AN ABSTRACT OF THE THESIS OF

Cherag R. Sukhia for the degree of Master of Science in Industrial Engineering presented on September 23, 1994. Title: Functional Analysis of Flight Crew Performance: A Systems Engineering Perspective on Crew Resource Management.

Abstract approved: Redacted for Privacy

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Many failures of interpersonal communication and coordination in the aircraft cockpit have been found to occur as a result of poor management of flightdeck 'resources'. Crew Resource Management (CRM) is a concept that has evolved within the aviation community to specifically address this issue of resource management.

The concept of CRM has necessitated a paradigm shift from individual pilot issues to crew behavior or group-level issues. Despite a decade of research, CRM remains a poorly defined concept.

Ongoing research in the field of CRM has led to the development of a few models of CRM and group performance, but although these models provide valuable insight into the issues involved, they fail to present a much needed, coherent theory of crew performance. I believe that the application of the principles of systems engineering can lead to a better definition of the terms and concepts involved in CRM, thereby leading to its better understanding.

Using the principles of Structured Analysis and Design Technique (SADT) and IDEF0, I developed a model of crew performance. By treating the crew as a system, performance was analyzed from a CRM perspective, resulting in a functional model of crew performance which acts as a framework for understanding and integrating the various terms and concepts involved in CRM, such as mental models and situation awareness. The model was then applied towards analyzing two aircraft accidents representative of "good" and "bad" CRM.

The model is potentially useful in developing objective measures of crew performance so as to enable the establishment of CRM standards for evaluation. A comprehensive representation of crew performance, it can be applied to analyzing aircraft accidents and incidents. It is also potentially useful as an instructional aid in the development of training programs for CRM instructors and check airmen, and in the design of flightdecks.

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Functional Analysis of Flight Crew Performance: A Systems Engineering Perspective on Crew Resource Management

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed September 23, 1994
Commencement June 1995

Master of Science thesis of Cherag R. Sukhia presented on September 23, 1994

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Cherag R. Sukhia, Author

This thesis is dedicated to my mother and father for their love, patience, and understanding; to my brother Darius, and my sister Jinobia.

ACKNOWLEDGMENTS

No thesis is solely the result of a single individual's effort. My thesis is no different from other theses in this aspect, and I would like to take this opportunity to thank those individuals who contributed to it.

Firstly, I extend my gratitude to my major professor, Dr. Kenneth Funk, without whose guidance and support, this thesis might not have been realized. Throughout my academic career at Oregon State, and particularly while I worked on my thesis, Dr. Funk has been much more than an academic advisor to me. He has been my mentor; a pillar of academic support and guidance, a storehouse of knowledge, and a wealth of wisdom. In my moments of despair, he has shown me hope; when I was frustrated, he has been patient; in times of grief, he has comforted me and given me hope. Above all, he has been a friend, a source of encouragement, and I sincerely thank him for this.

Of those at OSU, thanks are due to the faculty of the Department of Industrial and Manufacturing Engineering, particularly Dr. Sabah Randhawa and Dr. Edward McDowell, for not giving up on me, and for seeing me through with this project. I would also like to thank the members of my graduate committee, especially Dr. Richard Mitchell, who on such a short notice agreed to serve on my committee and take time off from his vacation to review my work. A word of thanks is also due to the staff of the Graduate School for being so utterly cooperative, friendly, and supportive. Finally, I would like to thank my colleagues in the Human Factors Engineering Group for the intellectually stimulating environment that they so obliviously provided.

Outside of OSU, I would like to thank Dr. Kathy Mosier of NASA Ames Research Center for her continual guidance and support, both academic and moral. All along, she has ungrudgingly been, as I sometimes fondly refer to, my "long-distance mentor". I would also like to thank Dr. Elizabeth Lyall of America West Airlines for her ideas and suggestions during the initial stages of my project, as well as for her review of my work towards the latter stage. Thanks are also due to Pete Russo and his colleagues at Evergreen Airlines for allowing me to learn from their operations and for permitting me to sit in on their CRM sessions.

Beyond academia, there were many who silently contributed to my success. Firstly, I would like to thank Mr. Joong Nam Kim for allowing me to use his computer in our office. I also owe a debt of gratitude towards Kathi Kaufman and Fred Beebee for loaning me their portable computer when I had to be out of the country and for allowing me the use of their color printer for my transparencies. Finally, I would like to sincerely thank

all my special friends and their families for the love that they showed me, for the sense of community and belonging that they so generously provided me with. As an international student, distant from friends and family, this was perhaps the most important factor that enabled me to successfully see this project to its completion. I want them to know that I appreciate this very much...it has meant a lot to me.

All the above individuals contributed to the realization of my goal. But my goal would have remained just a dream, had it not been for two individuals who I owe a lifetime of gratitude towards - my parents. All their life they worked hard and sacrificed all that they had for me and my siblings. Dear Mom and Dad, this thesis is my way of saying "thank you". I love you both very much.

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Functional Analysis of Flight Crew Performance:
A Systems Engineering perspective on
Crew Resource Management

1. INTRODUCTION

Safety is the overriding concern in any industry. With regard to the transportation industry, commercial aviation has a particularly good record of safety. Nagel (1988) notes that worldwide there are about two accidents for every one million departures. Inextricably linked with the concern for safety is the notion of human performance, in this case crew performance. Crew performance is usually gauged by studying and classifying errors in operation. Various sources indicate that over 60% of all aircraft accidents are caused due to 'pilot error'. In a recent airline safety review conducted by *Flight International,* Learmount (1994) reports that 27 out of a total of 46 worldwide accidents in the year 1993 were attributed to 'aircrew error'. An analysis of these so called 'pilot error' or 'aircrew error' accidents suggests the central theme in each of these cases seems to be an error resulting from a failure in interpersonal communications and crew coordination (Helmreich & Foushee, 1993).

1.1 Crew Resource Management (CRM)

Failures of interpersonal communication and coordination are viewed to occur as a result of poor management of flightdeck 'resources'. These resources include not just the aircraft hardware and software but also the human elements or liveware. Crew Resource Management (CRM), earlier known as Cockpit Resource Management, is a concept that evolved within the aviation community to specifically address this issue of resource management.

In the past when addressing 'pilot error' issues, research in the aviation community tended to focus on the individual pilot. Soon there was a realization that these problems could not be addressed at the individual level; CRM necessitated a paradigm shift, a change in focus from individual issues to crew level issues. Only by understanding crew behavior can one hope to be able to reduce the occurrence of breakdowns in performance. Thus, fundamental to the concept of CRM is the concept of understanding crew performance, which is the primary focus of this thesis.

1.2 Problem Statement

Ongoing research in the field of CRM has led to the development of a few models of CRM and group performance. Although these theories and models provide valuable insight into the issues involved, they fail to present a much needed, coherent theory of crew performance.

Presently, a primary goal of the aviation industry is the development of objective measures of crew coordination so as to enable the establishment of CRM standards for evaluation purposes. Since crew coordination is an aspect of crew performance, I believe that objective performance measures of crew coordination can be arrived at through the development of a coherent theory of crew performance.

Further, I believe that it is possible to arrive at such a theory through the application of the principles of systems engineering. Systems engineering allows for a rigorous, analytical treatment of systems. By treating the crew as a system, a systems analysis would result in a better understanding of the concepts underlying crew performance. Conducting the analysis with an emphasis on crew coordination may lead to a better understanding of CRM, thereby enabling the development of objective measures of performance.

1.3 Research Objectives

The focus of this research is CRM or crew coordination. The goal of this research is to provide a better understanding of crew coordination, through a better understanding of crew performance.

In order to provide a better understanding of crew coordination, issues and concepts underlying crew performance need to be understood. A goal of this research is thus to acquire and present an in-depth knowledge of the domain of crew performance.

I believe that a systematic analysis of the concepts of crew performance, through the application of systems theory, can lead to a better understanding of crew performance. A goal of this research thus is to acquire an adequate understanding of the concepts of systems engineering.

There are different methods of application of systems concepts to any particular domain. This means that for the application of systems theory to crew performance, a suitable methodology needs to be studied before it can be applied. A goal of this research thus is to gain a firm grasp of a suitable methodology which will then provide the framework for the analysis of the crew system.

A systems analysis involves the development of a model. A model of crew performance should establish a framework leading to a better understanding of crew performance. Since the overall objective is to gain a better understanding of crew coordination, the model should be developed with an emphasis on crew coordination. A goal of this research is thus to provide a framework which would be useful in the development of a coherent theory of crew performance. Such a framework could then allow for the determination of objective measures of performance.

1.4 Overview of Thesis

An understanding of crew performance or CRM necessitates an understanding of crew behavior. To merely say that this is not an easy task would be understating the issue. Coupled with the complexity of understanding the behavior of individuals, crew performance deals with complex interactions among individuals, making the understanding of crew performance even more difficult.

Despite a decade of research, CRM remains a complex and fuzzy concept. An objective of this research is to 'de-fuzz' the issue of CRM. This is done by providing a better understanding of crew performance through the application of the concepts of systems engineering. A model of crew performance is the result of this application. An overview of the thesis and organization of the material is presented below.

Chapter 2 provides an introduction to the airline industry and its concern for safety. As was noted above, the notion of safety is linked with human performance and the study of error. An introduction to error and an overview of the methods of studying error in aviation is also presented. The chapter concludes with an introduction to the concept of CRM.

Chapter 3 deals with the specific issues of CRM; its history and development. An overview of current research and training in CRM is presented.

Chapter 4 deals with the theory of crew performance. It presents a detailed presentation of key concepts underlying crew performance. Different perspectives on these concepts are reviewed and synthesized so as to provide a framework for developing a model of crew performance.

Chapter 5 deals with the concepts of systems engineering and their application to the domain of crew performance. The specific systems methodology adopted to analyze crew performance is explained. Finally, the application of this methodology to crew performance along with a detailed explanation of the resulting model is also presented.

The utility of the model is derived from the fact that it provides a better understanding of crew performance. The model being a way to understand crew performance is applied to aircraft accidents so as to demonstrate its utility in providing a framework for understanding actual crew performance. All this is dealt with in Chapter 6.

Various aspects of the research are discussed in Chapter 7. Specifically, these include a discussion of: (a) the general approach adopted, (b) modeling methodology, (c) the crew performance model, (d) model application, and (e) model utility and validity.

Chapter 8 presents the conclusions of this research along with recommendations for further research.

2. BACKGROUND

2.1 Aviation Safety

The focus of this thesis is on the performance of airline pilots. Linked with the concept of performance is the notion of safety, central to which is the concept of error. This chapter provides an overview of airline safety, followed by a discussion of the concept of human error and its ties with safety and pilot performance.

The airline industry has a remarkable safety record. Each year some 900 million passengers fly all over the world. Of these, approximately 800 persons are killed each year (Young, 1987). Despite the billions of passenger miles flown each year, commercial travel continues to be among the safest forms of transportation. Sears (1986) as cited by Nagel (1988) reports that on an average there are "...about 20 major accidents worldwide per year, of which about five occur to U.S. air carriers" (p. 263). Compare this with some figures on road travel. The Oregon Department of Transportation recorded 471 fatalities due to road accidents in the year 1992 alone (Transportation Safety Section, 1993). In the United States, the figure was an astonishing 39,235 as against 10,536 total aviation fatalities over the entire past decade (Learmount, 1994). If fatalities are an indication of transportation safety, there is no question that the airline industry is, relatively speaking, safe. Today the focus has shifted from absolute measures to continuous improvement measures. How safe is safe? Or rather, is it as safe as it can be?

In the words of William Reynard, then Director of the National Aeronautics and Space Administration's (NASA) Aviation Safety Reporting System, "when we start talking about safety in terms of accidents or number of people killed, what we are really saying is, how many people can we afford to kill and still call the system safe?" (Young, 1987). System safety, in particular, airline safety thus continues to be a cause for concern. Although it is true that the fatality rate has been dropping over the years, since 1975 the overall rate of decline has leveled off and there is concern about this rate actually increasing, given the intermittent slumps in passenger traffic due to changing economic forces.

2.2 Economy and Future Implications

The 1970s was a period of stagnation for the domestic industry, with a small increase in passenger revenue relative to the economy. At the time, government deregulation, as Greenslet (1993) writes, "...offered the best prospect for ending this stagnation and reviving the airline business as a growth industry" (p. 72). Today the domestic airline industry is once again in the throes of a major recession and chances of a recovery, according to Greenslet, seem slim. Fortunately, prospects for the airline industry on a worldwide basis are not as bleak. Changes in political situations and opening of markets around the world as in the former USSR, China, and India, prove to be promising for the world economy. Shifrin (1994) reports that "...for the first time since 1988, traffic in 1993 grew faster than capacity, with international scheduled traffic up 7.7% in 1993 and capacity up 5.2%" (p. 28). Further, Shifrin projects an 8% rise in traffic and 5% increase in capacity for the year 1994, based on which it is predicted that "world airlines are expected to return to profitability in their international scheduled service in 1994..." (p. 28). Proctor (1994) cites a recent study that predicts airline capacity to "...grow at a healthy average of 5.2% through the year 2013" (p. 32). Proctor further cites the study to predict that "...world passenger traffic will almost triple over the next 20 years." More and more people are going to be choosing air travel over other means as a safe, economic and efficient means of commuting. Even if the current rate of decline in fatalities were to level off, it would mean that there would be more fatalities (in terms of absolute numbers) than in previous years; an undesirable situation. So what can be done to make the system more safe and reliable? Perhaps a brief look at the history of the evolution of this complex human-machine system may provide some insight.

Flying used to be about heroes in 'white scarves and goggles' operating fabric-covered machines held together with baling wire by the 'seat of their pants' (Foushee & Helmreich, 1988). One look at a modern jetliner makes it obvious that a lot has changed since then. The past couple of decades has seen a tremendous advancement in technology. The introduction of microprocessor chips and the advent of computers have resulted in a significant increase in automation on the flight deck. Consequently, the role of the pilot has changed drastically. The machine is now capable of doing a lot of routine tasks that constantly engaged the pilot, such as making corrective control inputs to maintain stable flight. If it has reduced some of the pilot's apparent workload, it has added a lot to his/her 'invisible workload'. The pilot now has to perform newer tasks and assume newer responsibilities. Thanks to superb engineering and technology, the machine has become a lot more than a piece of 'fabric-covered machinery'; indeed it now exemplifies the cutting edge of sophisticated technology. But what about the pilot? How much has he/she changed? Is the human pilot just as reliable as the machine? Studies of aircraft accidents indicate that although the machine has become more reliable, the human has not. According to Foushee and Helmreich, if the decreased percentage of accidents due to hardware problems is "...a testament to this increased reliability, the percentage of accidents due to human error has not exhibited the same downward trend" (p. 192). They further write, "Although estimates vary, even conservative figures attribute about 65% of all accidents worldwide to the *human error* [italics added] category" (p. 192). In fact, in a report on an analysis of worldwide commercial jet accidents from 1959 to 1993, the Boeing Commercial Airplane Group (1994) determined the flightcrew to be the primary factor in 64.6% of all accidents. The same report found the airplane to be the primary factor responsible in only 15.7% of the accidents. Pilot error or flightcrew error being a primary factor in more than half of all accidents has significant implications for anyone interested in airline safety. Before moving on to understanding these implications, it becomes necessary to take a closer look at what is meant by *pilot error* or *human error*. These questions are addressed as follows.

2.3 Human Error

According to Senders and Moray (1991), "... for most people error means that something has been done which was: not intended by the actor; not desired by a set of rules or an external observer; or that led the task or system outside its acceptable limits" (p. 25). While this may serve the purpose of providing a general meaning of the term, it is rather inadequate, particularly when error leads to accidents resulting in loss of human life. If all human-machine systems are designed by people, isn't it ultimately the human who is responsible for any system failure? Can the pilot alone be held responsible for a mishap caused by a failure of some mechanical component or automation? Are such mishaps truly 'human error' or merely acts of God? Can anything be done about them or are they random events? These are the types of questions stemming from the concept of error which forms the backbone of the issue of system safety. Although the emphasis of this research is not the study of error, some of the issues surrounding the concept of error and the difficulties involved in dealing with errors is critical to this discussion. Without going into the details of error theory, some of the approaches adopted by researchers to study this concept will be presented.

Error is a complex issue. Yet, surprisingly, there have been few efforts to systematically study the concept of error (Senders & Moray, 1991). According to Senders and Moray, those who have studied the impact of error on complex human-machine systems generally believe that between 30% and 80% of serious accidents are due, in some way, to human error. The problem of human error in aviation is difficult, both to understand and to resolve. Understanding human error boils down to understanding human behavior, which is no simple matter. According to Nagel (1988), part of the reason why the problem of human error in aviation is so difficult, "... is that the human is so complex that the understanding of behavior is not nearly as advanced as that of physical phenomena" (p. 266). If human error is such an important issue, why is there so little research done on it? One reason for this, according to Senders and Moray is that error is frequently considered only as a result or a measure of some other variable, and not as a phenomenon itself. Concentrated efforts to systematically study error as a phenomenon in its own right have only recently begun as is evident from the first error conference, "...called The Clambake Conference on the Nature and Source of Human Error..." (Senders & Moray, 1991, p. xi), which was held in 1980 in Columbia Falls, Maine.

2.4 Human Error and Accidents

Human error, according to Sanders and McCormick (1993) can be essentially described as "...an inappropriate or undesirable human decision or behavior that reduces, or has the potential for reducing effectiveness, safety, or system performance" (p. 656). Further, the authors note that what is appropriate behavior and what is not, is usually determined by someone conducting a careful evaluation of the behavior after the error has occurred. They write, "In essence, what is considered to be a human error is somewhat arbitrary because the determination of what is appropriate may not have been established until the error was identified" (p. 656).

An accident is defined by Meister (1987) as an unanticipated event which damages either the system or the individual so as to affect the accomplishment of the system mission or the individual's task. In discussing accidents and human error, Sanders and McCormick note that human error is often used to describe operator error or error on the part of the affected or injured individual. This, as they believe, is a very narrow view of human error, and its determination to be the cause of the accident results from "stopping" at the operator and not further backtracking to determine the underlying causes. "How far back to go" then becomes the question and it is an open one. As Sanders and McCormick write, "One could stop at the operator's actions and call the event a human error, or one could investigate what caused the human to act as he or she did" (p. 656). This, they believe would lead to the cause being traced to "...other factors such as faulty equipment, poor management practices, inaccurate or incomplete procedures" (p. 656). Even these can be traced to factors such as poor design, inadequate maintenance, and inspection procedures, all of which are traceable to designers, maintenance personnel, and inspectors, who are also humans. Thus, philosophically speaking, one could conclude, as Petersen (1984) did, that human error is the basic cause behind all accidents. If human error is the basic cause behind all accidents, it is probably meaningless to ask what proportion of accidents were caused due to it. As Sanders and McCormick suggest, "a more meaningful question would be how much does human error contribute to accidents relative to other contributing factors?" (p. 663).

No accident can be attributed solely to a single cause. In any accident investigation, a little backtracking makes it evident that there were other factors involved that led to the accident; a 'causal link'. When a certain percentage of accidents are stated to have been caused due to 'human error', what is really being said, as suggested by Sanders and McCormick above, is the fact that human error contributed significantly to the accident relative to the other contributing factors. Human error is never the only factor involved in an accident. A causal link of factors implies that, had this chain of factors or causal events been broken at any point, the accident or mishap may not have occurred. In a modern aircraft, ultimate responsibility for the safety of the aircraft and its passengers rests with the pilot. To the extent that the pilot is seen as having been incapable of 'breaking' the causal link of events that leads to an accident, one can easily cite 'pilot error' as the cause of the accident. Traditionally this has been the approach taken by those responsible for investigating the cause of aircraft accidents. Part of the reason for such an approach can be attributed to society, which is punitive and blame oriented. Shealy (1979) as cited in Sanders and McCormick suggests that it is just human nature to blame the active operator when something goes wrong since our legal system is geared toward the determination of responsibility, fault, and blame.

2.5 Directions in Error Research

Humans are imperfect; 'to err is human'. As long as humans are involved in a system, they will make mistakes and errors will occur. Despite this, it would be foolish to adopt a fatalistic attitude and do absolutely nothing about errors. The question is, what can be done about them? The earlier discussion on the difficulties of determining 'human error' as the cause of accidents was not meant to obviate responsibility on the part of the human designer or operator, but simply meant to illustrate some of the problems encountered in dealing with the concept of error. As stated earlier, error is indeed a complex issue because its study is essentially a study of human behavior. Nonetheless, systematic studies of the phenomenon of error are being undertaken by a variety of professionals from many disciplines, including system designers, human factors engineers, and psychologists. Engineers and psychologists alike are drawing more upon the methods and principles of the behavioral and social sciences. These are increasingly being used in conjunction with those of science, and engineering, in an attempt to optimize human performance and reduce human error. Some of the results are not entirely disappointing. For example, it is now known that not all types of errors occur completely at random. Instead, they are associated with certain patterns of behavior, and a certain probability of occurrence can be associated with the exhibition of such patterns.

The formal study of error in aviation has a long tradition, but these efforts tended to focus primarily on traditional human factors issues such as the design of human-machine interfaces. (Helmreich & Foushee, 1993) As mentioned earlier, flying is no longer what it once was. Advances in engineering and technology such as turbojet engines, and composite materials have altered the structural design of the aircraft to make it a much more sturdy and reliable machine. Accidents resulting from problems in engines and airframes have diminished greatly. Microprocessor chips and computers have increasingly led to the automation of many of the tasks that the pilot once performed. These changes have resulted in a change in the role of the pilot from 'controller' to 'manager' (Billings, 1991). In many cases automation has taken over some of the pilot's routine tasks but has added different kinds of tasks to his workload such as the monitoring of the automation itself. Newer tasks lead to newer errors. Newer errors imply that newer ways to either prevent these errors or deter their leading to disasters need to be discovered. The aviation industry, particularly in the United States, is a classic example where government, industry and academia have all risen to this challenge. How this has been undertaken is discussed in the following sections.

2.6 Approaches to Studying Error in Aviation

Nagel (1988) writes that there are generally four approaches available to studying errors, learning about their causes, and exploring methods "of reducing or eliminating the incidence or severity of human error in a complex, operational system like the air transportation system" (p. 267). These are (a) direct observation, (b) accident and post-accident analysis, (c) self-report, and (d) laboratory and simulator studies. Each of these methods have been adopted to varying levels of usefulness.

2.6.1 Direct Observation

In direct observation, the observer watches the crew perform their duties on the flight deck, making a note of his/her observations. An obvious drawback of this method is that the presence of the observer might alter the behavior being observed. Further, the observer is not in a position to manipulate the environment and is thus not in control of all the variables that might be of interest. Despite its drawbacks, this method has been applied successfully by many researchers.

2.6.2 Accident and Post-Accident Analysis

The second approach to studying error, namely, accident and post-accident analysis can, as Nagel (1988) notes, provide useful data, although the information record is often incomplete. As he states, "...accidents are often catastrophic; typically, little information is available from which to piece together a complete or comprehensive picture of causality" (p.266) Another drawback of this method, as Sanders & McCormick (1993) note is that "In some cases, after-the-fact explanations are created by the involved people to rationalize their behavior, or they will create information because it seems as though it must have been that way to make sense out of the situation" (p. 669). Of course, there must also be a systematic way of conducting the investigation after the accident, as well as a method to maintain the voluminous amounts of data that can be generated over the years. This formidable task has been entrusted to the National Transportation Safety Board (NTSB), which according to Kayten (1993) is "the watchdog agency of transportation safety in the United States, responsible for determining the cause of all U.S. civil aviation accidents, as well as carefully selected accidents in other modes" (p. 283).

