile and the catalyst carefully. During the start-up, they replaced the flow of air at the chlorination zone with nitrogen.</p>	<p>The operator understood that the chlorination zone, downstream of the regenerator zone, was operating at a higher temperature. If the catalyst was not fully de-cooked in the regeneration zone, it would burn at the chlorination zone. At the higher temperature, the catalyst would melt and thus damaged. Since the section was starting up, the operators were unsure if the catalyst had been fully de-cooked at the regeneration zone. To arrest the situation, they replaced air with N2. Since N2 was inert, it would not react with the coke and melt the catalyst.</p>		<p>The operator knew that they cannot take it for granted that the start-up condition was exactly the way it was during the shut-down. He arrested possible problems before it happened.</p>	<p>Novice operator might not have the foresight and the knowledge.</p>			

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Storyline	Cues Strategies	Difficult Cognitive Demands	Common Error/Expert Novice Difference
The start-up was progressing slowly but fine, until the operator was away on his off-days. There were request from the management to increase the production back to 2400t/d. Under the stress from the management, the flow in platformer was increased. When the operator returned two days later, he exclaimed that the practice was unacceptable.	Based on his experience, he was aware that the coke deposited in the platformer would not be fully de-coked in the regenerator under the specification: 2400t/d flow in platformer with 60% flow in regenerator. It was necessary for the regenerator flow to reach 100% before the platformer flow was increased in steps. If the rule was not followed, coke would build up on the catalyst and it would be difficult to stabilize the unit.	The operator understood that the rate of coke deposition must match the rate of de-coking. He knew the limitation of the process and judged that the condition of the unit was dangerous.	Other operators were not able to predict the risk involved. Frequently, risks were taken to meet demands. There were times when there were no ill-effects.
Indeed, coke was building up. The production rate was lowered to 2000t/d and the pressure in the platformer was raised. When the pressure was raised, the Required Octane Number (RON) was affected. This meant that both quantity and quality of the product dropped.			

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Appendix D

Story ID: 9 Story Title: Accidental shutdown from another department				
		Expert ID	8	Job Title Senior Operator
Storyline	Cues	Strategies	Difficult Cognitive Demands	Common Error/Expert Novice Difference
The flange of the MPS steam supply to C2851 caught fire. The operator put out the fire.				
He suspected that there was a backflow of HCO from C2851 to the MPS supply. (See Figure)	Normally, the fluid in the flanch was steam. It was not possible for steam to catch fire. HCO, on the other hand was flammable and could auto ignite when there was a right mix of O2 and HCO at the flash point.			
He continued his rounds to the furnace.	The operator instinctively walked to the furnace that was on the downstream of C2851.			
He saw HCO pouring out from the off-gas lines. (See Figure)	(What is the colour of HCO?)			
The operator called the control room for the panel man to shut down the furnace.	The operator knew that this could cause an explosion in the furnace. The furnace was shut-down to arrest the situation.			
They got the fire department to be on standby.	HCO might also be leaking in other pipes and auto ignite at other location.			
The panel man found that Movements, the plant handling the flow of feed and product, had accidentally shut-off the run-down for C2851. This caused a built-up of HCO in C2851. The HCO overflowed to the upstream MPS supply and the down stream off-gas supply. (See Figure)				