The NTSB was created by the Department of Transportation (DOT) Act of 1966, and was later made completely independent of the DOT or any other federal agency by the Independent Safety Board Act of 1974. Immediately following an accident, the NTSB sends a team of investigators to collect data from the site of the accident. Typically, such data is recovered from instruments such as the digital flight data recorder (DFDR), the cockpit voice recorder (CVR) and other flight data recording devices such as Airborne Integrated Data Systems (AIDS) installed in some modern aircraft (Kayten, 1993). The NTSB completes its investigation, and after following a documented procedure of hearings and reports, publishes an accident report and makes recommendations to the appropriate agencies of the DOT. In the case of aviation-related accidents, this agency of the DOT is the Federal Aviation Administration (FAA). The FAA first came into being as the Aeronautics branch of the Department of Commerce, created by the Air Commerce Act of 1926, and has since assumed different names. The FAA, as it is now known, was created in 1966 by the same DOT act which was responsible for the creation of the NTSB (Birnbach & Longridge, 1993; Kayten, 1993). The FAA, upon receiving the recommendations from the NTSB is then required to respond to them, although as Kayten writes, "The NTSB has no authority to force any other agency, institution, or entity to implement a recommendation" (p. 285).

2.6.3 Self-Report

The self-report method is also aimed at obtaining useful data from the operational setting. However, it relies on obtaining such data, not from errors that have already led to catastrophic accidents, but from *incident reports* or self-reports of errors that could have led to an accident. In this method, operators of the system are encouraged to submit a self-report on any incident that might have occurred during the execution of their duties, which could have led to serious consequences. However, such feedback from operators in a real-world setting fraught with insecurities such as litigation and 'action' from management can only be expected in a relatively fear-free environment; an environment which does not seek to take punitive action against the reporter. Once again, the aviation industry in the US has risen to this challenge and there now exists such a system of reporting called the Aviation Safety Reporting System (ASRS).

ASRS was formed and developed by NASA for the FAA in 1976. It serves as the nerve center for the self-reporting approach to studying error in aviation operations. The system is designed to maintain confidentiality and provide relative immunity from prosecution to the reporter in cases other than those involving criminal actions (Nagel, 1988). Confidentiality is maintained by de-identification of reports. De-identification means the removal of all personal and organizational names, dates, times, and all other related information that could be used to trace the identity of the reporter. Operators of the system, including pilots, and air traffic controllers, voluntarily report incidents that, in their opinion, were potentially dangerous and could have led to a disaster. ASRS then keeps a confidential record of these incidents by de-identifying the report and maintains a database of all such reports. These reports are classified and made accessible for further research. An important feature of this system is that it allows for 'callback'. This means that although reporters are guaranteed confidentiality, it is possible for investigators to contact them, prior to de-identification. As Nagel writes, this is important because it allows learning about why errors are made, as well as learning about the circumstances that led to their occurrence. However, there are a few drawbacks with such a voluntary system of reporting. Firstly, as Nagel notes, by the very nature of their being voluntary reports, they are not made on a purely random basis and "...these sampling characteristics make quantitative analysis of the incident record difficult" (p. 270). What Nagel refers to here, is the fact that certain individuals under certain operational conditions may be more likely to submit reports and may thus be doing so on a more regular or frequent basis versus others who may not be choosing to do so. Thus, as Nagel points out, "we may learn a great deal about what errors are occurring but not necessarily be able to determine much about how often errors occur" (p. 270). More importantly, the incident report is in the form of a narrative submitted by the operator and is likely to be biased. The reporter will report what he or she perceived the situation to be like, and this may or may not be an objective representation of reality. Despite these drawbacks, the ASRS system has proven to be useful in understanding the problems encountered by the operators of the aviation industry. Several investigative studies have been conducted on the basis of ASRS reports and they continue to be one of the major resources for researchers in their understanding of the 'hows' and 'whys' of error.

2.6.4 Laboratory and Simulator Studies

The fourth approach to studying error involves laboratory experiments and simulators. In a laboratory study, the researcher can be in control of a lot of the variables he/she is interested in studying. As Nagel (1988) writes, the primary advantage of this method is that "Behavior can be stripped to its most elemental aspects and the root causes of errors dissected to yield predictive models of causality" (p. 270). The catch, however, is that for the results to be ecologically valid, the situation presented in the laboratory must simulate real-life as closely as possible. The problem here is that real-life situations are very complex, often leading to complicated chains of behavior and thus are difficult to duplicate in a laboratory setting. Thanks to modern technology though, there is a solution to this problem. Today's flight simulators make it possible to simulate almost all the operational complexity of actual flight, thus providing a controlled environment to better understand and study the cause of error. As would be expected, this technique has proven dramatically useful in error analysis and has been exploited by both researchers and the airline industry.

2.7 Fruits of Error Research

In the past, whenever 'pilot-error' was cited as a cause or contributing factor in an accident, research efforts focused on traditional human-machine interface issues. In essence though, the focus of the study was the individual pilot. Lately, due to the use of approaches discussed in the previous sections, the focus has changed. The usefulness of this shift in guiding future research is detailed below.

In the mid-seventies, there was a lot of research underway at NASA devoted to studying the phenomenon of 'pilot-error'. Researchers like Charles Billings and George Cooper at NASA-Ames Research Center's Man-Vehicle Systems Research Division, along with NTSB's John Lauber, developed a structured interview program "...to address some of the more perplexing problems which were the underlying factors causing so-called *pilot-error* [italics added] accidents" (p. 6). In 1976, the NTSB conducted a special study on flightcrew coordination procedures in air carrier instrument landing system (ILS) approach accidents. According to Kayten (1993), "...the special study found that flightcrew coordination procedures were either lacking or not followed in most of the accidents..." (p. 294). Thereafter, the NTSB made several recommendations regarding flightcrew coordination procedures (NTSB, 1976). Meanwhile, researchers analyzed NTSB accident data for jet transports (Cooper, White, & Lauber, 1980) while Murphy (1980) analyzed ASRS incident data at the same time. Both these studies provided invaluable insights into human error related accidents and incidents. Helmreich & Foushee (1993) summarize the results of these studies by noting that these investigations concluded that pilot-error in "...documented accidents and incidents was more likely to reflect failures in team communication and coordination than deficiencies in 'stick-and-rudder' proficiency" (p. 7). While researchers at NASA and NTSB were analyzing accident and incident data, the operational community was also playing an active role. Around 1974, one of the first airlines to recognize the importance of the crew concept was Pan Am which began to conduct both simulator training and checking in the context of a full crew conducting coordinated activities. All this signified a change in focus from the individual to the crew as being central to the process of understanding the determinants of safety in flight operations.

2.8 Cockpit Resource Management

In 1976, Patrick Ruffell Smith, a physician and pilot with a background of human factors in aviation conducted a full-mission simulation experiment, one of the first of its kind, at NASA Ames Research Center (Ruffell Smith, 1979). The goal of the experiment was to study the interaction of pilot workload with errors, vigilance and decisions, under highly realistic conditions. Although the study itself was one of errors, and their relation to workload, it proved to be a landmark in the history of aviation research, in the sense that it helped focus on crew level issues and developing notions about the role of management skills in cockpit operations (Lauber, 1993). For example, one of the errors studied is referred to by Ruffell Smith as 'errors of crew integration', which "...included episodes where P1 [Captain], failing to realize that P2 [First officer] or P3 [Second officer] was overloaded, asked them to retrieve information, further disrupting their performance" (p. 15). The study also noted "...large variations in respect to leadership, resource management and decision making..." (p. 28) with regard to the behavior of the captains. Among other resource management variations, the author noted problems in task assignments and task prioritization.

In summary, there was a lot of variability noted in the performance of the crews, and as Lauber (1986) writes, "it seemed to us that much of this performance variation could be attributed to the variable effectiveness of the pilots and flight engineers in utilizing available resources" (p. 7). Thus was born the concept of Cockpit Resource Management.

At the time of the Ruffell Smith study, airlines like Pan Am and Northwest were already beginning to focus on crew-level issues. Northwest, for example, already had a program called Coordinated Crew Training (CCT), which also made use of simulator studies. However, a lot of such efforts which were then in the early stages, really took shape and form after NASA sponsored the first workshop on "Resource Management on the Flight Deck" in June 1979. The workshop invited participation from all those interested in aviation, the regulatory agencies, the operational and research communities. Representatives included those from the FAA, the NTSB, and many major airlines. The workshop was successful in bringing together an industry wide focus on crew level issues and the Cockpit Resource Management movement was officially in place.

The focus of this thesis is on Cockpit Resource Management, and specifically on crew level performance issues. In the next chapter, a closer look is taken at Cockpit Resource Management; what it means, what it was, what it is, and what it promises to be.

3. CREW RESOURCE MANAGEMENT

3.1 History of CRM

In the preceding chapter, the outcomes of several approaches to studying error were considered. Analyses of accident and incident data coupled with data from NASA's structured-interview program provided evidence for the need to focus more on crew-level issues rather than on training of individual skills. Research in simulators like the classic Ruffell Smith (1979) study were responsible for the introduction of the concept of management of resources on the flight deck. NASA's sponsoring of the first workshop on flight deck resource management in 1979 formalized this notion of Cockpit Resource Management. Helmreich and Foushee (1993) write, "...with recognition of the applicability of the approach to other members of the aviation community including cabin crews, flight dispatchers, and maintenance personnel..." (p. 3), the term Cockpit Resource Management is being replaced by Crew Resource Management. The following sections provide a synopsis of the evolution of the CRM concept.

3.1.1 NTSB and CRM

Most major airlines today incorporate some kind of CRM training program. Such "buy-in" from the operational community would not have been possible were it not for the persistent efforts of the NTSB and the cooperation of the FAA. As Kayten (1993) writes, "...the NTSB has played a major part in fostering the wide acceptance CRM concepts now enjoy in the regulatory, airline, and military environments" (p. 283). Several accidents prior to 1979 also had what are today referred to as 'CRM problems'. The NTSB in their reports used to refer to these as problems centering around 'teamwork', 'inadequate flight management', 'task-sharing', and 'delegation of authority'. According to Kayten, earlier treatment of these issues was in the framework of operational procedures and airmanship. It was only after the NASA sponsored workshop in 1979 (see Cockpit Resource Management - Chapter 2) that "...these problems were thought to have a unique training solution" (p. 289).

Incidentally, the NTSB's first explicit mention of 'poor CRM' was in its report after the crash of a United Airlines flight, in 1978, in Portland, Oregon (Kayten, 1993). According to NTSB (1979), this accident "...exemplifies a recurring problem - a breakdown in cockpit management and teamwork during a situation involving malfunctions of aircraft systems in flight" (p. 26). Because of its significance, it is elaborated upon below.

On December 12, 1978, the three person flight crew of United Airlines' Flight 173 prepared to land the four-engine DC-8-61 at Portland International Airport. Upon lowering the landing gear on final approach, they heard a dull thump which seemed to be in the main gear area. Uncertain about what might have caused the thump or its implications, the crew decided to abort the landing and put the aircraft in a holding pattern. The aircraft stayed in this holding pattern for almost an hour during which the captain directed the crew to ascertain the cause of the noise. During this time, both the First-officer and Second-officer warned the Captain, on four separate occasions that they were running low on fuel. The Captain apparently ignored these warnings and insisted they stay in the holding pattern. Low on fuel, one of the engines finally flamed out. The Captain, bringing the plane near the field, demanded an explanation from the Second-officer for the cause of the engine failure. Meanwhile, the other three engines, with fuel tanks now dry, began to fail in sequence and the DC-8 nosed downward. The aircraft crashed into a wooded area near the airfield killing 8 passengers, the Second-officer, and a flight attendant. Among those seriously injured were 21 passengers, the Captain and the First-officer.

The NTSB determined the probable cause of the accident to be the Captain's failure "...to monitor properly the aircraft's fuel state and to properly respond to the low fuel state and the crew members' advisories regarding fuel state" (p. 26). The NTSB later made recommendations to the FAA to ensure that flightcrews were indoctrinated in principles of flightdeck resource management. By now, CRM was a familiar concept in the aviation community and the NTSB frequently referred to it in making subsequent recommendations to the FAA following similar accidents.

3.1.2 FAA and CRM

NASA and the NTSB have played important roles in the recognition of the concept of CRM, but it is the FAA in its dual role of enforcer and enabler (Birnbach & Longridge, 1993) which has been largely responsible for ensuring the indoctrination of the concept in airline operations. Following the 1978 Portland crash and the recommendations by the NTSB, the FAA played an active role in ensuring the implementation of CRM principles by air carriers. One of its first actions, as Kayten (1993) reports, was to issue "...Air Carrier Operations Bulletin 8430.17 Change 11, which included instructions regarding resource management and interpersonal communications training for air carrier flightcrew." (pp.

294-295). Subsequent responses to NTSB recommendations included the initiation of specific projects like the one to optimize Line-Oriented Flight Training (LOFT) to enhance CRM within the FAA's Aviation Behavioral Technology Program (Kayten, 1993), and the publication of its Advanced Simulator Plan as Appendix H to Part 121 in 1981 "...to encourage the use of advanced flight simulators and to specify their permissible use for training and checking..." (Birnbach & Longridge, 1993, p. 267).

In 1987, the FAA formed the Joint Government-Industry Task Force to review the FAA's airline crew standards. Perhaps the most significant of FAA responses to NTSB recommendations to urge the fostering of CRM concepts among airlines was by the Joint Task Force in the form of the Advisory Circular (AC) 120-51 on CRM training dated December 1989, and the issuance of the final rule for an Advanced Qualification Program (AQP) Special Federal Aviation Regulation (SFAR-58) dated October 1990. Of these, the AQP promises to be the most prominent catalyst for the acceptance of CRM by many major airlines. The AQP is a voluntary, alternative training program aimed at integrating a number of training features and factors aimed at providing airman performance when compared to traditional programs. As defined in SFAR-58 (FAA, 1990), the AQP "...provides for a voluntary, alternative method for meeting the training, evaluation, certification, and qualification requirements...the principle factor of the AQP is true proficiency-based qualification and training" (p. 40263). More detail on the role of AQP in CRM will be provided in a later section.

3.2 What is CRM?

Helmreich and Foushee (1993) define CRM as the "...application of human factors in the aviation system." (p. 4). In 1978, John K. Lauber, a psychologist with the NTSB, coined the term CRM. This CRM pioneer's definition is more formal and more widely accepted than other definitions of the concept. Lauber (1986) defines CRM as "...the effective utilization of all available resources - hardware, software, and liveware - to achieve safe, efficient flight operations" (p. 9).

The FAA (1991) Advisory Circular (AC 120-51) clarifies that CRM is not a training program, "...nor is it correctly used as a title for a training program" (p. 3). Further, it states, "CRM is a *concept* [italics added] that encompasses the aircrew expressed in behavioral terms in the context of the environment in which the behaviors occur" (p. 3).

CRM is evidently a broad concept. It encompasses the effective utilization of all possible resources available to the crew in order to safely and efficiently execute a mission. In the context of commercial aviation, this basically involves the transportation of a payload (of passengers and/or cargo) from one destination to another. This may seem like an accurate enough definition, but it is not adequate for a clear understanding of the concept. In an attempt to provide further insight into CRM, Lauber (1986) describes the 'dimensions' or 'elements' of CRM as including:

1. Delegation of tasks and assignments of responsibilities
2. Establishment of priorities.
3. Monitoring and cross-checking
4. Use of information
5. Problem assessment and the avoidance of preoccupation
6. Communications
7. Leadership

Each of the above seven dimensions of CRM are essential for the effective management of resources on the flightdeck. Yet these dimensions are not sufficient to systematically study or analyze CRM. What is needed is a framework to identify and further analyze the components of CRM so as to yield a better understanding of crew performance. A framework to understand CRM is provided in the FAA's Advisory Circular (AC 120-51) on CRM and is discussed in the following sections.

3.3 CRM: Guidelines, Research, and Training

Since its conception, there has been a lot of research in CRM being conducted by NASA's Aerospace Human Factors Division in conjunction with airlines. In 1990, the FAA outlined the National Plan for Aviation Human Factors. This provided the blueprint for addressing the needs of the aviation community. But perhaps the best guideline for the development of CRM was provided by the FAA's (1991) Advisory Circular (AC) on CRM mentioned earlier. Many of the findings in this circular are based upon research conducted by researchers at NASA in collaboration with Robert Helmreich and his colleagues at the University of Texas, Austin. This advisory circular made the initial stab at providing a "...contemporary explanation of aircrew behaviors..." as well as provided "...guidelines for developing training and evaluation programs..." (p. 1).

In attempting to provide an explanation of aircrew behaviors, the AC identified some "new" cognitive and interpersonal skills and attitudes in addition to the traditional individual technical skills and knowledge. This new "family" of skills was further classified under three "clusters" (a) communications process and decision behavior, (b) team building and maintenance, and (c) workload management and situational awareness. These three clusters are further subdivided into behavioral categories. These categories illustrate the kinds of behavior and associated skills that the concept of CRM encompasses. For instance, the 'communications process and decision behavior' cluster is subdivided into categories that include briefings/debriefings, inquiry/assertion, and conflict resolution, while the 'team building and maintenance' cluster includes categories of behavior such as leadership, concern for operation, and interpersonal climate. Once these behavioral categories included under CRM had been identified, the issue was one of being able to observe and identify behavior as classified under the clusters. For this purpose, the AC further identifies several 'behavioral markers' associated with the behavioral categories of each cluster. As Helmreich, Wilhelm, Kello, Taggart, and Butler (1991) write, "Behavioral markers are specific behaviors that serve as indicators of how effectively resource management is being practiced" (p. 7). Further, they point out that these markers are not intended to be "...exhaustive lists of behaviors that should be seen, but rather as exemplars of behaviors associated with more and less effective CRM" (p. 7).

While CRM emphasizes the importance of these Cognitive and Interpersonal (C&I) skills, it does not cease to recognize the importance of so-called, traditional, 'technical skills'. However, as the AC emphasizes, "it is now accepted that these two behavioral sets are in fact mutually supportive, provide an effect greater than the sum of their parts and must be taught and evaluated together." By describing crew performance in terms of integrated sets of technical, and C&I behavior, the AC essentially outlined a model of CRM. Research into CRM thus focused on several interrelations between these issues. In most cases, such research had to be conducted in conjunction with developing training programs.

In a study originally aimed at assessing the effects of fatigue on crew performance, Foushee, Lauber, Baetge, and Acomb (1986) found that fatigued crews, surprisingly, made fewer errors than did crews composed of rested pilots who had not yet flown together. In another study, Foushee and Manos (1981) analyzed the cockpit voice data obtained from the Ruffell Smith (1979) study. The approach involved classifying speech acts as to type and the primary conclusion was that crews who communicated more overall, performed better. Kanki, Lozito, and Foushee (1989) further refined the methodology and analyzed earlier gathered data. They concluded, as Helmreich and Foushee (1993) note, that "...greater information transfer in the form of 'commands' structuring activities and acknowledgments validating actions was associated with more effective crew performance" (p. 18). Hackman and Walton's (1986) theory of leadership provides insight into group performance, while Ginnett's (1987) study of Boeing 727-200 crews refined group theory by introducing the concept of 'shells' and discussed the importance of the initial meeting between crewmembers. While studies of this kind focused on team building and interpersonal skills, researchers like Orasanu (1990) focused on the cognitive aspect of CRM or decision-making skills. Orasanu (1993), in discussing various aspects of crew decision making, suggests *situation awareness*, *planfulness* and *shared mental models* to be three ingredients that contribute to effective crew decision making (these and other related concepts are discussed in Chapter 4). Other researchers also stress the importance of shared mental models and group situation awareness in team building and maintenance (Cannon-Bowers, Salas, Converse, 1993; Wellens, A. R., 1993). Even as research and training continue to evolve, several consistent findings are being made. For instance, survey data obtained from more than 20,000 flight crewmembers in civilian and military organizations in the US and abroad, by Helmreich and his colleagues, found an overwhelming acceptance of CRM concepts (Helmreich & Foushee, 1993). Data on attitudes indicate that these are amenable to change, and that these changes are measurable. However, one must remember that these conclusions are based upon survey data. As Helmreich and Foushee caution,

> the number of accidents involving crews with formal training in CRM and LOFT is too small to draw any statistical inferences regarding the role of these experiences in helping crews cope with serious emergency situations. (p. 36)

The AC also sets the stage for conducting training in CRM and provides broad guidelines for airlines. The AC stresses certain concepts seen as basic or essential to any form of CRM training. For example, it emphasizes the focus of the program to be the "...functioning of crews as intact teams, not simply as a collection of technically competent individuals..." (p. 10). It also stresses the need for training to be continuously reinforced (i.e., recurrent training should be a feature of any CRM training program). The AC further outlines three phases of CRM training. The first phase is the *indoctrination* or *awareness* phase which typically constitutes an introduction to CRM concepts in a classroom or seminar, involving role-playing, and group discussions. The second phase is the *practice* or *feedback* phase. This phase typically includes Line-Oriented Flight Training or LOFT which makes use of simulators accompanied with video feedback during debriefing. The full-mission scenarios in LOFT are oriented towards emphasizing critical CRM concepts such as decision making, team participation and leadership sharing. The third phase recommended in the AC is the *operational reinforcement* phase. A short, one-time CRM training course, cannot be effective in influencing behavior that has been developed over a crewmember's life span. The AC recognizes the fact that attitudes revert to their pre-training status in the absence of continual reinforcement, and therefore stresses the importance of this phase. It stresses the need for CRM training to include refresher curriculum, integrating feedback exercises such as LOFT with video feedback. The AC also stresses the important role of check airmen or CRM instructors, since these are the people who serve as role models for all crews in any airline.

3.4 A Model of Group Performance

Helmreich (1986) in making a distinction between 'resource management' and 'crew performance' considers performance, at both the individual as well as crew levels, to include "...two distinct components: technical proficiency and competence, and second, resource management or crew coordination" (p. 15). Thus, he uses the term resource management and crew coordination in an interchangeable sense, while further expressing that "...crew coordination is the cornerstone of resource management..." (p. 15).

To recapitulate, CRM, resource management or crew coordination is one aspect of crew performance, an aspect which has long been ignored. The other, interrelated aspect is technical proficiency. Both of these are necessary to produce superior crew performance. Initially, what was lacking was this insight - that crew coordination or resource management is an essential and integral part of crew performance. With the birth of the CRM movement, this aspect is now clear and widely accepted. The aviation community needs to go beyond simply accepting that this is necessary. As Chidester (1993) writes:

> human factors research should continue to shift from justifying CRM as a useful concept to focusing on how to select crewmembers, what to train, and how to design cockpit procedures to optimize crew coordination. (p. 330)

In essence then, what is needed is a sound theory of crew behavior and a more rigorous framework to discuss performance issues. One such framework to discuss crew performance in the context of CRM is the model proposed by Helmreich and Foushee (1993). Because of its significance and usefulness in serving as a basis for understanding the remaining sections of this thesis, the model is discussed below. The model is a three-factor model of the determinants of group performance and is based on McGrath's (1964) work in the field of social psychology. Basically, the model defines three major components of group behavior (a) input factors, (b) group process factors, and (c) outcome factors.