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Story ID: 10	Story Title: Broken catalyst		Expert ID	1	Job Title	Process Engineer
Storyline	Cues	Strategies	Difficult Cognitive Demands		Common Error/Expert Novice Difference	
Hydrotreater (HDT6) was used to desulphurize (reduce sulphur level) Light Cracked Oil (LCO) before it was transferred to the Gas Oil (GO) pool. The pressure, ΔP , in HDT6 was to be kept below 10 bars. At maximum ΔP , the top tray would break in the reactor and catalysts would fall and break the bottom gasket. This had to be prevented as repair would mean addition cost incurred to the company.	The process engineer noticed that there was an unusually high pressure in HDT6. Two options were generated and they were carried out concurrently. First, the process engineer would undertake measures to rectify the problem. These measures were online methods (methods that apply while reactor is still running). They didn't work. The process engineer recommended H2 stripping. Unfortunately, it did not improve the situation. Next, the process engineer suggested a CCN washing. Second, the process engineer had to plan a shut-down of the reactor before the tray and bottom gasket broke. The process engineer calculated the rate of increase in ΔP to extrapolate the time whereby the pressure would hit the critical 10bars. Also, the process engineer had to assess the impact of the shut-down on other units along the process flow. To minimize the loss in production, the process engineer had to find out when the other units were scheduled for shut-down, maintenance, etc. The process engineer could approach the Economics and Scheduling (E&S) team for the information.					
After shutting down, the process engineer went into the reactor through a manhole to investigate the problems such as physical fouling, or deposits of iron scales.	The process engineer found that the 'Rashid' rings in the reactor were broken. Also, there was a layer of powders on the top tray of the reactor. This was not normal. As these fines (second bed) were one bed above the catalysts (third bed), the process engineer suspected these were catalyst fines (broken catalysts). The powder was sent to the in-house laboratory to identify if they were catalysts. The lab verified the conclusion,				The process engineer had experience with inspecting hydrotreaters. Together with an experienced colleague, they identified that the fines were abnormal. Both saw that there was a problem with the white powder.	
Based on when the startup date was, the catalysts was decoded by different means.						
After the troubleshooting, the process engineer ensured that broken rings were replaced and a fresh bed of catalyst was layed. Operations of HDT6 resumed. However, the problem was not resolved.	The process engineer noted that the pressure was again too high. The usual pressure for a hydrotreater with a fresh bed of catalyst was approximately 3 bars. HDT6, however, was at a pressure between 6 to 7 bars. The process engineer has proposed for more pressure gages to be installed such that the problems can be localized to specific area. However, this would involve an installation cost. Hence, the solution has to be weigh against other options such as changing the brand of catalyst, or using other hydrotreaters.					

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Appendix D

Story ID: 11 Story Title: Regeneration valve failure				
	Expert ID	2	Job Title	Shift Controller
Storyline	Difficult Cognitive Demands		Common Error/Expert Novice Difference	
Cues Strategies				
<p>If cooling water leak, that part of the plant can become gassy. A passing unit man can detect the smell from the cooling water from exchanger. It is smelly. They may then suspect that it was mixed with gas in the exchanger. To verify this, lab test has to be conducted.</p> <p>In starting up a FCC plant, the temperature in the riser was not going up. The reactor was unable to run at the required temperature. The panel man suspected that catalysts feed was not coming in. The likely cause was that the slide valve was not open. A field check showed that this was true. The slide valve was stucked. Shut down was not done properly. This was a mechanical issue.</p>				

**To understand the organization structure, see page A16.

Cognitive Demands Table

Appendix D

Story ID: 12 Story Title: Shanghai Case Study			
Expert ID		Job Title	
1		Process Engineer	
Storyline	Cues	Strategies	Difficult Cognitive Demands
	View alarm summary to gather an overview. Look at the coding to identify location of alarm. Look at PV and SP values. Change SP if needed and monitor the situation.	Hands-on is very important. Even with theory and guidance from a master, fear in the novice cannot be removed until he starts to operate on the system. Only with practice will he be confident of operating the system.	It is difficult to consider the cause and effect in the process
Pipe leakage	Smell of oil in the air. Based on his previous experience, he can quickly identify that there is a leakage. Operator can touch the pipe to feel for the temperature. Logically, there would be a decrease in temperature if there is a leakage (pressure drops to atmospheric pressure).		Wrong diagnosis that leads to a bad outcome (false alarm).
From the video display, operators noticed smoke coming out from the tower.	Use of a backward sequential check		Understanding of the process flow and channeling.
Some parameters are coupled and they fluctuate in-phase. For example, valve A and B in Figure 5, are coupled and fluctuate in-phase as the flow (controlled by Pump C) varies.	The causes that experts generate have two characteristics: high probability and simple. They cycle through the causes until they find the correct one. This strategy is similar to Klein's Recognition Primed Decision Making (Klein, 1989). However, they coined this strategy "elimination".	Look at other related display. If parameters, which are supposed to be in phase, are not changing concurrently, the readings are suspicious.	Novices cycle through more wrong causes before deriving the correct ones.
Equipment error	To check if there are equipment errors, perform small adjustments and expect the display to change. If there are no changes, something is wrong.		Novices are unable to see the relationship between the various values. Frequently, they tunnel at one caused and missed other related cues.
Electric supply trip. This is a rare incident. However, the area that was affected was large. All control points are affected. Some resume automatically while others require activation by operators.	Flicker in the lighting system, all alarms are active. There are around 60 alarms. We try to resume the major processes first. These include the operation of pumps, the stability of the fluid flow and temperature. All field operators will go out to check their assigned areas. We traverse screen after screen until all the parameters are back to normal.		Novices are unaware of this technique. They will send the field operators to check.