Input factors, according to Helmreich and Foushee (1993), "...include characteristics of individuals, groups, organizations, and the operational environment." These characteristics include the individual's knowledge, skills, attitudes, personalities, motivation, physical and emotional states, including fatigue and a variety of life stresses. Characteristics of the organization include the 'culture' of the organization and any factors in the organizational context that are likely to influence the individual performance of a crew member, such as management's attitude towards staff, level of training, specific operational procedures, rules and regulations. Characteristics of the crew or group factors, include the structure, climate, roles, norms and style of leadership present. The authors write:

> The climate that develops in a group is multiply determined by the characteristics of individual members, by the structure imposed by the formal and informal norms of the organization, and by the quality and style of leadership present. (p. 11)

The operating environment primarily involves the environment (i.e., weather conditions and the aircraft along with its capabilities and limitations). The operating environment is further influenced by organizational and regulatory factors, such as the ability of the organization to provide timely and accurate information to the crew. In general, input factors "...provide the framework and determine the nature of group processes that lead, in turn, to the various outcomes" (p. 8).

According to Helmreich and Foushee (1993), *group process factors* include "...the nature and quality of interactions among group members..." (p. 8). The authors further classify group processes during flight operations under two broad categories, one consisting of interpersonal and cognitive functions, and the other including machine interface tasks. In elaborating upon the former category, the authors cite several studies which determined the central role of verbal communications processes in the cockpit. They further decompose the interpersonal and cognitive functions into three broad 'clusters' of observable behavior. These clusters are (a) team formation and management tasks, (b) communications processes and decision tasks, and (c) workload management and situation awareness tasks. The machine interface category is considered to reflect the technical proficiency of the crew and is further subdivided into two clusters, "...the actual control of the aircraft (either manually or through computer-based flight management systems) and adherence to established procedures for the conduct of flight" (p. 20).

Outcome factors are considered to include "...primary outcomes such as safety and efficiency of operations and secondary outcomes such as member satisfaction, motivation, attitudes, and so on" (p. 8). According to Helmreich and Foushee (1993), primary outcomes are readily recognizable and quantifiable, while secondary outcomes are influenced by group processes, which in turn influence input factors.

The model itself is iterative in nature (i.e., input factors affect group process factors which affect the outcome factors). The outcome factors may change input factors and may even directly affect group process factors. As the authors state, "it is the iterative nature of the factors determining group performance that makes its study both complex and challenging" (p. 9).

3.5 Need for a Better Definition

Fundamentally related to the issue of performance is that of measurement or evaluation. In the earlier section on CRM research and training, it was noted that survey data obtained by Helmreich and his colleagues clearly indicate the acceptance of CRM concepts. If this is true, why then does it become necessary to assess performance in CRM related skills? Indeed, as the AC on CRM notes, there are concerns expressed by industry as to the necessity of evaluating CRM, particularly since CRM training has been indicative of being effective in changing behavior when it is not evaluated. While there are some philosophical and psychological issues in this debate, from the regulatory standpoint, there is no question that performance in CRM needs to be evaluated.

Thus, from a regulatory perspective such as the FAA's, ultimately the issue of crew performance and training boils down to one of qualification and certification. Typically reflective of an industry whose regulatory structure as well as physical characteristics of operations focus on the individual, pilot training and evaluation, to this day, is done on an individual basis. With the advent of CRM and particularly under the auspices of AQP, this is being re-examined and is slowly changing. As Birnbach and Longridge (1993) note, "the changing role of the pilot warrants a complete reexamination of the standards which should be applied to a determination of competency...AQP provides a systematic methodology for such a reexamination" (p. 275).

Central to the issue of qualification and certification is that of the establishment of objective measures of performance or standards. FAA(1990) SFAR 58 notes that "once data have been collected to validate the effectiveness of CRM training sessions, the FAA believes that objective criteria for evaluation can be developed" (p. 40267). It further notes:

> Once the FAA has developed objective criteria for evaluating CRM performance of an individual, the criteria will be used in determining whether an individual is qualified...Thus, when CRM objective criteria are fully implemented, it will be possible for an individual to fail a CRM session. (p. 40267)

To this date, neither the airlines nor the FAA have been successful in coming up with objective measures of performance for crew coordination activities, and herein lies the challenge for further research.

Chapter 1 outlined the problem statement as well as the objectives of this research. Chapters 2 and 3 provided the background necessary to understand the concept of CRM. In the next chapter, the theory behind key concepts of CRM is studied. This provides the foundation necessary to understand the model of crew performance developed, which is described in Chapter 5.

4. THEORY UNDERLYING CREW PERFORMANCE

4.1 Knowledge Representation and Mental Models

Any attempt to understand human performance requires an appreciation of the core concept of human cognition. Central to the concept of human cognition is the issue of representation, specifically, the representation of knowledge in memory. As Rumelhart and Norman (1988) write, "In spite of its centrality (perhaps because of it) issues surrounding the nature of representation have become some of the most controversial aspects of the study of cognition" (p. 511). The concept of mental models is a particular case of representation of knowledge, a concept which is now recognized as being fundamental to the understanding of many aspects of human performance. The concept has also been logically extended to serve as a basis for explaining team performance, which is a primary objective of this research. Therefore to understand team performance, one needs to thoroughly understand the concept of representation and of mental models. This section deals with both these concepts. It begins with a detailed review of representational systems and leads into the concept of mental models.

4.1.1 Representations

Rumelhart and Norman (1988) define a representation as "something that stands for something else. In other words, it is a kind of a model of the thing it represents" (p. 513). A representational system consists of a world that needs to be represented and a representation or a model of that world (also known as the representing world). Not all aspects of the represented world are necessarily represented in the representing world; likewise, there can be several pairs of the representing and represented worlds. According to Rumelhart and Norman (1988), there are essentially three worlds to be represented: our environment, our brain and its states, and our phenomenal experience" (p. 514). Further, they write:

> most issues of representation are not about how the environment is represented in our phenomenal experience, but they concern the representational system in which our theories are the representing world, and the environment, brain states, and our phenomenal experience are the world to be represented. (p.514)

The concept of mental models has to do with just such a kind of representational system. Mental models are the representing world; they seek to represent our theories about the represented world, namely, our environment, our brain and its states, and our phenomenal experience. Mental models are discussed in greater detail in subsequent sections.

There have been many kinds of knowledge representational systems proposed over the years by philosophers, psychologists and scientists. Rumelhart and Norman (1988) classify these into four basic categories: propositional, analogical, procedural and distributed knowledge representational systems. Each of these systems have their own powers and efficiacies, along with their own limitations. The primary objective of these various representational systems however, remains the same, (i.e. to allow us to adequately formulate theories of human cognition).

4.1.2 Propositionally Based Representational Systems

Propositionally based representational systems rely heavily on the use of predicate calculus as a means for representation. Examples of these kinds of systems include the 'feature comparison model' by Smith, Shoben, and Rips (1974) and Tversky's '(1977) 'feature matching model'. In these models, which form perhaps the simplest of all representational systems, concepts are represented as a set of semantic features or attributes. Some of these features are considered necessary and sufficient and are termed as defining features, while others are considered to be characteristic. These models seem adequate to handle only particular tasks such as those of similarity and definition. They cannot and do not claim to account for the representation of knowledge in general.

Hence, as Rumelhart and Norman (1988) write, the idea of choosing representational systems in which "...knowledge pieces are connected to each other to form an associative network of interrelated pieces of knowledge" (p. 523), appealed to some and led to the development of the notion of *semantic networks*. In a semantic network, the smallest unit is a 'node', which represents a 'concept' in memory. A set of nodes interconnected together by 'relations', which are associations among nodes, form the basic structural element of a semantic network. The basic notion is that "knowledge can be represented by a kind of directed, labeled graph structure ... the meaning of a concept being given by the pattern of relationships among which it participates" (p.523). Even these fail to capture intuitions of the phenomenology of mental structures.

These and all such other systems of representation are broadly classified as 'propositionally based representational systems' because in each of these, "...knowledge is assumed to be represented as a set of discrete symbols or propositions, so that concepts in the world are represented by formal statements" (p. 515). Propositionally based representational systems, as mentioned earlier, are indeed useful in explaining certain selective aspects of human cognition, but they somehow fail to capture the richness of human cognition. What was needed was a framework of representing more than mere lexical or sentential knowledge. This need for the representation of knowledge in higher order structures (i.e. the need for representations of supra sentential knowledge) led to the development of the concepts of schemata, frames, scripts and plans, which finally led to the development of analogically based propositional systems.

4.1.3 Schema Theory

Of the notions of schemata, frames, scripts, and plans, the notion of schemata is perhaps most relevant to the understanding of the concept of mental models. Although the notion of schemata has been invoked by many psychologists in various contexts, it remains somewhat fuzzy. The roots of schema theory can actually be traced to Gestalt psychologists who were the first to propose that the key to problem solving lies in 'understanding' the problem. Further, they also believed that prior experience can have both positive and negative effects on problem solving.

According to Mayer (1983), a *schema* is "a general knowledge structure used in comprehension. A schema serves to select and organize incoming information into an integrated, meaningful framework" (p. 228). Thus, essentially, the process of understanding "involves the construction of a schema and the assimilation of incoming information to the schema" (p.228). It was Bartlett, the early 20th century psychologist, who is credited with a lot of work done on schema theory. His experiments on learning and problem solving served to show that memory is "*schematic* [italics added]- that both learning and remembering are based on general schemas rather than specifics" (p. 232). Learning refers to the assimilation of new information for subsequent storage in memory, while remembering refers to recalling information from memory.

Rumelhart and Norman (1988) define schemata (plural for schema) as "data structures for representing the generic concepts stored in memory" (p. 537). Further, schemata are believed to exist for various generalized concepts like objects, situations, and events. They are basically models of the world by which human beings are able to perceive and understand their surroundings. Schemata are considered to be like packets of information residing in long-term memory, each containing a fixed and a variable part. The fixed part is analogous to the "defining features" concept of earlier described propositional systems while the variable part roughly corresponds to the characteristic parts having 'default' values which are subject to change based on continuously received, current information from the environment. Further, schemata can embed themselves within one another. Thus, essentially, a schema comprises not just one knowledge structure, but consists of several configurations of subschemata within it. The authors also believe that schemata behave as active recognition devices - they process information by actively trying to match themselves with incoming data, trying to determine which one of themselves most appropriately matches the incoming data. Since schemata are believed to exist for various generalized concepts, they are considered to represent knowledge at all levels of abstraction, "from ideologies and cultural truths to knowledge about what constitutes an appropriate sentence in our language, to knowledge about the meaning of a particular word, to knowledge about what patterns of excitations are associated with what letters of the alphabet" (p. 538). Further, as the authors believe, "...schemata are our knowledge. All of our generic knowledge is embedded in schemata" (p. 538). According to them the entire memory system is thus composed of countless schemata, or countless packets of knowledge. Thus, with reference to meanings of words, schemata are thought to possess not just the dictionary-like meanings of words but along with it, they are supposed to possess information pertaining to 'encyclopedic knowledge' (i.e. knowledge of many facts and relationships about the particular concept represented by the word), in addition to an episodic meaning of the concept (i.e. they are also supposed to contain information about our experiences with that particular concept). Thus, schemata are considerably 'richer' knowledge representation structures, which seem to explain some of the richness of human cognition. Scripts and plans are particular examples of schemata developed by psychologists like Schank and Abelson (1977) to demonstrate whether such a kind of memory system can indeed serve as a practical basis for understanding specific situations around us.

4.1.4 Analogically Based Representational Systems

Propositional representational systems such as semantic networks and schemata serve to represent information stored in long-term memory. While these are 'rich' representational systems, they fail to adequately explain, for instance, the representation of images. Such considerations led to the development of analogically based representational systems in which it was proposed by some like Kosslyn (1980) that the knowledge underlying images is analogical versus propositional. Kosslyn has proposed a rather elaborate theory of imaginal representation. According to Rumelhart and Norman (1988), Kosslyn claims that there are two fundamental kinds of representations of imaginal information - a 'surface representation' , which was thought to consist of some kind of a 'matrix format' occurring in some spatial medium, (for which he used the metaphor of a CRT [Cathode Ray Tube] to elaborate upon) and a 'deeper representation', which was actually of some propositional form, from which the surface representation is generated. Thus, Kosslyn's view can be summarized by saying that he believed that knowledge was stored in long-term memory, essentially in propositional form, which was converted into an image whenever needed. Such a kind of 'matrix format' for a surface representation seems adequate to describe simple cases of imagining objects and performing simple transformations on them. But human beings are able to imagine a much wider range of activities which incorporate more than just visual stimuli. Indeed, humans can imagine the occurrence of entire events, complete with sounds and smells! They are able to imagine a dinner setting, complete with the clinking of glasses of champagne and the smell of pot roast. It is possible for human beings to imagine being pushed and falling off a bicycle. In playing a game of chess, players are able to 'make' their moves in anticipation of the other's moves, and thereby predict the outcome of a certain move. In other words, they actually 'simulate' moves based on different strategies, and then select the one with the most favorable outcome. It is primarily to account for the human's ability to imagine such a wide range of activities that Rumelhart and Norman (1988) suggest that we should think of a 'mental model' rather than just a 'mental image'.

4.1.5 Mental Models

4.1.5.1 An introduction

The concept of mental models has been invoked by many researchers in different professions, with varying backgrounds and for various purposes. Of all the different perspectives, two are predominantly apparent, that of ergonomists or human factors specialists and that of psychologists and cognitive scientists. The primary interest of psychologists and cognitive scientists stems from their wanting to understand or explain the complex function of human cognition whereas ergonomists or human factors specialists, by virtue of the 'applied' nature of their profession tend to see mental models as a basis for explaining complex human behavior like naturalistic decision making. Expectedly, these different perspectives are reflected in the varying definitions or conceptions of 'mental models' invoked and further refined. A fact that becomes apparent by even a cursory glance at the literature, and one which has been quoted in several instances, is how extensively the phrase 'mental models' has been used and yet how few formal or explicit definitions exist (Wilson & Rutherford, 1989; Rouse & Morris, 1986). There are several reasons for this. As Rouse and Morris point out, "...this most likely reflects the extent to which the concept has come to be acceptable on an almost intuitive basis" (p.349). As Wilson and Rutherford write, "...this might reflect the many different domains of application of the concept and the narrow or operational nature of the definition consequently used" (p.618). Further, they write, "any differences [in conception] are accentuated by an apparently mutual lack of communication between the human factors community and psychologists" (p.619).

Nevertheless, the importance of a better and more concrete understanding of this concept has been recognized by the aviation community, particularly those involved in the training of crews and the development of CRM training programs. Indeed, the concept of mental models has been extended to that of 'shared mental models' which have been invoked by many researchers to explain the performance of teams and team decision-making (Cannon-Bowers, Salas, & Converse, 1993; Orasanu, 1990). Some are wise to plead caution in their usage - as Wilson & Rutherford (1989) point out, "there is a danger that workers in human factors and systems design may see the mental models notion as a key - even a panacea - for successful design and development."

With this introduction to the concept, current research on mental models is examined in greater depth. What exactly is meant by the term 'mental models'? What purpose do they serve? What are their defining characteristics? Each of these questions is addressed below.

4.1.5.2 What are mental models?

The term model brings to mind some sort of representation, which is in essence what mental models really are. Norman (1983) outlines in very simple and general terms the concept of a mental model. According to him, "in interacting with the environment, people form internal, mental models of themselves and of things with which they are interacting."

Wickens (1984) also invokes the concept of "internal models" in his attempt to explain the decision making process of operators. According to him, "as patterns of correlation are learned by experience and training, an internal 'model' of the environment is formed" (p. 110). Rouse and Morris (1986) cite Wickens (1984) who reminds us that "...mental models are constructs used by researchers to explain display sampling, scanning, formulating of plans, and translating of goals into actions" (p. 350).

Rasmussen (1990) also invokes the concept of mental models in talking about goal-controlled knowledge-based performance. He writes, "at this [knowledge-based] level of functional reasoning, the internal structure of the system is explicitly represented by a 'mental model' which may take several different forms" (p. 63).

Wilson and Rutherford (1989) summarize the different perspectives of mental models amidst the human factors community, as:

> a representation formed by a user of a system and/or task, based on previous experiences as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance. (p. 619)

4.1.5.3 What purpose do they serve?

Broadly speaking, from a knowledge representation viewpoint, mental models, as described above, provide a "richer" framework to account for the richness of human cognition. All the earlier described systems of knowledge representation, such as propositional and analogical are capable of explaining only certain aspects of how human beings process information. Mental models, thus, essentially are a way of representing and thereby explaining our view of thinking. Ultimately, they seek to represent theories about the represented world, namely, the environment, the human brain and its states, and the phenomenal experience of humans.

Perhaps the essence of this is captured in Wilson and Rutherford's (1989) words, "A mental model is a theoretical entity. In less grand terms, it is an idea that is employed to account for empirical data" (p. 630).

Nevertheless, like all representational systems, they serve useful purposes. Norman (1983) points out that mental models provide predictive and explanatory power for the operator's understanding of the interaction between the individual and the system environment with which he/she is interacting.

Wickens (1984), in talking about the "internal models" of the environment formed by operators of the system, suggests that, "This internal model then provides a framework for easier integration of information that is consistent with it and removes much of the burden of working memory associated with processing large amounts of uncorrelated information" (p. 110). Elsewhere, in discussing display compatibility and implications for display design, he writes that "there is good evidence that continuously changing systems have continuous analog mental representations. These internal representations form the basis for understanding the system, predicting its future behavior, and controlling its actions" (p.178-179).

Veldhuyzen and Stassen (1977) in reviewing the use of the term "mental model" in manual control theory conclude that mental models are the basis for estimating the *state* of the system. They further see them as the basis for all further actions such as the development of plans and strategies and selection of control actions.

Rasmussen (1990) while discussing functional reasoning in the knowledge-based realm, sees the mental model of the causal structure as the basis of mental data processing. Further, he views the modification of mental model as an effective way to counteract the limitations of attention and optimize the transfer of previous results thereby minimizing the need for new information. According to him, the efficiency of human cognitive processes depends on such modifications or model transformations.

Rouse and Morris (1986) provide a good 'functional definition' of mental models based on a modification of Rasmussen's (1979) taxonomy of mental models. Mental models, are thus defined by Rouse and Morris as "the mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states" (p. 351).

It would appear from the above descriptions that the concept of mental models is a 'fuzzy' one. Although there are several unresolved issues surrounding this concept, some of these, as Rouse and Morris (1986) point out may never be resolved. They offer a detailed discussion of these issues and the limits constraining their resolution. Some of these limits, they point out may be fundamental. They write:

> the problem of subjectivity and arbitrariness is aggravated in the study of mental models because, in effect, such studies amount to one or more persons developing models of others' models of the external world. This dilemma is fundamental and cannot be resolved. (p. 359)

However, there are certain aspects of mental models which can and need to be clarified. Some of these are examined in the following sections.

4.1.6 Characteristics of Mental Models

4.1.6.1 Mental models and knowledge

If the concept of mental models appears fuzzy from the above descriptions, one need only think about the concept of knowledge and the difficulties encountered in its definition. It is precisely because of the ambiguity of the concept of knowledge and our attempt to "capture" it or "represent" it, that has led to the development of the theories of knowledge representation described earlier.

Although mental models are a type of knowledge representation, they do not represent all knowledge, or knowledge in general. Indeed, as Rouse and Morris (1986) point out, the differentiation of the concept of mental models from that of knowledge in general poses a significant difficulty. Yet, they assert that "it appears to be reasonable to use the concept of mental models to denote *special types of knowledge* [italics added] " (p. 350). The topic of attempting to determine precisely the 'knowledge contents' of mental models is addressed in subsequent sections.

4.1.6.2 Mental models and schemata

A related issue of interest is that of the difference between mental models and schemata as systems of knowledge representation. After all, schemata have been viewed as organized knowledge structures used to interpret incoming information and predict future events, just as the functional definition of mental models proposed by Rasmussen (1979) (see above) suggests that they are mechanisms for generating explanations of system functioning and observed system states, and predictions of future system states. To what extent are these two concepts related or are they distinctly separable?

Rumelhart (1984) describes a mental model as the total set of schemata instantiated at the time. Wilson and Rutherford (1989) cite Johnson-Laird (1983) as suggesting that "...schemata provide the procedures from which mental models are constructed" (p. 624). Brewer (1987) identifies the time when particular representations are created as a point of distinction between mental models and schemata. According to Brewer, as cited by Wilson and Rutherford (1989), "...mental models are creations of the moment, and although the same mental model may be reconstructed several times, it is schemata that are considered to be stored and activated" (p. 624). Finally, in accepting that there may not be a distinct cut-off point between the two concepts, Wilson and Rutherford conclude that "...the major difference between mental models and schemata is that the latter are taken to be data structures in memory, which can be activated, whereas the former are regarded as utilization of such information in a computationally dynamic manner" (p. 624). They further emphasize that it is the dynamic computational ability of a mental model beyond that presumed of background knowledge that provides the notion of mental models with its theoretical utility.

4.1.6.3 Mental models and conceptual models

Another issue concerns the distinction between 'mental models' and 'conceptual models'. Norman (1983) proposes a scheme of classification. He maintains that the designer's conceptual model of the system is not to be confused with the operator's/user's mental model. According to him, "Conceptual models are devised as tools for the understanding or teaching of physical systems. Mental models are what people really have in their heads and what guides their use of things" (p. 12). Thus, a user may have a 'conceptual model' of the system based on what he/she has been taught, whereas his/her actual interaction with the system will lead to an evolution of his/her 'mental model'. As Wilson and Rutherford (1989) write, "the latter [mental model] is based on users' expectations and experiences and on their current perception of the system and provides a basis of their understanding" (p. 619). Thus, if the system being studied is 'mental models of users', any representation of a user's mental model would necessarily be, as Norman (1983) writes, "...the scientist's conceptualization of a mental model...a model of a model" (p. 8).

4.1.7 Knowledge Content of Mental Models

In the earlier section, it was noted that mental models are distinguished from general knowledge by considering them to be special types of knowledge. This raises the question of what precise knowledge is contained in mental models. This section addresses this issue by first considering the differences between types of knowledge. The section concludes with a summary of what is meant by mental models, thereby making explicit the types of knowledge supposedly contained within them.

In the literature on representational systems, there is generally a distinction made between *procedural* and *declarative* knowledge. Knowledge of or about something is referred to as declarative knowledge, whereas knowledge about how to do something is called procedural knowledge (Rumelhart & Norman, 1988). Rumelhart and Norman (1988) further distinguish between declarative and procedural knowledge by claiming that declarative knowledge is often accessible, whereas procedural knowledge tends to be relatively inaccessible, in the sense that it is not available for examination. In other words, "we seem to have conscious access to declarative knowledge; but we do not have this access to procedural knowledge" (p. 561). However, the most relevant feature of the distinction between procedural and declarative knowledge is the fact that data and process are closely bound together i.e., "in some sense all knowledge is declarative upto the point where the final machinery that actually performs the physical actions is reached" (p. 565). To elaborate further, any procedure has to be in some kind of declarative form for a 'mechanism' such as an interpreter to interpret, follow and execute. This knowledge in declarative format may not be accessible at any other level but the one where it is used. Finally, "the difference between knowledge that is declarative and knowledge that is procedural simply depends upon one's viewpoint" (p. 565).

4.1.8 Summary of Mental Models

Evidently, there are a number of viewpoints about mental models and its knowledge contents. For the purpose of this research, a summary of mental models is presented. Firstly, like many psychological phenomena, I accept that mental models are basically hypothetical constructs. They are essentially a way of representing and thereby explaining our view of thinking.

For purposes of defining what is meant by mental models, both Wilson and Rutherford's (1989) as well as Rouse and Morris' (1986) functional definitions previously mentioned, are acceptable. I also concur with the views expressed above that mental models are distinct from schemata and that their primary utilitarian value is derived from the fact that they possess a dynamic computational ability, by means of which it becomes possible to project future situations. Bainbridge (1988) notes that Johnson-Laird used the term mental model "..to designate the temporary data structure built up during understanding..." (p. 82). I therefore presume that a mental model resides in working memory and relies or draws upon the contents of more permanent or long-term data structures such as schemata.

4.1.8.1 Specific knowledge contents of mental models

For the sake of completeness, I summarize that the mental model shall be assumed to contain the following declarative knowledge:

- Descriptive knowledge about system topology/structure.

- Understanding of system purpose and system functioning.

- Current (represented) state information (as perceived by the pilot; different from 'actual' state)

- Each of the scenarios that lead to future system states.

- Information on predicted future system states as a result of "running" the mental model.

Further, I assume that a mental model must also contain the following kinds of procedural knowledge:

- Procedural knowledge to explain system topology/structure.

- Procedural knowledge to interpret incoming information, relate it with knowledge of system topology/structure developed from schemata, and generate an explanation of current system state.

- Procedural knowledge to use this current system state, and (again with the help of schemata) "simulate" the system, thereby predicting a future system state.

- Procedural knowledge to appropriately store these future system states along with the actions (descriptions generated via simulations) required which result in the respective system states.

4.1.8.2 Concluding remarks on mental models

The above concludes the discussion on the subject of mental models for now. Although I have tried to neatly 'capture' the notion of mental models and attempted to define them in terms of the knowledge contained in them, we must not lose sight of the fact that the notion of mental models is by construction, a nebulous one. Finally, in conclusion I see it appropriate to remind the reader of Norman's (1983) six observations on mental models, in which he describes mental models to be "incomplete", "unstable", not having "firm boundaries", "parsimonious" and "unscientific" in the sense that "people maintain 'superstitious' behavior patterns even when they are unneeded because they cost little in physical effort and save mental effort" (p. 8).

The subsequent section examines the concept of Situation Awareness. I believe an understanding of this concept will enhance the understanding of crew performance.

4.2 Situation Awareness

Situation awareness has a seemingly intuitive meaning; something to do with being aware of one's situation. A highly popular term in the field of aviation, its use, unfortunately, as Sarter and Woods (1991) write, "...is often based on an intuitive, not necessarily appropriate, understanding" (p. 46). The concept of situation awareness is inextricably linked with performance. This section treats this concept in detail, but before doing so, it is examined briefly from the intuitive perspective.

According to Schwartz (1991), "In simplest terms, it [situation awareness] is knowing what is going on around you - a concept that is embraced in the need to think ahead of the aircraft." (p. 18). Wellens (1993) cites Press' (1986) review of the origins of the term situation awareness in the military flight environment in which he attributes the success of WWI flying aces to the "...ability to gain awareness of the enemy before the enemy became aware of him [them]" (p. 268). In loose terms, it is also referred to as the "big picture". In the old days, when flying used to be about flying in open cockpits with very little automation, the pilot was literally in control of the aircraft. In a sense, it was thus easier for the pilot to achieve the "big picture" of the environment for survival. In today's aircraft, complex automation has changed the role of the pilot so as to have removed him/her from the 'inner control loop'. In fact, as Sarter and Woods (1991) point out, "especially in the commercial aviation domain, there are concerns that advanced applications of flight deck automation may have a negative impact on the phenomenon" (p.

45). Thus, according to Wellens who cites Endsley (1988), "it has become a major design goal for the developers of new aircraft systems to help the pilot achieve a composite picture of the environment required for successful task performance" (p. 268). From an informal standpoint, it is not losing sight of this big, composite picture so essential for task performance, that is implied by the term 'situation awareness'.

4.2.1 Need for Studying Situation Awareness

As Sarter and Woods (1991) correctly assert, "situation awareness is supposed to be an essential prerequisite for the safe operation of any complex dynamic system" (p. 45). It is not difficult to see the veracity of this statement. If a pilot does not know 'what is going on around him/her', there is little chance that he or she will be able to ensure safe task performance. In a modern aircraft, the reasons for a loss of situation awareness can be varied. Complex automation in modern commercial aircraft requires a lot of monitoring, and tends to remove the pilot from the 'inner control loop', leading to a loss of situation awareness. Sometimes, the pilot whose role is now reduced to that of a monitor instead of a controller, begins to rely too much on the automation and becomes complacent, again leading to a loss of situational awareness. There are a number of research programs specifically designed to address the issues of automation and the problems and concerns that arise from the interactions between the pilot and such automation (Billings, 1991). However, as Sarter and Woods point out, "a thorough understanding of the concept of situation awareness and its relation to automation is largely missing" (p. 45). Even so, the aviation community already has other concerns about situation awareness. Some analysts view situation awareness as a design criteria, while others are concerned whether it is an individual difference variable, whether it is something specific that can be trained or not (Pew, 1994). More importantly, while the reasons for the loss of situation awareness may be varied, the effects or the consequences are not; a loss of situational awareness can lead to a disaster. There exist innumerable instances where a loss of situation awareness has been cited as a major contributing factor in aircraft accidents and incidents. As Schwartz (1989) points out, "a distinct relationship exists between situational awareness and accidents. High situational awareness yields lower mishap potential, low situational awareness yields higher mishap potential" (p. 18).

Given that situation awareness is so critically linked to system safety, it is examined in greater depth below. What exactly is meant by situation awareness; what are its components, what constitutes being 'situationally aware', how can it be measured? Some of the definitions of situation (or situational) awareness are first examined. The concept is then examined in the context of related psychological constructs such as mental models.

4.2.2 Situation Awareness: Definitions

Stein (1986) as cited in Harwood, Barnett, & Wickens (1988) defines situational awareness as:

> the knowledge available to the pilot on critical matters such as the overall tactical situation, his own mission profile, weapons status, the positions and objectives of friendly aircraft, disposition and apparent objectives of hostile flights, presence of threats, refueling rendezvous and other mission data. (p. 316)

Airbus Training Center's Aircrew Integrated Manual (AIM) is cited by North (1992) to define situation awareness as "...an accurate perception of the factors and conditions that affect the aircraft and flight crew during a specific period of time" (p. 64).

According to Wickens (1992), "situation awareness refers to the ability to rapidly bring to consciousness those characteristics that *evolve* during a flight" (p. 3).

Sarter and Woods (1991) define situation awareness as "the accessibility of a comprehensive and coherent situation representation which is continuously being updated in accordance with the results of recurrent situation assessments" (p. 55).

A generally accepted definition among the aviation community is that proposed by Endsley (1988) who defines situation awareness as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (p. 791).

Smith and Hancock (1993) define situation awareness as adaptive, externally-directed consciousness.

As might be obvious from the preceding sections, there remains considerable ambiguity regarding the concept of situation awareness. In fact, as Sarter and Woods (1991) remark, "it is not even clear whether situation awareness really denotes a distinct phenomenon" (p. 45). Even though the term 'situation awareness' has ubiquitously replaced 'workload' as the buzzword of the 90's, there exists a healthy skepticism about it, and some like Pew (1994) even wonder whether they should try to work with it as an overarching concept at all, "one that is anything more than what we think about in the traditional assessment of human performance requirements in any particular system" (p. 2). Some, like Flach (1994), refer to the concept as a "new fad" that has replaced workload -

which is "no longer fashionable" (p. 241). In fact, given the current state of understanding of this relatively new concept, Flach finds it difficult to see how situation awareness is different from even skill or expertise.

4.2.3 More about the Situation

Situation awareness is about two concepts: the situation and awareness of the situation. In general, little attention has been devoted to understanding the 'situation' component of situation awareness. Flach (1994) believes that :

> the weak link in our human factors is not our failure to understand 'load' or 'awareness' but our failure to understand 'work' or 'situations'... we must shift our emphasis from 'awareness' and we must begin to build theories and methodologies to attack the problem of 'situations'. (p. 243)

Further, he writes, "our theories of 'situation awareness' must arise from an understanding of situations" (p. 244). Most definitions that center around the 'situation' component, according to Sarter and Woods, (1991) focus on determining what particular information the pilot has to pay attention to, as a result, "...little progress has been made with respect to important issues such as supporting the acquisition of information in general or supporting effective attention-filtering in changing, data-rich environments" (p. 47).

Situation awareness, as Harwood et al (1988) write, "...refers to the pilot's knowledge of a dynamically changing situation" (p. 316). The flight deck is a dynamic environment. Therefore, as Sarter and Woods (1991) point out:

> Any attempt to define the critical components of situation awareness in general suffer from the fact that, given the dynamic environment of the flight deck, the relevance of data and events depends on their context and will therefore vary within and between flights as a function of specific task, the environment, and the tactical objective. (p.47)

Further, as Sarter and Woods note, "on the other hand, attempts to define the 'situation' component that are broad and account for the context-sensitivity of data, run the risk of being too general to really help in understanding the basis of situation awareness" (p. 47).

4.2.4 The Components of Situation Awareness

Harwood et al (1988) and Wickens (1992) seek to identify the critical components of situation awareness and provide some more insight into the phenomenon by outlining four basic components or dimensions of situation awareness. Each of these dimensions lead to certain kinds of information about the situation and are hence referred to as the contents of the situation. Harwood et al refer to these components as (a) *spatial* awareness - "the pilot's knowledge of his location in space and of the spatial relationships between objects"; (b) *identity* awareness - "the pilot's knowledge of the presence of threats or objectives ... the pilot's awareness of system state variables such as engine status and flight performance parameters"; (c) *responsibility* or *automation* awareness - "knowledge of who's in charge"; and lastly (d) *temporal* awareness - "knowledge of the occurrence of events as the mission evolves" (p. 316). Wickens refers to the first three dimensions as *navigation*, *systems*, and *task* awareness respectively, while referring to the fourth one as temporal awareness.

Of all these, it is 'temporal awareness' that Harwood et al (1988) refer to as the "hallmark" of situation awareness (p. 316) Sarter and Woods (1991) remark that "temporal awareness is important for both the diagnosis and the prevention of problems" (p. 48). What exactly is meant by temporal awareness and why is it so important ? Perhaps this is better understood when we look first at Smith and Hancock's (1993) definition of situation awareness and then at Pew's (1994) further exploration of the 'situation'. As was mentioned earlier, situation awareness includes two components, a) the situation and b) awareness of the situation. The detailing of the four dimensions of the situation above provides some insight into what kinds of information evolve during the flight and what the pilot needs to be aware of. What exactly is a *situation* ? When does one *situation* end and when does the other begin? These are important questions and are addressed below.

Smith and Hancock (1993) define situation awareness as adaptive, externally-directed consciousness. By doing so, they view consciousness to be that part of an agent's knowledge-generating behavior that is within the scope of intentional manipulation. Further, they view situation awareness as being "directed toward achieving a goal in a specific task environment", i.e. goal-driven behavior, hence the part 'externally-directed' in the definition. Who specifies these goals ? Certainly not the agent itself - if that were the case, situation awareness would always be perfect. The authors argue that it is the task-environment, an 'external arbiter' that specifies these task goal requirements. Further, since they submit that situation awareness is adaptive, and like adaptation, "is a dynamic concept that exists at the interface between the agent and its environment...", a notion "which implies complete and 'natural' adherence to task goals and to criteria for performance. This, in turn, implies the existence of a specification of the task the agent is to perform and of measures for evaluating that performance" (p. 29). In summary, the authors are saying that the environment [external-arbiter] imposes some task goal requirements on the agent. The agent, in order to possess situation awareness must "necessarily have developed a level of adaptive capability sufficient to match the specification of [these] task goals and of criteria for assessing performance variables" (p. 29). Further, they maintain, "while individuals may exhibit situated, outwardly-directed consciousness, it is not until the externally-defined task is made explicit that their behavior achieves the status we wish to reserve for situation awareness" (p. 29).

The ideas of Smith and Hancock regarding the goal-directed nature of situation awareness are reflected, albeit a little differently, by Pew (1994). If situation awareness literally refers to being aware of the situation, it becomes imperative to answer questions such as "what is a situation?" and "when does one situation end and the other begin?" In attempts to do so, Pew defines a *situation* as "a set of environmental conditions and system states with which the participant is interacting that can be characterized uniquely by its priority goals and response options" (p. 2). Pew is not explicit about where these priority goals and response options originate from, however, I believe that these priority goals and response options [that characterize the situation] are generated by virtue of the agent adapting to the 'environmental conditions' (or the external arbiter according to Smith and Hancock). As Smith and Hancock (1993) stated, "to qualify as situation awareness, the agent first must intend its goals, beliefs, and knowledge to match the task and performance specified by dicta from its environment and then, must succeed to some degree in meeting those expectations" (p. 29).

Further, Pew (1994) and his colleagues believe that:

> ...in complex decision-making situations, an individual has multiple goals in the priority stack. At any one time, one or two of those goals are paramount and those goals, and the response options associated with them provide the basis for defining situation awareness requirements. (p. 2)

According to them, a situation is characterized by its priority goals and response options. A situation changes when the priority goals and response options accompanying it change, thereby changing the situation awareness requirements. These requirements, according to Pew, are "the essential elements of information and knowledge needed to cope with each unique situation" (p. 2). This understanding clarifies the need to not be "aware of all things at all times", which would have rendered useless the whole concept of situation awareness. Instead, by clarifying that a situation is characterized by its priority goals and options, it becomes possible to define the requirements of what would constitute situation awareness. Also, as the situation as defined above changes, the priority goals and response options would change, which the 'adaptive' agent would become aware of and thereby redefine the requirements of being aware of one's situation.

4.2.5 Temporal Awareness: The Hallmark of Situation Awareness

Given this understanding of the situation, it is now possible to take a closer look at the temporal dimension of situation awareness. What is meant by it and why is it considered to be the "hallmark" of situation awareness? As mentioned above, Harwood et al (1988) define temporal awareness as "...knowledge of the occurrence of events as the mission evolves" (p. 316). Sarter and Woods (1991) explain further what is meant by temporal awareness. They write:

> In dynamic environments such as the flight deck, minor deviations or failures that are not critical in themselves may evolve or interact over time to become a major threat. It is therefore essential for the pilot to observe, integrate, and remember these events. (p. 47)

The key word here that lends value to the temporal dimension is 'remember'. Temporal awareness plays an important role in the diagnosis of problems that might have been caused or influenced by events in the past. It is also important, according to Sarter and Woods (1991) in "...the prognosis and prevention of potential future problems based on the analysis of currently available data" (p.49). Smith and Hancock (1993) stress the importance of the adaptive nature of the agent to match its goals, beliefs and knowledge with the task goal requirements specified by the environment or the external arbiter. Pew's (1994) definition of a situation elaborates upon this idea of situation awareness being goal-directed behavior and that the awareness requirements are defined on the basis of priority goals and response options that characterize the situation, the requirements being the "essential elements of information and knowledge needed to cope with each unique situation" (p. 2). The concept of temporal awareness stresses the fact that for an accurate diagnosis of the problem, those "essential" elements of information and knowledge need not be currently available from the environment but would have to be recalled from memory, which in turn implies that the agent would have to integrate and remember the essential elements of a situation for future recall if necessary. In fact, that is partly what constitutes being 'aware' of the situation, and I shall say more about this when discussing 'awareness'. In the words of Harwood et al (1988), "the past is important for disambiguating the present, and the past and present must be used to predict the future. The relationship of time with the other three components is what sets situational awareness apart as a unique concept" (p. 316).

Having examined what is meant by 'situation', attention is now turned towards 'awareness'.

4.2.6 More about Awareness

In the preceding section on 'situation', Smith and Hancock's (1993) views about situation awareness being 'externally-directed' or goal-directed behavior were discussed. However, while doing so, the authors "do not deny that there is internally-directed consciousness, but maintain that consciousness directed to internal representations (e.g., mental models) is a meta-construct that leads to a number of philosophical polemics that fail to help resolve current practical questions about situation awareness" (p. 29). Therefore, for "practical purposes", they have sought to impose some operational bounds in defining their terms. Hence, their claim that situation awareness is active, information-seeking, action-taking behavior; "a generative process of knowledge creation and informed action-taking" (p. 29). While their definition helps to focus on the behavioral or performance aspect of situation awareness, it circumvents, for reasons quoted above, an analysis of the actual cognitive processes that underlie the processing of information acquired by situation awareness. Instead, they use the theme of distinction between 'performance' and 'competence' as "leverage...to understanding the performance we observe - the normatively focused knowledge-generation and action-taking that characterize situation awareness" (p. 30). They define performance as action situated in the world which is contingent upon information made available by the environment while competence as knowledge that supports behavior but is independent of the situation, which is invariant of the particulars of the situation. Further, "an analysis of competence is unconcerned with the actual processes" (p. 30). Basically, they adopt Neisser's (1976) perception-action cycle as a framework for explaining how situation awareness works, without being concerned about the actual processes that produce the agent's performance. Briefly, information and action flow continuously around the perception-action cycle. Essentially, the environment which provides the information, the agent who possesses the knowledge, and the action taken by the agent constitute the components of the perception-action cycle. As the authors write:

> Starting arbitrarily at the top, the environment informs the agent, modifying its knowledge. Knowledge directs the agent's activity in the environment. That activity samples, and perhaps, anticipates or alters the environment which, in turn, informs the agent. The informed, directed sampling and/or anticipation capture the essence of the performance of situation awareness. (p. 31)

Further, they believe that "situation awareness is the invariant at the core of an adapted agent's perceptual cycle that generates both up-to-the minute knowledge and action that anticipates signals in the environment" (p. 28), its function being to codify the information made available by the environment, the knowledge required by the agent to assess that information, and the action the knowledge will direct the agent to take to meet its goals.

Viewing situation awareness as a facet of consciousness, as behavior which is externally-directed or goal-driven, may be a reasonable enough explanation for those concerned only with what may be called the 'observable' aspect of performance. However, it is believed that it would be worthwhile to also consider the other facet of consciousness, the 'internally-directed' aspect of situation awareness. This is, so as to speak, the cognitive aspect of situation awareness, which deals with those internal representations of knowledge and information processing, or mental models.

A comparison of Rouse and Morris' (1986) definition of mental models (see section on Mental Models) and Endsley's (1988) definition (above) of situation awareness shows remarkable similarity. Indeed, one of the questions that researchers debate about is whether the two are indeed different phenomenons or as Sarter & Woods (1991) so aptly word as illustrations of "...the tendency of applied cognitive science to coin new terminology in the face of ill-understood issues" (p. 45).

4.2.7 Situation Assessment and Situation Awareness

An important aspect of Endsley's (1988) definition of situation awareness is 'situation assessment'. Sarter and Woods (1991) who offer an excellent treatment of the concept, claim that "situation awareness is based on the integration of knowledge resulting from recurrent situation assessments." In other words, *situation assessments* lead to situation awareness. What exactly is 'situation assessment'? Endsley as cited by Sarter

and Woods (1991) describes situation assessment as "a complex process of perception and pattern matching greatly limited by working-memory and attentional capacity" (p. 50). The process of situation assessment is considered to involve three different levels:
a) Level I - Perception of situational elements.
b) Level II - Information integration.
c) Level III - Projection of future status and actions of situational elements - or "the mental simulation of future system state and behavior to eliminate surprises" (p. 51).

Earlier, Rouse and Morris (1986) defined mental models as "the mechanisms whereby humans are able to generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states" (p. 351). There is obviously an overlap between the two psychological constructs of situational awareness and mental models. The issue is clarified below.

4.2.8 Mental Models and Situation Awareness

In clarifying the difference between mental models and situation awareness, Sarter and Woods (1991) see mental models as the basis for adequate situation assessments. Earlier, they were quoted to claim that situation assessments lead to situation awareness. In the words of Sarter and Woods (1991), "adequate mental models are one of the prerequisites for achieving situation awareness" (p. 49). Thus, mental models are the actual 'processes' (or mechanisms) which are responsible for generating descriptions of system purpose/form, explanations of system functioning and observed systems, and predictions of future system states. These are the basis for accurate situation assessments which in turn result in situation awareness. The adaptive, externally-directed consciousness that Smith and Hancock referred to as situation awareness, is in essence what cognitive psychologists refer to as situation assessments, which lead to the state of being situationally aware or 'situation awareness'. Harwood et al (1988) capture this same notion as follows, "...a pilot who is 'situationally aware' could also be described as possessing an accurate mental model of the situation. This model must be updated continuously in order to maintain situational awareness in the dynamically changing environment" (p. 318). To this should have been added, "which is done through accurate situational assessments."

4.2.9 Approaches to Measuring Situation Awareness

Although the concept of situation awareness remains shrouded in clouds of ambiguity, efforts are being made to measure and thus gain a better understanding of it. Harwood et al (1988) envision these approaches as "varying in the extent to which they tap explicit or implicit situational knowledge" (p. 318). They liken these to a continuum; the 'probe technique' otherwise known as intrusive in-flight assessment techniques, lies on the 'explicit' end of the continuum, while methods or approaches to 'capturing' the agent's mental model lie on the 'implicit' end of the continuum. Endsley's (1988) SAGAT or Situation Awareness Global Assessment Technique is a classic example of those that lie on the explicit end. Basically, in such techniques, a simulated flight scenario is frozen at random intervals of time, all cockpit displays as well as the outside view are blocked out, and the pilot is asked a series of questions, as Sarter and Woods (1991) quote Endsley (1988), to "determine his [the pilot's] knowledge of the situation at that exact moment in time" (p. 54). Sarter and Woods (1991) point out that such techniques measure at best what information the pilot is able to 'recall' while being deprived of the dynamic flight context, which in the real world is a very important source of information for dealing with the situation. According to them, they do not provide data about the "natural character and occurrence of situation awareness" (p. 54). Harwood et al (1988) refer to the work of Marshak, Kuperman, Ramsey, and Wilson (1987) to measuring situational awareness in map displays, and group them as the 'probe technique', also lying on the 'explicit' end of the continuum. However, while referring to the same technique, Sarter and Woods believe that such "...after-the-fact data collection such as debriefing requires context-deprived intentional retrieval of information. Because situation awareness can comprise information that is unconscious in the first place until it becomes activated by incoming data patterns..." (p. 54). Thus, such techniques lead to a distortion in the assessment of pilot's situation awareness.

As stated above, at the implicit end of the continuum are approaches to 'capturing' the agent's mental model. Harwood et al (1988) suggest that "mental models may be captured by tapping knowledge structures, represented as domain-specific procedural knowledge" (p. 318). The connection between situation awareness and mental models has already been established. Harwood et al infer that the "organization of this information [information regarding the four dimensions of situation awareness discussed above] in memory has a critical impact on the construction of an accurate situational representation, and on the resulting performance" (p. 318). By using techniques such as Multidimensional Scaling (MDS), Wickens (1992) and his colleagues are currently working on assessing the pilot's structural knowledge component in a dynamic environment, from which an inferred assessment of situation awareness can hopefully be made. Mental models and the difficulties, including the fundamental limitations of being able to 'capture' them, at least in totality, have already been discussed.