**To understand the organization structure, see page A16.

Cognitive Demands Table

Storyline	Cues	Strategies	Difficult Cognitive Demands	Common Error/Expert Novice Difference
Sudden rise in pressure reading		Experts understand that it is illogical to have an immediate rise in the pressure. In addition, experts are able to perform calculations to predict the situation.	Understanding of physics	

**To understand the organization structure, see page A16.

Graphics for story

Story ID: 6

Normal

Faulty screw thread

Appendix D

Story ID: 7

¹ - 1st stage of checking: SME found a low flow in the H₂ supply

² - 2nd stage of checking: SME found that the total input was 50% instead of 100%. A novice operator did not increase the recycled H₂ flow after he cut the fresh H₂ flow.

Story ID: 8

Story ID: 9

Library of Descriptors

TYPE	SUB-TYPE	DESCRIPTOR	CODE
Technical	system	catalytic cracker	34
	system	crude distiller	
	system	HFA	37
	system	hydrotreater	37
	system	hydrotreater (S)	98
	system	platinum reformer	99
	system	procedures	
	system	R&R	35
	equipment	column-HCO	C
	equipment	compressor	K
	equipment	compressor-booster	K
	equipment	compressor-recycle	K
	equipment	exchanger-chiller	E
	equipment	exchanger-heater	E
	equipment	flange	
	equipment	flare	
	equipment	flow control hopper	
	equipment	furnace	F
	equipment	lube oil	
	equipment	pipelines	
	equipment	reactor	R
	equipment	regenerator	R
	equipment	structure	
	equipment	valve-discharge	
	equipment	valve-steam	X
	component	discharge valve	X
	component	flanch	
	component	flow control hopper	
	component	inlet	

Motivation-Expectation Space

Appendix D

	component	locking	
	component	locking-screwthread	
	component	outlet	
	component	pump	
	component	recirculation valve	X
	component	screw thread	
	component	tubes	
	component	valve	X
	component	valve-governor	X
	component	valve-recirculating	
	component	valve-slide	X
	supply	air	
	supply	catalyst	
	supply	cooling water	
	supply	corrosive gas	
	supply	fresh hydrogen	
	supply	fuel gas	
	supply	gas	
	supply	hydrocarbon feed	
	supply	MPS steam	
	supply	nitrogen	
	supply	off gas	
	supply	oxygen	
	supply	recycled hydrogen	
	supply	trip	
	plant	Area 1 - CDU	
	plant	Area 2	
	plant	Area 3 - Ular	
	plant	Movements	
	plant	rundown	
Event	component	flashpoint	

Motivation-Expectation Space

Appendix D

	equipment	cavitation	
	equipment	coking	
	equipment	leakage	
	equipment	overheating	
	equipment	recomissioning	
	equipment	choking	
	equipment	deposit of iron scales	
	equipment	explosion	
	equipment	physical fouling	
	supply	hydrogen production	
	system	chlorination	
	system	damage	
	system	hydrogenation	
	system	internal circulation	
	system	production	
	system	reforming	
	system	regeneration	
Action	automation	decreased	
	automation	increased	
	automation	tripped	
	nature	affected	
	nature	attained	
	nature	backflowed	
	nature	built-up	
	nature	caught fire	
	nature	cavitated	
	nature	coked	
	nature	contaminated	
	nature	damaged/faulty	
	nature	decreased	
	nature	dislodged	

	nature	eroded	
	nature	exploded	
	nature	failed/stopped	
	nature	increased	
	nature	jammed	
	nature	leaked	
	nature	melted	
	nature	overflowed	
	nature	overheated	
	nature	persisted	
	nature	shaked	
	nature	starved	
	nature	unsuited	
	human	circulated	
	human	decreased	
	human	extinguished	
	human	filled	
	human	forced in	
	human	identified	
	human	increased	
	human	isolated	
	human	monitored	
	human	notified	
	human	opened	
	human	prevented	
	human	recomissioned	
	human	repaired/maintenance	
	human	replaced	
	human	restarted	
	human	resumed	
	human	shut	

Motivation-Expectation Space

Appendix D

	human	standby	
	human	undo	
	human	unloaded	
Measurement		airflow	F
		differential pressure	dP
		discharge	
		level	L
		pressure	P
		quality	Q
		ratio	R
		required octane number	RON
		speed	S
		temperature	T
		weighted average bed temperature	WABT
Social		control room	
		duty manager	
		duty manager	
		Economics & Scheduling	
		fire department	
		Technologist	
		Training	

Motivation-Expectation Space

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