This concludes the discussion on the concept of situation awareness. The next section treats Individual Factors and their relevance to crew performance.

4.3 Individual Factors

A goal of this research is to provide a better understanding of crew performance. With regards to pilot performance, Helmreich (1986) cites ability, personality, and attitudes to be three individual characteristics that are major determinants of pilot performance.

Ability in this context refers to knowledge and skill. The preceding sections discussed in detail the two concepts of mental models and situation awareness. Both these concepts lay the foundation for understanding individual performance. Previously, it was noted that mental models are a way of representing individual knowledge. Essentially, they allow for a framework to understand human performance. Even Rasmussen (1990) in discussing human performance as being either skill-based, rule-based, or knowledge-based, invokes the concepts of "...dynamic internal world model" and "...*mental model* [italics added] which may take several forms" (p. 63). Mental models thus provide a framework for understanding what Helmreich (1986) refers to as "ability". But what about personality and attitudes?

This section is devoted to understanding the aspects of performance related to the concept of personality and attitudes. An overview of the theories of personality is presented, with the goal of providing a better understanding of this ambiguous concept. This is followed by an overview of current research concerning the role of personality and attitudes and their influence on pilot performance or behavior. Although personality and attitudes are thought to distinctly influence behavior by some, not everyone agrees with this notion. A summary of both viewpoints is presented. Finally, the understanding of the concepts of personality and attitudes is sought to be enhanced by offering an interpretation of these concepts in terms of the concept of mental models.

4.3.1 Definition of Personality

Hawkins (1993) describes personality as being "...deep-seated characteristics which constitute the essence of a person. They are stable and very resistant to change though certain traits seem to have some tendency to alter in middle age" (p. 172). An attitude according to him, "can be seen as a learned and rather enduring tendency to respond favorably or unfavorably to people, decisions, organizations, or other objects" (p. 173).

There are other definitions of personality, based on the theory or viewpoint adopted. These are better understood in the context of the specific theories which are discussed below.

4.3.2 Theories of Personality

Human beings respond to stimuli or changes in the environment. The concept of personality seeks to address both, how we react to these stimuli as well as why we react the way we do. Apparently distinct, these questions are actually interrelated.

Personality, according to Carson (1969), generally "...refers to the regularities or inconsistencies that characterize a given individual's behavioral repertoire; these regularities are believed somehow to distinguish the individual as a person and to render his behavior predictable" (p. 9). The two theories of personality basically disagree over how these regularities or inconsistencies that characterize a person are acquired.

As Carson (1969) notes, there are several ways that the above mentioned regularities of behavior can be sought to be explained or accounted for. One such set of explanations make up what Carson refers to as "inherited disposition theories" (p. 8). Since early days, psychologists have believed that there are some *innate* characteristics within an individual which cause him/her to consistently react in certain ways. These characteristics are very resistant to change, and typically remain stable throughout one's life. i.e. "...tend to suggest a permanent and static quality - a relatively invariant structural foundation" (p. 8). These characteristics, or the individual's makeup is known as personality.

Inherited disposition theories are disputed by others who do not agree in attributing a static quality to personality. In the early days, proponents of the inherited disposition theories suggested a kind of inherited reaction pattern approach to explaining or predicting behavior. This strategy, as Carson points out, failed because in order to do so, one would have to postulate an indeterminate number of possible inheritance patterns. Further, as a social psychologist would argue, people change throughout their lives. Sometimes, dramatic alterations of behavior are seen as a result of a radical change in the individual's environment, for example as seen in prisoner-of-war camps. An opposite viewpoint of personality thus emerges, which recognizes the importance of the individual's environment and its tendency to make consistent or uniform demands upon him. The recognition of this aspect of behavior, as the author mentions has been responsible for the sociological theories of personality. A radical form of this view is that which "...asserts that personality is nothing more than the constellation of a person's social roles" (p. 8).

But even such a theory is countered by empirical observations where people continue to display salient individual differences in behavior despite being subjected to the influence of powerful and uniform environmental demand characteristics, as in the military.

While the above two theories present opposite ends of the spectrum, there is a middle-ground, as Carson (1969) refers to, which are known as interactional theories of personality. Carson's writings reflect the ideas of Sullivan (1953), the eminent American psychiatrist and social scientist, who defined personality as "...the relatively enduring pattern of recurrent interpersonal situations which characterize a human life" (p. 110). Reflecting upon the ideas of Sullivan, Carson writes that Sullivan "...regards personality as inconceivable other than in the context of interpersonal relations, except perhaps as a mere 'hypothetical entity'" (p. 25). As Carson further clarifies, personality can thus be conceived of "...as manifesting itself only in interpersonal relationships, whether real or illusory" (p. 26).

The thrust of these theories is that dispositional tendencies do not exist within individuals (i.e., are not innate characteristics per se) but are acquired in the course of experience as a result of interactions with other individuals who are part of a stimulus providing environment. Another important feature that this view stresses upon is the fact that it is not so much the environment that determines the response, but one's perception of the environment that influences behavior. Perhaps this idea is best captured by the words of Kurt Lewin (1935) as cited in Carson (1969) who states, "a person's behavior in any situation is jointly determined by the characteristics of that situation, as he perceives them, and by the particular dispositions of which he is possessed at that time" (p. 9).

4.3.3 Attitudes and Performance

In discussing the role of personality and attitudes on individual performance, Helmreich, Chidester, Foushee, Gregorich and Wilhelm (1990) note that "...personality characteristics of crew members may be a limiting factor on the potential impact of crew coordination training" (p. 10). In addition to the use of personality tests traditionally used for pilot selection and training, Helmreich (1984) has developed a Cockpit Management Attitudes Questionnaire (CMAQ) as a tool to assessing the role of attitudes on flightdeck training. Since then research has been conducted by him and his colleagues to determine the correlation between measured attitudes and crew coordination capabilities as assessed by check airmen. (Helmreich, Foushee, Benson, & Russini, 1987). Results from their studies indicate that attitudes among crewmembers differ significantly on a number of issues regarding flightdeck management. Further, as Helmreich (1986) notes, while attitudes are more amenable to change than basic personality traits, "...they [attitudes] also have considerable inertia and resistance to modification." Further, as Helmreich et al (1990) note, "...while training can be shown to change attitudes (as on the CMAQ), it is not likely to alter deeply ingrained, stable, personality traits" (p. 10). Such studies have provided valuable guidelines for CRM training such as the importance of involving crewmembers in the development of CRM training programs and the reinforcement of training through recurrent means such as LOFT.

4.3.4 Personality and Performance

In a study of job performance by Helmreich, Sawin, & Carlsrud (1986), it was found that while personality factors did not predict performance in training, they were likely to influence performance in the long run (i.e., after the training was over). These results, as Helmreich (1986) notes, "...were interpreted in terms of a 'honeymoon effect' -- the tendency of all individuals to try hard during the excitement of training for a new position" (p. 17).

Chidester and Foushee (1988) used statistical techniques such as cluster analysis for analyzing attitudinal data collected with the help of the CMAQ as part of the evaluation of a U.S. Air Force Military Airlift Command recurrent training program in CRM. They identified subgroups of pilots along performance-related personality dimensions. They identified three clusters or subgroups of pilots: positive instrumental/interpersonal, negative instrumental and low motivational. Subsequent studies involving full-mission simulations attempted to identify the impact of differences between pilot personalities and crew coordination training, using the results of the cluster analysis (Chidester, Helmreich, Gregorich, & Geis, 1991). Findings of these studies were consistent with those of Helmreich and his colleagues. Basically, Chidester et al identified consistent differences in crew performance based on the three discernible personality types of captains. They agreed that "personality appears to set some limits, is stable over time, and is resistant to change" (p. 41). Their findings appear to have significant implications for pilot selection and training.

4.3.5 The Other Side

Despite the apparently convincing empirical studies cited above, there are many among the aviation community who challenge the very hypothesis that personality traits and performance are related. While denying the existence of any useful relationships between personality traits and pilot performance, Besco (1994) writes, "The concept of performance-related personality traits is akin to the emperor's new clothes" (p. 24). He cites the work of Hunter and Burke (1990, 1992) who upon conducting a thorough search of the literature "...found no useful relationships between existing measures of personality and pilot performance" (p. 25). After all, "every human personality characteristic known to behavioral scientists can be found at all performance levels....[thus] what does distinguish good pilots from mediocre pilots is the results they achieve...not the personality traits they bring to the cockpit" (p. 27).

Besco (1994) criticizes existing measures of pilot personality and their use in selection programs as being lacking in scientific validity and practical utility. When problems of validity do arise, he claims that most personality researchers tend to attribute these to "...poorly defined concepts as 'the honeymoon effect' and to the restricted range of personality characteristics found in the pilot population" (p. 25). On the basis of these observations, he cautions against using present personality screening instruments to improve the performance of pilot groups. Besco notes that most breakdowns in pilot performance that are sought to be linked with personality traits are actually more correctly categorized as cockpit resource management problems. In disagreeing with attributing CRM breakdowns to pilot personalities, he states:

> In the absence of data demonstrating that personality problems lead to resource management breakdowns, it seems that behavioral scientists who promote the personality difference theories have developed those theories

> based solely on personal biases, professional preconceptions, and academic armchair logic. (p. 25)

4.3.6 Interpretation of Personality

It is clear from the above paragraphs that there exist several viewpoints with regards to personality. To date, the very concept of personality remains a debatable issue among psychological and sociological circles. This is reflected in the disagreement in the aviation community with regards to the validity of the personality-performance connection and the utility of existing personality measures as applied to pilot performance and selection.

It is not attempted to resolve this dilemma although for the purposes of this research it becomes important to clearly define what is meant by personality. Instead, it is believed that personality and attitudes are better understood by invoking the concept of mental models earlier discussed.

Previously it was noted that Norman (1983) outlines the concept of mental models by stating, "In interacting with the environment, people form internal, mental models of themselves and of things with which they are interacting" (p. 7). Further he points out that these mental models provide predictive and explanatory power for the operator's understanding of the interaction between the operator and the system environment with which he/she is interacting.

Although much of our discussion in the section on mental models might have appeared to center around systems involving *things* or equipment, Norman's (1983) definition reminds us that individuals may form mental models of more than just "things" in the environment, but of other individuals as well as of themselves. Although a simple premise, it is important to recognize that an individual's environment consists of more than just things or equipment. Thus, it is plausible that an individual holds a mental model of the interactions with those individuals, in fact he/she might hold several different mental models of interaction depending on the situation. Carson (1969) captures the interactional concept of personality as follows:

> The behavior of the two persons engaged in a typical dyadic interaction is determined by the dispositional tendencies inherent in each of them at the time and by their perceptions of their own and of each other's behavior, as well as their perceptions of other aspects of the situation - perceptions biased in turn by their dispositional tendencies. (p. 12)

The concept of mental models offers an interpretation of the above concept of personality. A mental model of one's self would incorporate many of the responses to one's environment or dispositional tendencies, which would include a repertoire of responses to the other individual's in the environment as well as other aspects of the situation. In short, an individual's mental model of self and of others would include what is characteristically known as the individual's personality and attitude.

Besides personality and attitudes there are other individual characteristics or factors that are uncontroversially linked with individual performance. Examples of these are fatigue, deterioration of the senses such as loss of sight, and incapacitation. I refer to these as the physiological component of individual factors. This physiological component is distinct from the cognitive or interpersonal components which are the focus of this thesis. Although they do affect performance, their further consideration is considered to be beyond the scope of this thesis.

This concludes the discussion on Individual Factors. The next section treats crew performance from a group perspective, as different from the individual perspective so far adopted.

4.4 Crews and Teams

The preceding sections discussed concepts underlying human performance, but focused on the individual. In other words, human performance with the individual perspective was discussed. Most modern commercial aircraft, however, are not flown by individual pilots, but by crews or groups of two or three pilots. In fact, an airline cockpit crew is a team (Hackman, 1993). Thus, as Hackman suggests, "...understanding the behavior and performance of cockpit crews requires careful attention to team-as-a-whole issues, not just to the behaviors of individual team members" (p. 47). But what is meant by crews, groups and teams? And what is meant by 'team-as-a-whole' issues? Do these terms really mean something different, or are they merely hypothetical constructs to account for some things inexplainable? This section addresses these questions and more. First, a closer look is taken at what is meant by the terms by examining some key definitions within the context of group theory. Some of the current research into crew performance from a group perspective is then briefly discussed. This is then followed by an interpretation of team building within the context of the theory of shared mental models.

4.4.1 Group Dynamics

Group theory is concerned with the study of groups and group processes. The field of group processes, also known as group dynamics, refers to the study of individuals interacting in small groups (Luft, 1984). Groups are ubiquitously present in every facet of society; no one denies their existence. If an individual is considered to be the basic unit of humanity, a group can be considered the basic unit of society. However, there exists considerable ambiguity surrounding the notion of groups.

Various definitions of 'group' abound in the literature, depending on the context, viewpoint, and purpose of the definition.

Vander Zanden (1977) define a group as "two or more people who share a feeling of unity and are bound together in relatively stable patterns of social interaction" (p. 400). In describing the characteristics of a group as being a product of social definitions, he clarifies that "...groups are states of mind - mental models or images at varying levels of awareness" (p. 403). Further, he states that groups are intangible, without substance in the real world and are fabricated in the course of social interaction by clustering people together in social units.

Luft (1984), as a basic point of reference, refers to a group as "...a living system, self-regulating through shared perception and interaction, sensing, and feedback, and through interchange with its environment" (p. 2).

While definitions might differ, almost everyone, including Ginnett (1993) agrees that "...groups are something more than merely a collection of the individuals comprising them" (p. 76). It is this 'something more' that no one is quite clear about. The following section tries to explain what groups are really about.

4.4.2 Groups and Crews

According to Luft (1984), to constitute a group, a collection of people must meet certain criteria:

1. Some interaction must take place.
2. Some purpose or goal must be shared.
3. Some differentiation of behavior or function must begin to emerge.
4. There must be more worth or value in being within the group than being outside of it. (p. 7)

Comparing an airline cockpit crew with Luft's criteria, there is no doubt, as Ginnett (1993) states, that "A crew is a group..." (p. 71). During the course of performing its duties, crewmembers obviously interact with each other. They share many goals, at least one of them being to safely transport their passengers or payload from one destination to another. The functions of each crewmember are clearly defined, as are their behaviors. Each crewmember is highly trained and is aware of the role he/she plays as part of the crew. Thus, there already exists a differentiation of functions; there isn't a need for it to 'emerge'. Most pilots take great pride in their work; indeed most of them fly for the "love of flying." Once in the air, each crewmember does his/her best to accomplish the mission's goals. No matter which way one looks at it, pilots certainly attach a lot of worth to being a part of a crew.

4.4.3 The Group as an Emergent Whole

The 'something more' in groups is often explained through the understanding of a group as an *emergent whole.* The Merriam-Websters dictionary (1993) explains emergent as something that arises unexpectedly, something that is newly formed, which involves the appearance of complex new characters or qualities that cannot be predicted solely from the study of less complex levels. The group as an emergent whole gives rise to certain associated *emergent properties* which describe group behavior. In order to understand the theory underlying group dynamics, it is necessary to have an understanding of this concept.

In contemporary group dynamics, one often comes across terms that seem to reflect the idea of a group as some kind of an entity distinct from each of the individual members, something more than their mere 'sum'.

For instance, Vander Zanden (1977) notes that groups are social entities that exist "apart from the particular relationships that people have with one another" (p. 404). Further, he writes, "The whole is greater than the sum of its parts. Groups have a distinctive character in their own right, a character that lies in the linking of people apart from the particular individuals who are linked" (p. 404).

Luft (1984) cites several examples of terms such as *herd instinct* (Trotter, 1916), *group mind* (Le Bon, 1960) and *syntality* or *group personality* (Cattell, 1956), that have been around for decades, each attempting to capture a phenomenon distinct from those associated with individuals. Kurt Lewin (1948), who Luft notes is considered to be the father of group dynamics, attributed the success of a teacher in a classroom to 'group atmosphere'. According to Luft, "...all these showed the need for group-relevant terms to serve as intervening variables in the building of adequate theories" (p. 11). In defending the group perspective, Luft writes, "There is nothing mystical about assuming that a group (as well as a certain number of individuals) is present. The group perspective is but another way of approaching a familiar phenomenon" (p. 11).

The idea of a group as an emergent whole may be difficult to grasp, at least initially. To do so, there has to be a paradigm shift in focus from the individual to the group. Part of the difficulty in understanding groups, as Luft (1984) writes, "...stems from the overemphasis on individual personality as well as in contemporary psychology" (p. 135). Further, on commenting upon the overemphasizing of egocentrism, he writes, "Whether we are attending to dyads, face-to-face groups, or larger communities, we tend to seek explanatory ideas by referring to individual personalities rather than to group characteristics" (p. 140). In fact, it is precisely such schools of thought that urge researchers like Besco (1994) in the aviation community to want to discard the ideas of using personality tests as measures for pilot selection and performance assessment. In the aviation context, Ginnett (1993) writes, "We are an individualistic culture...we do not focus as much attention on the accomplishments of groups as we do on the accomplishments of individuals" (p. 71). He mentions the importance assigned to the 'solo' flight as the goal of a trainee pilot as a classic example of the individual focus.

Luft (1984) asserts the importance of going beyond the individual focus to understand group behavior. He writes, "Understanding the isolated parts of a new phenomenon may not be sufficient to understand the whole. The principles of behavior of a group are best understood at the level of group activity rather than at the level of individual personality" (p. 11).

4.4.4 Properties of Groups

Having recognized the significance of seeing the group as an emergent whole, attention is now focused on understanding some of the emergent properties or characteristics of groups. It is much beyond the scope of this thesis to thoroughly examine all group properties, nevertheless, the basic ones are outlined here. An understanding of these is necessary to better understand group behavior and thereby crew performance.

Freud (1922) first proposed the idea that the group as a whole was constantly in a state of (focal) conflict at any given time. Klein (1948) suggested that this conflict arose out of the wishes and fears of members at a particular stage in a group's development. The idea of central conflict at the group level is almost analogous to Sullivan's (1953) explanations of the driving forces of individual behavior as seen to be arising out of the two kinds of needs in individuals; the need for satisfaction and the need for security (avoidance of anxiety) (Carson, 1969). The notion of focal conflict has invoked some interesting psychodynamic concepts. Firstly, members of the group are not aware of this conflict. Secondly, in order to ensure the smooth performance of the group, someone has to bear the responsibility of helping to reduce this conflict. Typically, such a person is called the leader. As Luft (1984) writes, "The focal issue usually centers on questions surrounding authority, the leader, and intermember relationships" (p. 12). In an airline cockpit crew, the captain is supposed to be the leader of the group, and it is the captain's responsibility to ensure the smooth functioning of the group by reducing focal conflict.

Luft (1984) distinguishes between group *process* and *content*. Content refers to the task at hand or the subject matter which the group is concerned with, while "Process refers to the real meaning of ongoing activity in a group, in a relationship, or in an individual" (p. 13). Processes are subtle, difficult to identify, and are not made particularly explicit, yet they need to be learnt by experience and dealt with in order to reduce group conflict. Group processes are better understood by examining them within the context of group structure.

4.4.4.1 Boundaries

Groups have boundaries; these define who belongs to the group and who does not. Those who are inside the group serve as reliable possibilities of interaction, while those who are outside do not. A boundary, like other properties being discussed, is an emergent socio-psychological property. As Vander Zanden (1977) writes, "Group boundaries act not as physical barriers, but as discontinuities in the flow of interactions" (p. 401). It is seldom explicitly defined, it evolves over the process of interaction. Milgram and Toch (1969) qualify boundaries as being penetrable or permeable. The boundary is imagined as a kind of mesh or screen which filters some people in and leaves others out. Generally speaking, the more permeable the boundary, the greater are the possibilities of interaction.

As Ginnett (1993) writes, the boundary of an airline cockpit crew is defined to some extent by the technology. For example, a cockpit with two seats limits the expected boundary to Captain and First Officer. Despite this, the boundary does not have to be impermeable. In fact, in a study conducted by Ginnett (1987) at NASA, he found that captains who were ranked by other check airmen as being "highly-effective" tended to expand the group's boundaries to include cabin crewmembers, Air Traffic Control (ATC), gate and maintenance personnel and in some cases even the passengers. These captains tended to use "we" as against less-effective captains who used "us" for the cockpit crew and "you" for cabin crewmembers.

Thus, one of the important functions of a captain in ensuring that the group performs effectively is to expand its boundaries, and include other personnel who can all be potentially valuable resources on the flightdeck.

4.4.4.2 Group structure

According to Luft (1984), "The structure of a group refers to the arrangement of its parts and how those parts relate to one another and to the group as a whole" (p. 16). Parts refer to persons, units, roles, status, and hierarchy of group subunits while relations of the parts to one another is explained in terms of group norms, rules, and procedures. Further, structure in a group is invisible, it has to be inferred. A group which has a task assigned will develop certain structure. In other words, "...structure grows out of a need for effective group work" (p. 16). A cockpit crew has a well defined task to perform. Much of its structure is defined prior to its formation but as the group evolves, its structure changes.

4.4.4.3 Roles

Luft (1984) defines a role as referring to "...a set of expectations shared by group members concerning the behavior of a person who occupies a given position in the group" (p. 21). As Luft points out, role is not to be confused with personality or an individual. Role is instead imposed by the context of the situation and is associated with a particular position. Ginnett (1993) defines a role as "a set of expected behaviors associated with a particular position (not a person) in a group or team" (p. 78). Roles evolve because group behavior is not random but involves patterns of behavior. Sometimes roles are not clear, or match the personalities of individuals occupying those positions either perfectly, partially, or not at all.

In an airline cockpit crew, the roles are well defined. However, group members may assume alternating or multiple roles depending upon the situation. A captain is expected to assume the role of leader, the first officer and second officer assume the roles of followers. Sometimes however, conflicts do arise because of roles.

As Luft (1984) notes, "role conflict arises out of discrepancies between how one is expected to behave and one's natural inclinations" (p. 21). Ginnett (1993) refers to this kind of conflict as person-role conflict. He also identifies three other kinds of role conflicts: intra-sender conflict, inter-sender conflict and inter-role conflict. Intra-sender conflict arises when the same person in a group provides another with conflicting signals about their expected role. Inter-sender role conflict arises when more than one person in a group provide another with conflicting signals on expected behavior. Finally, inter-role conflict arises because of two or more different roles played by the same person.

It is again, the leader's (captain's) responsibility to ensure that role conflicts if any are resolved so that they do not manifest themselves in situations which can lead to a breakdown in performance.

4.4.4.4 Status

According to Ginnett (1993), "Status is the relative ranking of individuals within a group setting" (p. 81). As Luft (1984) notes, "Status (value, prestige, power) and hierarchy of group subunits are aspects of structure, and these may be established formally or informally" (p. 16). In the case of airline cockpit crews, status pre-exists with the position that each crewmember occupies. Conflict can arise as a result of incompatibility or incongruence in status, similar to role conflict. Assessing and taking appropriate action to resolve status conflict is thus also an important function that is the captain's responsibility.

4.4.4.5 Authority

Ginnett (1993) defines authority as "...the right to use power and influence" (p. 81). Responsibility and authority go hand in hand. Authority is derived from the legal or legitimate power given to a crewmember and is associated with his/her position, but authority can also be derived or commanded from other group members based on expertise. For instance, the foreman in a group in an industrial setting is typically the one with the authority assigned to him/her but this authority, if not controlled or channeled properly, is easily eroded if the foreman lacks technical expertise, particularly if another group member demonstrates a higher level of expertise than the foreman.

The same is true for an airline cockpit crew. The captain is the one assigned the authority. As Edwards (1988) writes, "Problems have arisen and have been reflected in the accident record, when the captain's role has been overemphasized and when it has been underemphasized" (p. 16). Edwards (1975) refers to the authority variable to be optimized as the trans-cockpit authority gradient (TAG) and notes that its appropriate establishment is necessary to ensure high standards of flight-deck management and interpersonal relationships. However, research in simulator studies shows that there is generally little danger of the captain's authority being usurped. On the contrary, it often becomes necessary for the captain to "lower" the TAG so as to encourage input from other crewmembers who may be reluctant to speak up. In fact, the focus of early CRM training was on "assertiveness training", or training the crewmembers to assert themselves, particularly under potentially critical conditions. The TAG is also known by some as the *authority dynamic* (Ginnett, 1993). Ginnett cites a study by Harper, Kidera, & Cullen (1971) in which first officers were reluctant to take over control even though the captains feigned incapacitation. From this study, he infers that "...the authority dynamic surrounding the role of the captain must be extremely powerful" (p. 81). Ginnett also notes that the authority relationship in airline crews is bound to factors such as aviation history, regulations and to individual crewmember characteristics.

4.4.4.6 Norms

Ginnett (1993) defines norms as "the informal rules that groups adopt to regulate group members' behavior" (p. 79). Hackman and Walton (1986) note that "Norms regulate many aspects of group life....for example, how members relate to one another or how much effort they expend on the task" (p. 84). Norms provide expectations about behavior. Like other emergent properties, they are not made explicit, but group members learn them as they evolve; typically they are established in the early stages of the group's life. Ginnett (1993) points out two important features of norms: 1) They do not govern all behaviors but just the ones the group feels are important, and 2) they are more likely to be noticed by an outsider than a group member.

Ginnett (1993) notes that a captain may communicate norms in a variety of ways. For example, the captain may make explicit certain norms in the crew briefing or by talking explicitly about their importance, or the captain may communicate the norm by setting an example. In Ginnett's (1987) study, he noted that the most common norms made explicit by effective captains were those regarding the importance of safety, and the importance of effective communication and cooperation among crewmembers. Attention is now focused on teams.

4.4.5 Teams

Above were discussed preliminary concepts of group theory relevant to understanding crew performance from a group perspective. From this perspective, it is the group or the crew who flies the airplane and not just a collection of individual pilots. Since it is the group that is flying the airplane it is important to understand what makes the group effectively perform its duties, and in order to do so, some key group dynamic concepts as relevant to the crew were discussed. The responsibility of ensuring the smooth performance of a group is often referred to as the function of team-building and maintenance. Ginnett (1993) makes some specific recommendations for the group leader to ensure smooth group functioning while Hackman and Walton (1986) provide a discussion of the theory underlying team building and maintenance. Some elements of these are further elaborated upon below.

Before proceeding with a theory of team building, a closer look is taken at *teams*. Why is an airline cockpit crew referred to as a team? Is team different from group? Some definitions of teams are examined below.

In discussing current research on group decision making, Orasanu (1990) points out two distinct lines which according to her, seldom interact. She notes that one line of research focuses on group deliberation, typically involving groups whose goal is to reach some kind of a consensus on a problem, for example faculty committees or jury trials. The other line of research, she notes, deals with groups who are involved in making decisions which play a role in ongoing behavior (i.e., are within the context of performing some kind of a task other than merely reaching a decision). Further, she writes, "Most often we would call these groups teams or crews. They exist to perform some task...not just to make a decision, and possess knowledge and skill relevant to the task" (p. 3).

Cannon-Bowers, Salas, and Converse (1993) define a team as "A group of two or more individuals who must interact cooperatively and adaptively in pursuit of shared valued objectives" (p. 222). Further, in accordance with Orasanu's (1990) above definition, Cannon-Bowers et al note that members of a team are homogeneous with respect to expertise, roles and responsibilities i.e. "...have clearly defined differentiated roles and responsibilities, hold task-relevant knowledge, and are interdependent" (p. 222).

Even though some researchers have attempted to delineate between a group and a team, the distinction remains fuzzy. Yet, this may not be as much of a dilemma as it might appear. After all, a team could be viewed as a "special case" of a group, with additional constraints or requirements. It is therefore concluded that there might not be a distinct cut-off between the concept of group and team. In fact, they could be conceptualized to lie along a continuum, the team denoting a highly effective group in a task-performing environment (F. Bernieri, personal communication, June 29, 1994).

4.4.6 Team Building and Maintenance

Hackman and Walton (1986) propose a theory of team performance by applying a functional approach to analyzing team behavior. In maintaining that "...there is no single, unidimensional criterion of team effectiveness..." (p. 79), they define group effectiveness along three dimensions which briefly involve the degree to which the group performs what it was supposed to accomplish, the degree to "...which the process of carrying out the work enhances the capability of members to work together interdependently in the future" (p. 78), and the degree to which the group experience was personally rewarding or satisfying to each group member. For the sake of brevity, I refer to these three dimensions as the task dimension, the social dimension, and the personal dimension respectively.

In recognizing the difficulties in using traditional cause and effect thinking in understanding group effectiveness, Hackman and Walton (1986) instead analyze group effectiveness in terms of necessary ingredients. Their result is a list of five conditions which they believe are the "...key to the effectiveness of task-performing teams in organizations..." (p. 87). These are listed below:

1. Clear, engaging direction.
2. An enabling performance situation.
   * A group structure that fosters competent task work.
   * An organizational context that supports and reinforces excellence.
   * Available, expert coaching and process assistance.
3. Adequate material resources. (p. 87)

Hackman (1993) notes that "it is now generally recognized throughout the aviation community that cockpit crews are task-performing teams" (p. 54). In applying the conclusions of the above functional analysis to cockpit crews, he notes three important facts about cockpit crews: cockpit crews are teams, the captain is the team leader, and crews operate in an organizational context. Each of these facts have several implications for the organization, the captain, as well as the crewmembers for ensuring team-effectiveness. Among the implications for the organization (senior managers) are its being able to provide clear direction i.e. "communicate to captains...what is expected of them and their crews and...the degree to which captains are given sufficient latitude to achieve those directions" (p. 57). The organization also bears ultimate responsibility for providing adequate material resources such as proper training, but both these points pertain to the conditions outside the cockpit.

Ensuring team-effectiveness inside the cockpit consists of taking into consideration the implications of the second point noted above (i.e., providing an enabling performance situation). Primary responsibility for this essential function implicitly rests with the captain, but is nevertheless shared by all crewmembers. Hackman (1993) notes three team-building activities that captains can and should perform. They are, establishing group boundaries, "...helping the crew come to terms with any special requirements of the day's work, and establishing the basic norms of conduct that will guide behavior in the crew" (p. 56). Ginnett (1993) confirms these activities in his observations of crew behavior. In addition to Hackman's suggestions for fine-tuning team performance he suggests the establishment of an appropriate authority dynamic as being an important team-building activity, particularly where airline crews are concerned.

4.4.7 Team Building and Shared Mental Models

Previously, it was noted that the concept of mental models has been invoked as a framework to explain the cognitive mechanisms underlying individual human performance. This notion of (individual) mental models has quite logically been extended by researchers to explain group or team performance. In doing so, researchers (Klein & Serfaty, 1989; Cannon-Bowers et al., 1993) have proposed the notion of *shared mental models*. In referring to the phenomenon of team performance and team decision making, Cannon-Bowers et al. propose that conceptualizing teamwork in terms of shared mental models "...provides an effective means to understand this rather elusive phenomenon" (p. 222). Orasanu (1990) also invokes the concept of shared mental models by stating, "*Shared Mental Models* [italics added] are needed if all crewmembers are to work toward the same goal" (p. 4).

Groups have traditionally been assigned emergent properties as discussed above. Likewise, the notion of shared mental models associated with teams may be viewed as an emergent property of teams.

A fundamental purpose of mental models is to enable the prediction of the situation in the future (i.e., generate an expectation or projection of system state). The main purpose of shared mental models thus, is to generate common expectations among team members. Cannon-Bowers et al. (1993) hypothesize that "team effectiveness is a function of the compatibility of expectations generated from team members' mental models" (p. 228). Although the formation of shared mental models does imply the generation of common expectations among members, as Cannon-Bowers et al clarify, it does not mandate individual mental models held by team members to be identical. Cannon-Bowers et al define shared mental models as:

> knowledge structures held by members of a team that enable them to form accurate explanations and expectations of the task, and, in turn, to coordinate their actions and adapt their behavior to demands of the task and other team members. (p. 228)

Shared mental models are formed through effective communication between team members. The importance of effective communications in ensuring the efficiency and safety of operations has since long been recognized. With the advent of video-taped full-mission simulation, several studies have been conducted to closely analyze communications under different situations and determine the link between communication patterns and performance (see section on 'CRM- Guidelines, research and training' in Chapter 3). A full-mission simulation study by Chidester, Kanki, Foushee, Dickinson, and Bowles (1990) and its subsequent analyses by Kanki, Palmer, & Veinott (1991) made interesting observations on the link between personality, communication patterns and performance (also see previous section on 'Personality and Performance'). As Kanki and Palmer (1993) note, "Negative expressive captains initiated less total speech than did other types of captains, and these were the same crews who made the most errors..." (p. 117).

In an analyses of data collected from simulation studies conducted by Foushee, Lauber, Baetge, and Acomb (1986) and the Chidester et al. (1990) study mentioned above, Orasanu (1990) analyzed communications in crews determined as high and low performing. In doing so, she focused on the role of communication patterns in building shared situation models. On the basis of her observations, she suggests that "...the good captains, by articulating plans and strategies, create a context in which their commands and information requests take on meaning. This articulation helps to build a shared mental model for the situation" (p. 15). Finally, she concludes that "through communication crews develop a shared understanding of the nature of the problem, solution strategies, cue significance, and participant roles and responsibilities" (p. 15).

Since a system can be understood at various levels, it is hypothesized that individuals hold multiple mental models of a system (Rouse & Morris, 1986). Based on the notion of multiple mental models, Cannon-Bowers et al (1993) suggest that team members interacting with a system may hold several mental models of the task at hand and of the team. Specifically, they outline four types of models that may be held by individual team members, namely (a) equipment model, (b) task model, (c) team-interaction model, and (d) team model. The equipment model refers to the dynamics and control of the equipment with which they are interacting. The task model refers to an understanding of task procedures, likely contingencies, likely scenarios, task strategies and environmental constraints. The team-interaction model refers to the individual's roles, responsibilities and role interdependencies, while the team model refers to familiarity with the knowledge, skills, abilities, preferences and tendencies of other team members. The team model is essentially the shared mental model that would be formed by a sharing of individual mental models of the self, previously discussed in the section on 'personality and mental models'. Further, as Cannon-Bowers et al note, these shared mental models are not independent of each other (i.e., they do interact with each other).

Sharing of these four models held by individual team members would result in there being at least four shared situation models. This enables the definition of the knowledge content of shared situation models. Cannon-Bowers et al (1993) hypothesize that for effective team performance, "...team members must share those mental models that describe when and how they must interact with one another in order to accomplish the task" (p. 234). They therefore conclude that individual team members may not need to share their individual equipment models, but they would need to share their other three mental models viz. those of the task, team-interaction, and of the team.

From the above, it can be concluded that the building and maintenance of a team would comprise the formation of at least three 'shared situation models' as follows:

Shared Task Model - This would include knowledge about each other's tasks, task procedures, and task strategies. This would "...create expectations about how events are likely to unfold and how the team is likely to respond to task demands..." (p. 234).

Shared Team-interaction Model - This would include knowledge about how each team member must interact with the other. In terms of group theory, this would mean a shared understanding and acceptance of group characteristics such as norms, roles, status, and authority. This model would lead to the generation of expectations about behavior, enabling team members to effectively monitor each other's behavior and adequately respond to it.

Shared Team Model - This would include information regarding the knowledge, skills, abilities, preferences, and tendencies of particular teammates so that behavior can be tailored accordingly. Essentially, this refers to a sharing of individual mental models of the self. In accordance with the discussion on 'mental models of the self' and for the sake of consistency, these will be referred to as *Shared Team-personal Models.*

4.4.8 Team performance and Group Situation Awareness

Previously, it was noted that individual mental models are seen as being the basis for adequate situation assessments. Accurate situation assessments, in turn result in situation awareness, which is critically linked with performance. In other words, accurate individual situation models lead to individual situation awareness. (see section on Mental Models and Situation Awareness).

Extending the concept of individual situation awareness to group settings, Wellens (1989) defines *group situation awareness* as "the sharing of a common perspective between two or more individuals regarding current environmental events, their meaning and projected future status" (p. 6). Further, he assumes that high degrees of group situation awareness results in high degrees of group coordination and task performance.

The concept of extending the notion of individual situation awareness to group situation awareness is similar to the extension of the notion of individual mental models to that of shared mental models. As such, the distinction between (individual) mental models and (individual) situation awareness (Sarter & Woods, 1991) is also relevant to the distinction between the concepts of shared mental models and group situation awareness.

As was mentioned earlier, Cannon-Bowers et al (1993) clarify that the sharing of mental models does not mandate individual mental models to be identical. Wellens (1993) with regards to maintaining high degrees of group situation awareness notes, "This is not to say that all members of a group should strive to obtain totally overlapping SA [situation awareness] zones" (p. 272). Further, he notes that, "The key to optimal group SA appears to be arranging group members such that enough overlap occurs to maintain group coordination while allowing enough separation to maximize coverage of the relevant environment" (p. 272).

The above views are briefly summarized as follows. Shared mental models lead to group situation awareness. The greater the sharing of mental models, the higher is the level of group situation awareness. This results in high degrees of group coordination and task performance, resulting in a high degree of team effectiveness.

The above completes the interpretation of groups and teams in the context of mental model theory. This concludes the chapter on the theory underlying crew performance. In the next chapter, principles of systems engineering and modeling are applied towards developing a model of crew performance which creates a framework for its understanding.

5. MODELING CREW PERFORMANCE

Chapter 4 presents elements of the theory underlying crew performance. In Chapter 2, it was noted that the concept of CRM remains fuzzy. Many of the issues surrounding CRM need more definition. An application of systems theory can lead to a better understanding of crew performance and consequently of crew coordination.

This chapter details the approach and the specific methodology adopted to analyze crew performance. Briefly discussed below are fundamental concepts of systems theory, along with a discussion of their importance and relevance to crew performance. This is followed by a discussion of other concepts including system models and system modeling. A detailed description of the specific methodology adopted to analyze crew performance is then provided, followed by a detailed description of the model developed as a result of the analysis.

5.1 System Concepts

The concept of systems is fundamental to human factors. There are many viewpoints and thus definitions of systems. From the perspective of general systems thinking, Weinberg (1975) defines a system as "...a point of view....a way of looking at the world" (p. 52). Douglas Ross, in the foreword to the book by Marca and McGowan (1988) writes, "The world and everything in it, including our thoughts about it, can be viewed as a system of interacting systems of systems" (p. xii).

Bailey (1982) as cited in Sanders and McCormick (1993) defines a system as "an entity that exists to carry out some *purpose*" (p. 13). The concept of 'purpose' is fundamental to that of a system. As Sanders and McCormick state, "Every system must have a purpose, or else it is nothing more than a collection of odds and ends. The purpose of the system is the system goal or objective, and systems can have more than one" (p. 16).

Marca and McGowan (1988) distinguish between natural and constructed systems in our world. Natural systems are those existing in nature, such as the solar system, whereas constructed systems are designed by human beings and serve to satisfy human needs. Almost every constructed system involves the interaction of one or more human beings with a machine or a physical component. As such, these systems are referred to as *human-machine* systems and the word system will primarily be meant to refer to these human-machine systems. Sanders and McCormick (1993) thus define a system as "composed of humans, machines, and other things that work together (interact) to accomplish some goal which these same systems could not produce independently" (p. 14).

From a systems perspective, an aircraft and its crew operating inside the cockpit form a complex human-machine system whose purpose is to safely accomplish the mission of transporting either a payload of passengers or cargo from one destination to another. By treating the crew as a system, it is possible to subject it to the analytic methods of systems engineering.

5.2 Systems Engineering

In earlier days, systems evolved largely due to a process of trial and error. Modern systems are far too complex and expensive to be simply allowed to evolve. Instead, they are analyzed and designed then implemented and tested and finally put into operation (Marca & McGowan, 1988). There exists no universally accepted definition of systems engineering. McGuire, Zich, Goins, Erickson, Dwyer, Cody and Rouse (1990) note that "System engineering specialists generally use the term to describe a rigorous and highly disciplined development process that is carefully structured to achieve optimum performance of the end product" (p. 4). Broadly speaking, system or systems engineering is the discipline that concerns itself with the analysis, design, implementation, integration, testing and operation of complex human-machine systems. While all phases in the system development process are important, the success of all constructed systems depends critically on the functions of analysis and design.

Marca and McGowan (1988) define system engineering as a "discipline for specifying subsystems, components, and how they interconnect; for identifying the constraints under which a system must operate; and for deciding upon an effective combination of people, machine and software to realize a system" (p. xv). The process of system description is fundamental to the problem of understanding or the analysis of systems. In describing the problems involved in the analysis and design of complex systems, the authors write, "Our inability to easily describe, and hence understand, these kinds of systems makes their specification, development, and maintenance time-consuming and expensive, and increases the risk of failure" (p.7).

Wymore (1976) distinguishes between system *analysis* and system *design* by defining system analysis as "the process or act of developing and manipulating a model of a large-scale, complex, man/machine system that is already in existence....system design on the other hand, means to develop a *model* from which a new system will be created" (p. 1).

5.3 Models and Modeling of Systems

On models of performance, Wickens (1984) writes, "...models are theoretical representations of systems that specify the major components involved and the relationships among them" (p. 8).

In Chapter 3, the topic of representation and mental models was discussed. Everything that was said about models in general still applies. A model, in general terms, is a representational system; a mental model is a specific case of a knowledge representation system. All models by themselves constitute a representational system that seeks to represent a represented world. Rumelhart and Norman (1988) were cited in Chapter 3 to define a representation as "something that stands for something else. In other words, it is a kind of a model of the thing it represents" (p.513).

As noted above, the world is a system of interacting systems of systems. The goal of an analysis of any system is to better understand the interactions between and within systems. Typically, these interactions are better understood by creating a model of the system. Weinberg (1975) states, "The main role of models is not so much to explain and to predict - though ultimately these are the main functions of science - as to polarize thinking and to pose sharp questions" (p. 43). Further, he writes, "We do not create the world, we make a model....Every model is ultimately the expression of *one thing we think we hope to understand in terms of another that we think we do understand*" (p. 28).

In less philosophical terms, a model as Marca and McGowan (1988) describe it, "is an understanding of a system" (p. 8). Further, modeling a system, is "...the act of developing an accurate description of a system" (p.7).

There are many ways to develop a description or a model of a system. As Wymore (1976) writes, "The model can take several forms; it might be as simple as a written verbal description, or it might be a set of equations or it might be as complicated as a computer program by which the system is simulated" (p. 1).

5.4 Structured Analysis and Design Technique (SADT)

A primary goal of this research is to provide a better understanding of crew performance. To do so, the crew is viewed as a system as described above. It is hoped that a rigorous analysis of this system, based on the principles of systems engineering will provide this better understanding. The result of this analysis will be the model that is developed.

In the following sections, a graphical model of crew systems, based on a structured analysis technique is developed. First, the specific methodology that was used to analyze the crew system is described. The application of the methodology to analyzing the crew system is described in subsequent sections along with a representation of the model developed.

The Structured Analysis and Design Technique (SADT) is a system description language and methodology developed by Douglas T. Ross of SofTech, Inc. and first introduced in 1973. Although in use by Ross and his colleagues under different names and notations in unrefined forms even prior to its formal introduction for over a decade, SADT found its first major application in the United States Air Force's Integrated Computer-Aided Manufacturing Program (ICAM or AFCAM) where it was used to describe the functional architecture of manufacturing (Marca & McGowan, 1988). The U.S. Department of Defense recognizing the value of SADT made public a subset of SADT, which was known as the Integrated DEFinition Language Zero (IDEF0) (Triune Software, Inc., 1993). Since then, SADT under the name IDEF0 has been used in various applications by both military as well as commercial organizations. In fact, a 1991 Small Business Innovative Research Program report on systems analysis quality metrics by Williamson (1991) states that "IDEF0 is the most widely used systems analysis methodology throughout the DoD [Department of Defense] and industry" (p. 1).

As the name suggests, SADT is an analysis tool based on structured logic. It is a graphic language and modeling methodology which uses a set of logical analysis procedures developed to help accurately describe and thus better understand constructed systems of medium complexity. SADT mainly involves two kinds of modeling, *function* or *activity* modeling and *data* modeling. Marca and McGowan (1988) describe activity and data models as follows:

> Activity models present system activities in a successively detailed manner, and they define the relationship among those activities through the things of the system. Data models are the duals of activity models and thus present a continually detailed description of system things interrelated by system activities. (p. 8)

IDEF0 is the activity modeling subset of the SADT methodology, and is the one adopted for the purpose of analysis of crew systems. Activities are also known as functions, hence IDEF0 modeling is also referred to as a structured functional modeling technique.

5.5 Concepts of IDEF0 Modeling

IDEF0 is a structured, graphic modeling methodology which seeks to describe a particular system by focusing on system activities as against system things.

5.5.1 Purpose and Viewpoint

Above, it was noted that the concept of *purpose* is fundamental to the concept of system. Inextricably linked with purpose is the concept of *viewpoint.* Another look at the definitions of system would serve to clarify this point. Weinberg (1975, p. 52) states, "A system is a point of view....a way of looking at the world" (p. 52). Bailey (1982) as cited in Sanders and McCormick (1993) defines a system as "an entity that exists to carry out some *purpose*" (p. 13). Marca and McGowan (1988) write, "The purpose of the model is, by definition, answering a set of questions" (p. 8). The modeling process is thus stopped when the model is considered to have adequately answered a set of questions implicit in the purpose. IDEF0 also stresses the importance of viewpoint, or the perspective from which the system is being modeled. Marca and McGowan further write, "*Viewpoint* [italics added] is best thought of as a place, person, or thing one can stand in to view the system in operation" (p. 9). A single viewpoint is important for a consistent system description. It is important to note that the same system modeled from a different viewpoint may result in a different model or description of the system. In IDEF0, system purpose and viewpoint are given due importance by requiring the analyst (one who models the system) to explicitly define these.

5.5.2 Subject and Boundary

No system exists in isolation. Depending on how the system is defined, it can always be seen as being part of larger systems. Similarly, a particular system can be viewed as being composed of several smaller subsystems. This would depend on one's viewpoint. What is considered inside the system, and what is considered outside of it would thus depend on how one defines the *boundary* of the system (Sanders &

McCormick, 1993). Defining the boundary of the system is referred to as 'bounding the subject' in SADT modeling. (Marca and McGowan, 1988). Marca and McGowan write, "By bounding a subject, an SADT model helps focus attention on just the system being described and avoids introducing extraneous subjects" (p.8). Sanders and McCormick (1993) refer to all that is outside the boundaries of the system as its *environment.*

5.6 SADT/IDEF0 Models

IDEF0 modeling begins with the definition of system subject, purpose and viewpoint. Marca and McGowan (1988) describe the process as:

> The subject defines what to include in, and exclude from, the model. The viewpoint guides the SADT model builder in selecting the right things to say about the subject and staying focused within them. The purpose becomes the criterion for determining when to stop the model. The end result of this process is a collection of carefully coordinated descriptions, starting from a very high-level description of the entire system and ending with detailed descriptions of system operation. (p.9)

An SADT model is essentially a hierarchically organized collection of coordinated descriptions of system operation. IDEF0 refers to each of these descriptions as a *diagram,* which is the basic work unit of the model. An IDEF0 diagram consists of only boxes and arrows. Below is presented an overview of the characteristics of boxes and arrows, syntax and semantics. The goal is to provide a basic understanding of the IDEF0 modeling methodology.

5.6.1 Boxes

An IDEF0 diagram box is drawn as a rectangle (see Figure 1). Each box represents a system function or activity. Boxes represent functions or active parts of a system, hence boxes are named with verbs or verb phrases. Each side of a box has a specific meaning, the left side being reserved for *inputs*, the top side for *controls* or *constraints*, the right side for *outputs* and the bottom side for *mechanisms*. Each box has arrows touching the respective four sides which define the interconnections between boxes. Arrows are discussed in further detail below.

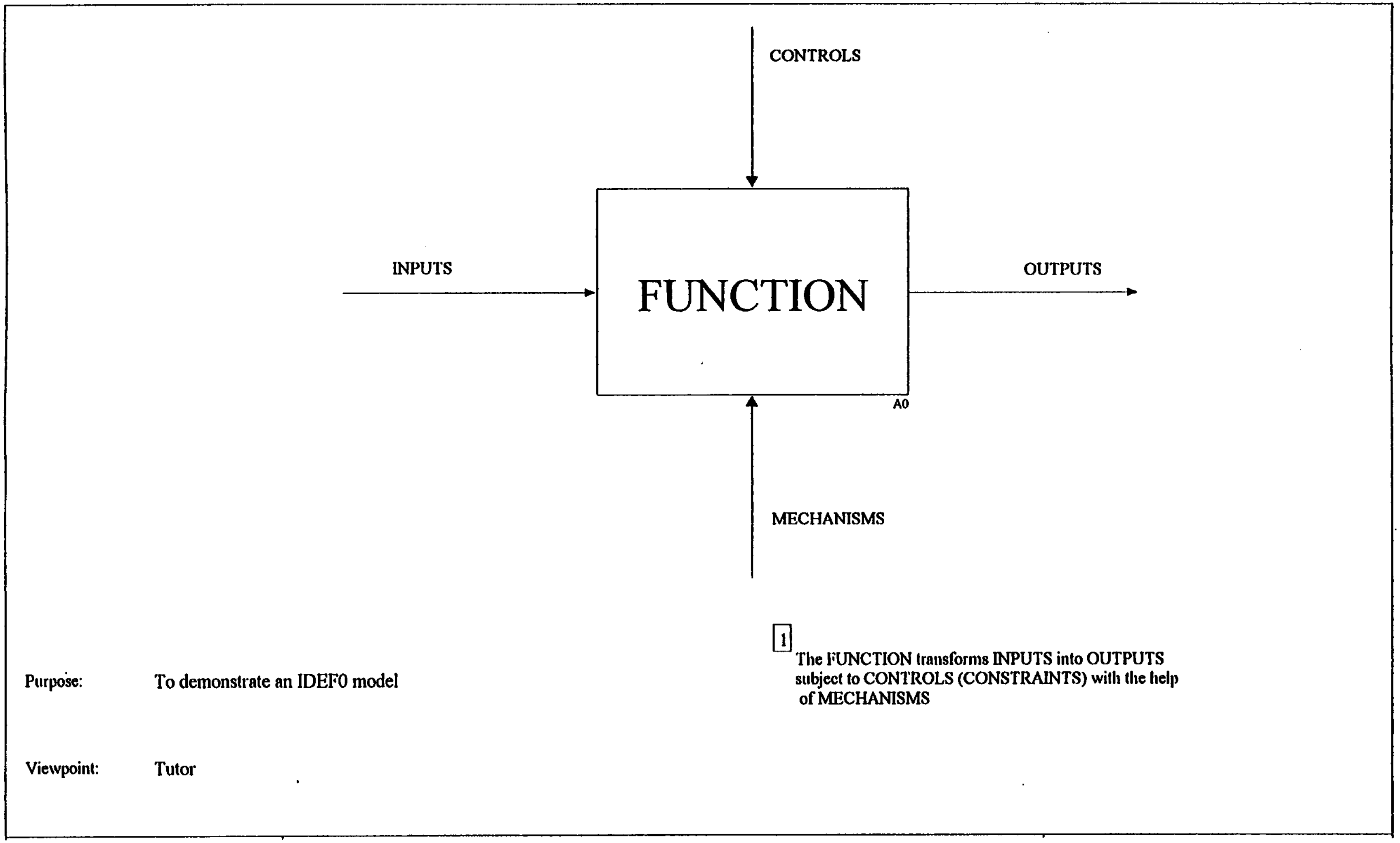

CONTROLS
INPUTS
FUNCTION
OUTPUTS
A0
MECHANISMS
1
The FUNCTION transforms INPUTS into OUTPUTS subject to CONTROLS (CONSTRAINTS) with the help of MECHANISMS
Purpose: To demonstrate an IDEF0 model
Viewpoint: Tutor

Figure 1. CRS/A-0 Function

The box forms the universal unit for structured analysis in SADT (Marca & McGowan, 1988). Each box bounds a well-defined subject (the name of the box). Each subject can be divided into its structured pieces; the boxes and arrows that make up a diagram. A division of a box into its structured pieces is called *decomposition*. IDEF0 models evolve through a process of top-down or hierarchical decomposition. At the top level, there is only one box, along with the arrows which touch its four sides. This box defines the overall system task to be accomplished, and thus bounds the model. Everything inside the box is part of the system to be described and everything outside it forms the system's environment. This box is then decomposed into its constituent system activities or boxes along with the arrows that interconnect them.

5.6.2 Arrows

Arrows in an IDEF0 model are single lines with arrowheads at their ends. The tail of an arrow is known as its source and its head (with the arrowhead) is known as its destination or sink (Marca & McGowan, 1988; Williamson, 1991). Each arrow represents a *thing* or a collection of things. A thing in SADT modeling has a general meaning and can mean either a physical entity such as raw materials, products, a crewmember or even information presented in any form. In IDEF0, things are also referred to as *data* and are labeled with nouns or noun phrases. There are four kinds of arrows or things : *Inputs*, *Controls*, *Outputs*, and *Mechanisms*. An arrow represents a relationship between boxes i.e. data represents interconnections among activities, each relationship or interconnection being represented by an arrow connected to one particular side of a box. Input arrows enter the function (box) from the left; Output arrows leave the function from the right. Control arrows enter the function from the top while Mechanism arrows enter the function from the bottom.

The basic IDEF0 activity-data unit of analysis is thus the box along with the arrows, the concept being that the function transforms the Inputs into Outputs by Mechanisms, subject to the constraints imposed by Controls. (McGuire et al., 1990) As Marca and McGowan (1988) clarify, "Input arrows represent those things used and transformed by activities....Control arrows represent the things that constrain activities....Output arrows represent those things into which inputs are transformed....Mechanism arrows represent, at least in part, how activities (i.e., the functions of the system) are realized" (p. 15).

5.6.3 Diagrams

Williamson (1991) notes that there are two kinds of diagrams in IDEF0 modeling : Context diagrams and decomposition diagrams. "Context diagrams are diagrams which are thought of as being 'above the top' of the hierarchical decomposition....the latter terminology [decomposition diagrams] is our own invention for 'diagrams other than context diagrams'" (p. 30). Every IDEF0 model requires one context diagram. This is known as the A-minus-zero (A-0) diagram.

The A-0 diagram contains only one box which bounds the subject of the model. The A-0 diagram, Williamson notes, is the only diagram in an IDEF0 model having a specific requirement for textual material, indicating the purpose and viewpoint of the model.

Decomposition diagrams as noted above, are all diagrams which are not context diagrams. By definition, a decomposition diagram will contain more than one box. In order to keep the diagram simple, SADT methodology requires that each diagram has no fewer than three and no more than six boxes. Boxes on a diagram are not placed randomly. Instead, they are ordered in terms of *functional dominance*. According to Marca and McGowan (1988), "Dominance can be thought of as the influence one box has over other boxes in a diagram....the most dominant box is placed in the upper left-hand corner of the diagram, the least dominant box in the lower right-hand corner..." (p. 13). It is important to note that IDEF0 does not address time or sequence (McGuire et al., 1990), hence the ordering of the boxes in a particular way does not imply that the functions take place in that particular sequence. Boxes are also numbered according to their dominance, a larger digit implying greater functional dominance. The solitary box on the A-0 context diagram is numbered A0 (digits are preceded by the letter 'A' to indicate 'activity').

5.6.4 Diagram Identification

A decomposition diagram is formed by the division of a subject as defined by a box, into its structured pieces. The box which has been decomposed is called the *parent box* and its containing diagram is called the *parent diagram.* Likewise, the diagram formed by its decomposition is called the *child diagram.*

Models are typically assigned a unique name, usually in abbreviated form. For the purpose of individual identification, decomposition diagrams are numbered as well as titled. The name of the parent box becomes the title of the child diagram. The number of the parent diagram (also known as 'node number'), along with the number of the parent box, form the basis of identification of diagrams in IDEF0.

The node number for the context diagram, as already noted, is A-0. Node numbers are usually preceded by the model name and a slash. Thus for a model whose name was 'CRM', the context diagram would have 'CRM/A-0' as its node number. The node number for the diagram that decomposes the context diagram is the same node number without the hyphen. Using the same example, the node number of the diagram that decomposes the context diagram would be CRM/A0. All other node numbers are formed by taking the node number of the parent diagram and appending it to the number (as determined by functional dominance) of the box that is being decomposed.

5.6.5 More on Boxes and Arrows

Williamson (1991) notes that there are no specific syntax rules for diagram boxes specified in what he refers to (and so shall I) as the *IDEF0 Users Manual* (Air Force Wright Aeronautical Laboratories, 1981). The two rules or guidelines for drawing IDEF0 boxes have already been noted above, however, for the sake of being explicit, they are enumerated as: 1) The three-to-six box rule which suggests that any IDEF0 decomposition diagram contain no less than three and no more than six boxes, 2) Boxes are laid out in a diagonal from top-left to bottom-right, to denote functional dominance as well as to reduce clutter.

As noted previously, arrows represent things or collection of things. It thus follows that an arrow can be formed by a combination of two or more arrows (known as bundling or joining) and it can also be decomposed into its constituent components (known as branching or splitting). Marca and McGowan (1988) write, "Arrow branches and joins are the syntax that allows one to describe the decomposition of arrow contents" (p. 31).

Marca and McGowan (1988) outline the rules for the labeling of bundled and branched arrows. These rules are intuitive and easy to follow. As a common rule for both, an arrow is always labeled before a branch and after a join. Labels on the arrow branches (after a split) make explicit the contents of the branches. An unlabeled branch is assumed to contain all the things indicated by the label before the branch. Similarly, labels on each branch (before a join) make explicit the contents of these individual branches. If a branch is not labeled, it is "...assumed to contain all the things contained by the aggregate label after the join..." (p. 17).

Arrows can also be tunneled (i.e., have a hidden source or a destination). Tunneled arrows that appear from an unknown or hidden source have their tails parenthesized. This indicates that they have a source either from some other part of the model or from outside the model directly. Similarly, as Marca and McGowan (1988) write, "tunneled arrows that go to an unknown destination have their heads parenthesized, indicating that they go to some other part of the model or to outside the model directly, or are not further treated in the model" (p. 34).

It was previously noted that input arrows represent things that are transformed by the function. Control arrows on the other hand constrain or limit the activities that perform this function. According to Marca and McGowan (1988), they contain "...the rules and the facts that constrain the operation of a function" (p.36). As they further note, "by emphasizing the difference between inputs and controls, SADT gives an analyst the capability to describe explicitly the constraints imposed on transformation functions" (p. 34). The emphasis on distinguishing between inputs and controls is one of the strong points of IDEF0. Another characteristic feature of SADT is the importance it places on mechanism arrows. Initially, the system is described from a functional viewpoint hence the specification of mechanism arrows is not mandated, "...but ultimately it [the system] must be realized (i.e., it must be made operational)..." which is where mechanism arrows play an important role in giving "...an analyst the ability to precisely define how a particular function will operate,..." (p. 35). Besides these broad guidelines, there are no formal rules to distinguish between inputs, controls and mechanisms or specify the utilization of mechanisms. As a result, distinctions between inputs, controls and mechanisms remain fuzzy and tend to depend strongly on the analyst's point of view. Williamson (1991) in attempting to arrive at substantive quality metrics for IDEF0 notes several such shortcomings and offers valuable insights into possible refinement of IDEF0. A few relevant ones are discussed in the subsequent paragraphs.

As an example, SADT requires every box to have at least one control arrow, and at least one output arrow. It does not however mandate inputs. In fact, as Williamson (1991) notes, the *IDEF0 Users Manual* states, "If it is uncertain whether an arrow is a control or an input, make it a control" (p. 26). In such cases, since the function is producing an output, it is obviously transforming something, which implies the transformation of either a control or a mechanism. As Williamson further notes, "It is quite common for a control to be manipulated to produce an output....this causes almost everything to be characterized as a control..." (p. 32).

Further, in talking about box semantics and the difficulty in distinguishing between controls and mechanisms, Williamson (1991) ponders, "A control is a constraint which is not transformed by the activity. So is a mechanism! Is the distinction merely intuitive?" (p. 32). Also, even though it is clear that an activity cannot be performed without a mechanism, IDEF0 does not require a mechanism arrow on every box. In summary, as Williamson notes, "IDEF0 provides structure without restraint" (p. 62).

Despite its lack of formalization of certain issues, IDEF0 offers a powerful, structured analysis methodology which finds applicability in a variety of domains. As Williamson (1991) notes, "we believe this structure without restraint characteristic is the primary reason for IDEF0 popularity" (p. 62).

5.7 A Model of Crew Performance: Description

The preceding sections discussed the SADT methodology. In the following sections, the application of the SADT methodology to the domain of crew performance is discussed. The format essentially consists of a detailed node-by-node description of the model developed. The model is named CRM because of the crew coordination focus adopted.

The model was developed using the Automated Business Logic Engineering Process Modeler or ABLEpm software developed by Triune Software, Inc. (1993), hereafter referred to as Triune. ABLEpm runs on an IBM compatible computer in a Microsoft Windows environment. ABLEpm is a tool for developing IDEF0 models. It provides easy to use graphic capabilities for the drawing of models along with several strong features that facilitate the modeling process. For example, changes made to a higher level data item are "rippled" or automatically propagated to lower levels. ABLEpm also has a *glossary* feature which provides easy access to the meanings or definitions of activities and data elements on any particular diagram.

The primary reading rule for SADT diagrams, according to Marca and McGowan (1988) is, "...read the diagram first, and only then read the matching SA [Structured Analysis] text for that diagram" (p. xiii). The matching text corresponds to ABLEpm's glossary feature mentioned above. The glossary provides a comprehensive listing of the definitions or meanings of every data item (arrows) in the model. The complete model is shown in Appendix II.

A node-by-node description of the model follows. The description is mainly in narrative form, describing the system in a top-down fashion (i.e., starting at the highest level diagram and proceeding with lower level of decomposition). The model relies mainly on the theory described in Chapter 4, and should be self-explanatory. Even so, examples to illustrate the modeling logic are included where necessary. Redundancies in explanations are omitted, as in when the same control appears on lower levels.

5.7.1 CRM/A-0

Node CRM/A-0 (Figure 2) represents the context diagram which bounds the system by a solitary box having a single subject. The activity bounds the subject of accomplishing the commercial transport mission and is numbered as A0. The title of the diagram is Accomplish Commercial Transport Mission.

The general purpose of the commercial transport mission is to transport a payload of either passengers or cargo, from one destination to another. This is accomplished by two to three pilots who are assisted in doing this by a modern commercial airplane (Billings, 1991).

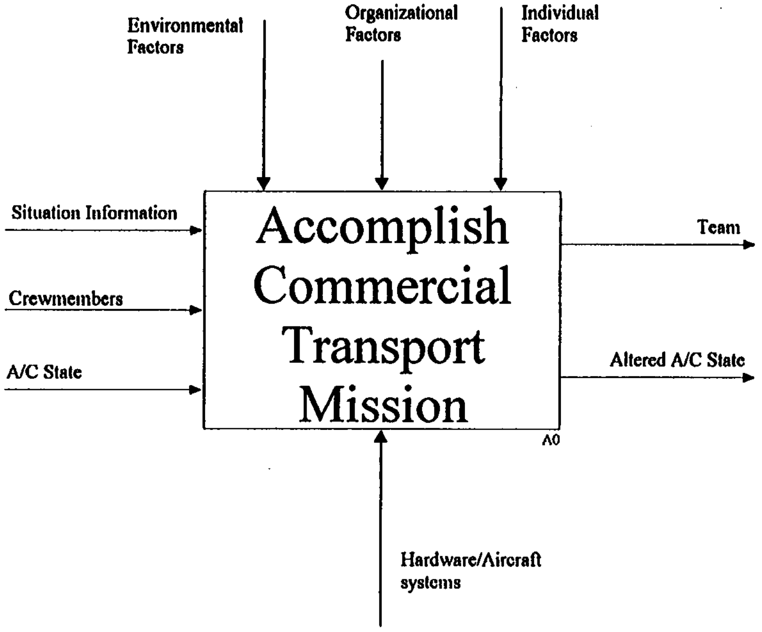
The function Accomplish Commercial Transport Mission transforms the inputs Situation Information, Crewmembers, and Aircraft (A/C) State into the outputs Team, and Altered A/C State subject to the constraints Environmental Factors, Organizational Factors, and Individual Factors with the help of the mechanism Hardware/Aircraft Systems.

The purpose of the model is to describe crew performance with an emphasis on crew coordination or CRM related activities. It is intended to be a normative description of the activities that an airline crew engages in during the process of accomplishing a commercial transport mission. By describing the activities, the model will answer questions pertaining to what limits or constrains the execution of activities and thus provide a framework for better understanding crew performance.

Aviation researchers constitute a mix of professionals from a variety of disciplines like Psychology, Sociology, and Human Factors Engineering whose primary focus is Aviation. The viewpoint adopted is that of an aviation human factors researcher.

The controls to the function are (a) Environmental Factors, (b) Organizational Factors, and (c) Individual Factors.

Environmental Factors include temperature, humidity, pressure, wind direction and velocity, visibility, runway conditions, and other meteorological conditions liable to affect or constrain the accomplishment of the overall mission.


Environmental Factors
Organizational Factors
Individual Factors
Situation Information
Crewmembers
A/C State
Accomplish Commercial Transport Mission
A0
Team
Altered A/C State
Hardware/Aircraft systems

Purpose:	To describe crew performance with an emphasis on crew coordination or CRM related activities
Viewpoint:	Aviation human factors researcher

Figure 2. CRM/A-0 Accomplish Commercial Transport Mission

Organizational Factors refer to all factors related to the organization that can affect crew performance such as company policies, rules and regulations, and special requirements. These are also considered to include the designated flight plan for a particular mission, local operating procedures, federal aviation regulations (FAR's), and advisory circulars.

Individual Factors refer to those characteristics of the individual crewmembers that potentially constrain the function. These include individual knowledge, skills, attitudes, fatigue, and personality (see section on Individual Factors, Chapter 4).

Hardware/Aircraft systems aid the accomplishment of the commercial transport mission and are hence mechanisms to the crew system.

Inputs to the function are (a) Situation Information, (b) Crewmembers, and (c) A/C State. Outputs from the function are (a) Team, and (b) Altered A/C state.

Situation Information refers to all information about the situation that is potentially available for the accomplishment of the mission. Situation Information includes information about the environment, information about the aircraft, and information about crewmembers. It also includes information made available through and/or about the environment of the crew system under consideration (refer to section on System Concepts), such as ATC/maintenance/gate personnel communications, cabin crewmembers and passengers.

Crewmembers refers to cockpit crewmembers. The number of crewmembers typically ranges from two to three (Captain, First Officer (F/O), and Second Officer (S/O)), depending on the type of aircraft. For example, older aircraft such as the Boeing 727 have three crewmembers while the newer Boeing 747-400's have only two crewmembers.

Aircraft State refers to the current actual state of the aircraft. 'State' is a systems concept. According to Wymore (1976), "A description of what is going on inside the box [the system under consideration] is called the state of the system" (p. 17). If the aircraft were viewed as a system, then its state would be a description of changes in the aircraft and its subsystems. In this case, the system under consideration is not the aircraft itself but the crew system, to which aircraft state is an input.

Funk (1991) defines state as "...the set of system attributes at a given time" (p. 272). Examples of Aircraft State include aircraft position, altitude, airspeed, fuel level, and position of flaps. Accomplishing the commercial transport mission results in transforming the values of these parameters, or results in the output Altered Aircraft State.

The process of accomplishing the mission transforms the crewmembers into a Team, which is shown as an output. Team and Altered Aircraft State are better understood when lower levels of decomposition are described.

5.7.2 CRM/A0

Node CRM/A0 (Figure 3) shows the decomposition of the parent box A0 and is titled Accomplish Commercial Transport Mission.

Accomplish Commercial Transport Mission (A0) is decomposed into three functions (a) Maintain Individual Situation Awareness, (b) Build and Maintain Team, and (c) Accomplish Technical Tasks. The functions are numbered A1, A2, and A3 respectively and denote order of functional dominance. The functions are described below.

(a) Maintain Individual Situation Awareness (A1)

This function transforms the input Situation Information into the output Individual Situation Models subject to the constraints Individual Factors, Organizational Factors, and Environmental Factors with the help of the mechanism Hardware/Aircraft Systems.

Situation Information was discussed at the A-0 level above. Situation Awareness was elaborated upon in Chapter 4. Crew performance depends vitally on this activity and Maintain Individual Situation Awareness is therefore depicted as being the most functionally dominant activity. Endsley's (1988) previously discussed definition of situation awareness clearly alludes to perception, which in turn is affected by several individual characteristics, such as "...information that is unconscious in the first place until it becomes activated by incoming data patterns..." (Sarter & Woods, 1991, p. 55). It depends on individual factors such as personal biases of perception and decision making, on the individual's pre-existing knowledge, and even on attitudes. In addition to the individual cognitive and interpersonal components, physiological components such as fatigue also (negatively) affect the function of maintaining individual situation awareness. Therefore, Individual Factors are a control to maintaining situation awareness.

Organizational Factors also constrain this function. The primary purpose of information automation is to assist the pilot in maintaining situation awareness (Billings, 1991), but there has been considerable concern generated in the aviation community that thereliance on automation and the very use of it, particularly under high workload conditions which tend to further increase pilot workload (a term referred to as "clumsy automation" by Wiener, 1988, 1989) can adversely affect the function of maintaining situation awareness (Sarter & Woods, 1991). For instance, empirical studies by Sarter and Woods (1992) conducted to obtain data about the Flight Management System (FMS), a core system of cockpit automation, have shown that pilots can lose situation awareness concerning FMS status and behavior.

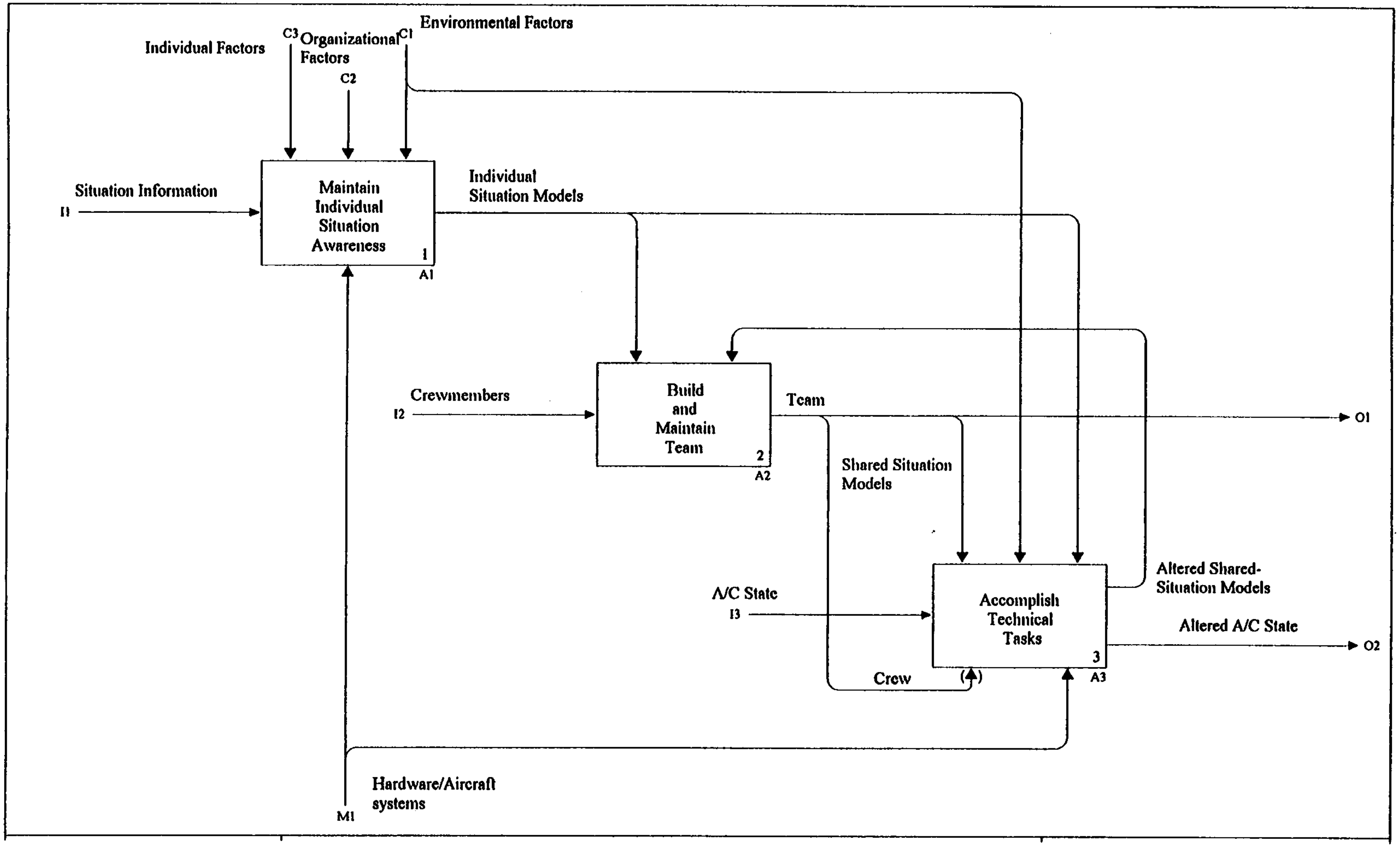

Individual Factors
C3
Organizational Factors
C2
C1
Environmental Factors
Situation Information
I1
Maintain Individual Situation Awareness
1
A1
Individual Situation Models
Crewmembers
I2
Build and Maintain Team
2
A2
Team
O1
Shared Situation Models
A/C State
I3
Accomplish Technical Tasks
3
A3
Altered Shared-Situation Models
Altered A/C State
O2
Crew
Hardware/Aircraft systems
M1

Figure 3. CRM/A0 Accomplish Commercial Transport Mission

The problem of situation awareness and pilot-automation interaction is only exacerbated when airlines have policies that insist on the pilot's usage of automation features, particularly during situations when it would be far more beneficial for pilots to resort to "lower-levels" of control automation (Wiener, 1985; Billings, 1991). As Wiener (1985) notes, such company policies are aptly captured by what crews call "we bought it, you use it" (p. 92).

Any combination of environmental factors (such as reduced visibility and abnormal meteorological conditions) are adequate to influence the maintenance of individual situation awareness. Environmental Factors are thus shown as a constraint to this function.

Individual Situation Models is the output of this function. It acts as a control to Build and Maintain Team and to Accomplish Technical Tasks. It is important to understand what is meant by Individual Situation Models. In simple terms, these refer to mental models of the situation. 'Mental models' as well as 'situation' have both been discussed in detail in preceding sections.

Modern aircraft are equipped with a host of automated features. As earlier mentioned, a primary goal of automation is to assist the pilot in doing whatever he/she is supposed to be doing. Automation, in plain terms, is supposed to make the life of a pilot easier. Displays and controls in the cockpit provide the pilot with a host of information, potentially aimed at helping the pilot maintain situation awareness (the fact that advanced automation may instead be negatively contributing to the phenomenon is what is referred to (Billings, 1991) as the 'automation paradox'). Nevertheless, the aircraft hardware and its subsystems assist the pilot in maintaining situation awareness. Hardware/Aircraft systems are thus shown as mechanisms to the function.

The process of maintaining individual situation awareness is, by nature, iterative. Maintaining situation awareness in a task-performing dynamic environment such as flying an aircraft invariably leads to changes in the person's environment, which result in a change in the situation and consequently lead to an update of the individual's mental models. This concept is better understood by a decomposition of the function at lower levels (see below).

(b) Build and Maintain Team (A2)

This function transforms Crewmembers into Team subject to Individual Situation Models and Altered Shared Situation Models.

'Crewmembers' has been defined at the A-0 level. Individual Situation Models are a constraint to this function and have been discussed while considering the function Maintain Individual Situation Awareness above.

Shared Situation Models are formed through specialized communication (Orasanu, 1990). Like individual mental models, they are updated or altered as a result of interactions between crewmembers which involve further sharing or communication of information. The difference is that the updating of individual situation models is an unconscious process, whereas shared situation models are formed as a result of explicit sharing of information or patterns of communication. Accomplishing the technical task may result in changes in task priorities and team assignments depending on the current situation. These changes are shared or explicitly communicated as part of the Accomplish Technical Task function described below. This communication alters the (existing) Shared Situation Models, resulting in an Altered Shared Situation Models which consequently act as a control to Build and Maintain Team.

Team is the output of this function. It is defined by this function as: A crew with a shared task model, a shared team-interaction model, and a shared team-personal model. These have been discussed in the section on Team Building and Shared Mental Models - Chapter 4). The team's shared situation models affect the accomplishment of technical tasks and are shown as a control to Accomplish Technical Tasks'.

(c) Accomplish Technical Tasks (A3)

This function transforms A/C State into Altered A/C State and Altered Shared Situation Models subject to Shared Situation Models, Environmental Factors, and Individual Situation Models with the help of the mechanisms Crew and Hardware/Aircraft Systems.

Shared Situation Models, Individual Situation Models, and Environmental Factors have been discussed in preceding paragraphs. A/C State, Altered A/C State, and Altered Shared Situation Models have also been discussed.

The Crew is shown as a branch of Team and is tunneled at its destination on entering Accomplish Technical Tasks. Crew represents the members of the group working together as a team. It is shown as a tunneled mechanism merely to highlight the significance of the fact that ultimately it is the Crew that performs the function of Accomplish Technical Tasks. Since it is tunneled, it will not appear on lower levels of decomposition.

Hardware/Aircraft Systems are the means by which Aircraft State is altered. It is thus depicted as a mechanism to this function.

The A0 is essentially the first layer or level of decomposition. Subsequent levels of decomposition are formed by decomposing each of the three functions on the A0. These decompositions are described in the following sections.

5.7.3 CRM/A1

Node CRM/A1 (Figure 4) shows the decomposition of parent box A1 and is titled Maintain Individual Situation Awareness.

Maintain Individual Situation Awareness (A1) is decomposed into three functions (a) Assess Situation, (b) Acquire Information and (c) Update Situation Models. The former two functions are numbered A11 and A12 respectively. According to the IDEF0 methodology, Update Situation Models would have been numbered A13. However, since Update Situation Models is not decomposed any further, ABLEpm does not number it on the diagram. The layout of the functions and their numbering denote functional dominance. These functions are described as follows:

(a) Assess Situation (A11)

This function transforms Acquired Situation Information into Situation Assessment, subject to Individual Situation Models.

In the section on Situation Awareness in Chapter 4, it was noted that situation assessments play an important role in maintaining individual situation awareness. Sarter and Woods (1991) noted that "situation awareness is based on the integration of knowledge resulting from recurrent situation assessments" (p. 50). Assess Situation which generates the output Situation Assessment is thus ranked highest in functional dominance and is placed at the node's top-left corner. The control to this function is Individual Situation Models generated as an output of Update Situation Models.

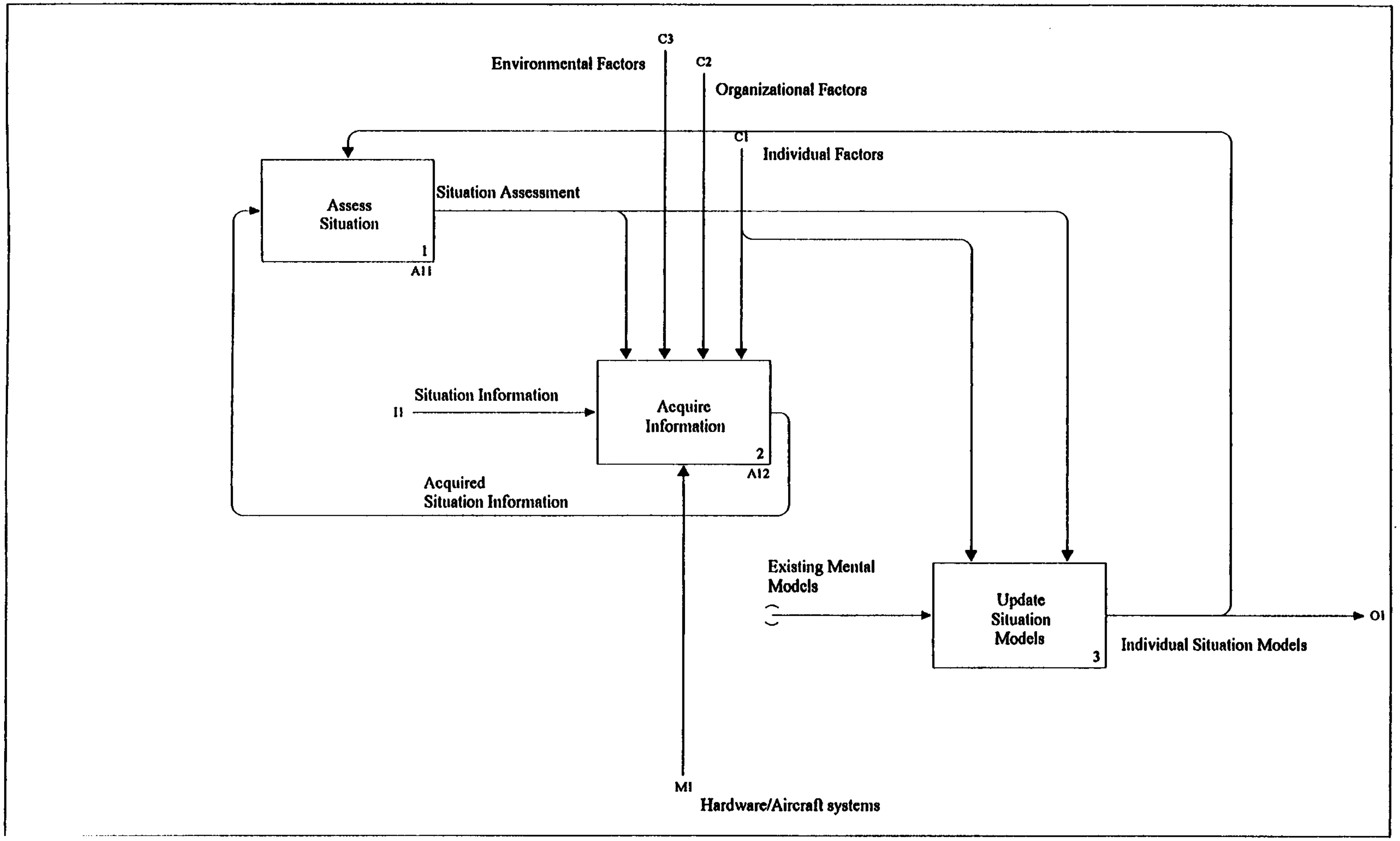

C3
Environmental Factors
C2
Organizational Factors
C1
Individual Factors
Assess
Situation
1
A11
Situation Assessment
Situation Information
I1
Acquire
Information
2
A12
Acquired
Situation Information
Existing Mental
Models
Update
Situation
Models
3
O1
Individual Situation Models
M1
Hardware/Aircraft systems

Figure 4. CRM/A1 Maintain Individual Situation Awareness

In the preceding section on Mental Models and Situation Awareness (Chapter 4), Sarter and Woods (1991) were cited to have stated that, "...adequate mental models are one of the prerequisites for achieving situation awareness" (p. 49). The discussion concluded that mental models in turn were the basis for accurate situation assessments, which in turn resulted in situation awareness. Thus, Individual Situation Models are depicted as a control to Assess Situation.

Situation Information refers to all information about the situation that is *potentially* available for the accomplishment of the mission. However, not all information that is potentially available becomes *actually* available to the pilot. Smith and Hancock's (1993) definition of situation awareness as being adaptive, externally directed consciousness that is within the scope of intentional manipulation directly alludes to the point being made that the process of maintaining situation awareness, by definition, focuses on potentially available information, thereby making the agent "aware" of the information. Only when the agent becomes "aware" of the information does potentially available information become actually available to him/her. This actually available information is depicted by the data element labeled Acquired Situation Information, which is an input to Assess Situation.

(b) Acquire information (A12)

This function transforms the Situation Information into Acquired Situation Information subject to Situation Assessment, Environmental Factors, Organizational Factors, and Individual Factors with the mechanism Hardware/Aircraft Systems.

Situation Information and Acquired Situation Information, inputs and outputs of this function, respectively, have both been discussed above.

An aspect of assessing the situation involves determining the need for additional information. Thus, depending on the assessment of the situation, the agent (pilot) may actively direct his consciousness (attention) to acquiring information from the situation. Situation Assessment is thus a control to Acquire Information.

Individual Factors also have a constraining effect on this function. As Sarter and Woods (1991) write, "On the one hand, the resulting expectancies [a result of situation assessments] may facilitate perception...On the other hand, they involve the potential for ignoring or misinterpreting the unexpected" (p. 51). Thus, individual factors such as one's pre-existing knowledge (schemata) are liable to induce biases which constrain the execution of this function. Individual Factors is therefore shown as a control to Acquire Information.

The process of acquiring information is also constrained by Environmental and Organizational Factors. Poor visibility, or abnormal meteorological conditions may restrict the pilot's ability to acquire information from the environment (outside the aircraft) while turbulence may constrain the ability to acquire information from displays (inside the aircraft). Organizational Factors like certain company policies which require strict channels of communication between crewmembers may also constrain this function. Company policies dictating the use of certain levels of automation during certain phases of flight also serve to constrain the acquisition of information. Another example is company policies that do not allow for pilots to access maintenance records, thus constraining the function. Environmental Factors and Organizational Factors are therefore depicted as controls to Acquire Information.

An important role of automation in the cockpit is to provide the pilots with a lot of information about the environment, the aircraft, and the automation itself. Billings (1991) refers to such automation as information automation. The pilot acquires information with the help of the aircraft and its display and control subsystems. These systems do not change or are not transformed in any way. Hardware/Aircraft Systems is thus shown as a mechanism to Acquire Information.

(c) Update Situation Models (A13)

This function transforms the tunneled input Existing Situation Models into Individual Situation Models subject to Situation Assessment and Individual Factors.

The process of updating a situation model (mental model of a situation) is an unconscious one, which is interpreted as being the internally-directed facet of situation awareness as against Smith and Hancock's (1993) view of situation awareness being externally directed and intentionally-manipulable. The concept of mental models as well as that of the situation have both been dealt with in great detail in their respective sections in Chapter 4.

Essentially, a mental model of a situation is one that is continuously being updated through the individual's interaction with his/her environment. The updating is an iterative process, one which the agent adapts to unconsciously. Accurate mental models are the basis for accurate situation assessments (Sarter & Woods, 1991) which in turn are updated as a result of the situation assessment. However, the situation assessment also serves to constrain the updating of the mental models, similar to how Situation Assessment acts as a control to Acquire Information. Situation Assessment is thus shown as a control to Update Situation Models. This represents the idea captured in the earlier section on Mental models and Situation Awareness in Chapter 4, in which Wickens (1988) states that a situationally aware pilot could also be described as possessing an accurate mental model of the situation, which must be continuously updated in order to maintain situation awareness in a dynamically changing environment.

Individual Factors include the individual's pre-existing knowledge. This pre-existing knowledge influences how an individual's situation model is updated. Individual Factors should thus be a control to Update Situation Models. As noted previously, mental models are a form of knowledge representation, which would imply that they are a part of Individual Factors. By definition, it is the mental model itself which is being transformed by the function Update Situation Models. Since a function transforms an input into an output, mental models would thus have to be an input to Update Situation Models. This would imply that Individual Factors are a control as well as an input to Update Situation Models! To resolve this dilemma, the IDEF0 methodology would dictate that Individual Factors be shown as a control (see 'More on Boxes and Arrows' above). However, in order to be explicit, Existing Mental Models are shown as an input to the function. Since Existing Mental Models appear out of context, they are shown as a tunneled input.

Node CRM/A11 (Figure 5) shows the decomposition of the Assess Situation (A1) function and is titled Assess Situation.

Assess Situation (A11) is decomposed into three functions (a) Perceive Current Situation, (b) Integrate/Comprehend Situation, and (c) Project Situation. According to the IDEF0 methodology, these functions would be numbered as A111, A112, and A113. However, since they are not decomposed any further in the analysis, they are simply numbered as 1, 2, and 3 respectively. These functions are described below.

Assessing the situation or situation assessment, according to Endsley (1988) involves perception of the situational elements, information integration, and the projection of future status and actions of situational elements (see section on Situation Assessments and Situation Awareness' - Chapter 4).

(a) Perceive Current Situation

This function transforms Acquired Situation Information into Perceived Information subject to Individual Situation Models.

Acquired Situation Information is perceived by the individual and results in Perceived Information. Previously, potentially available information was distinguished from actually available information. This actually available information is first perceived by the individual as part of the process of assessing the situation.

Individual Situation Models include biases of perception and are thus shown as a control to Perceive Current Situation.

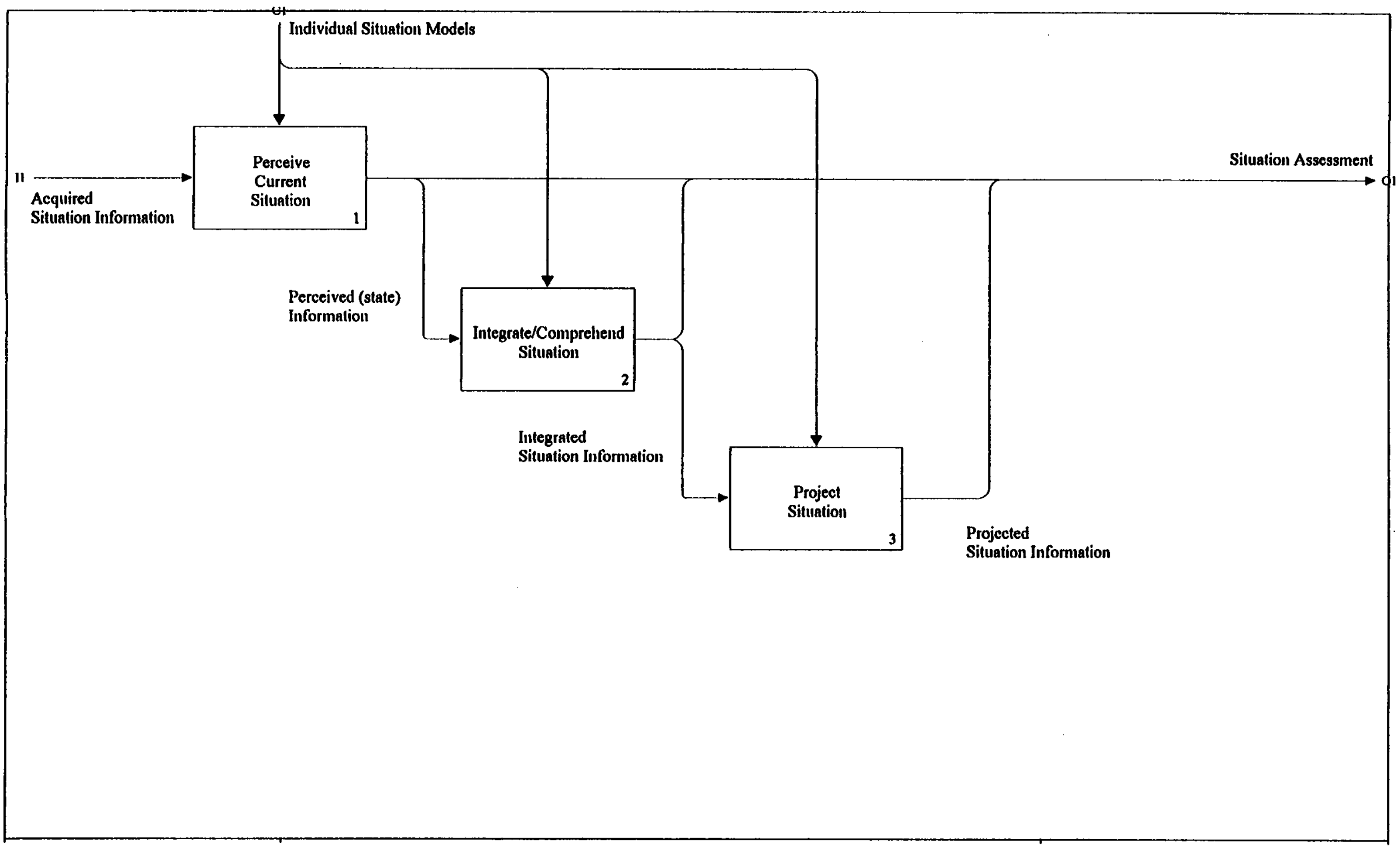

Individual Situation Models
I1
Acquired
Situation Information
Perceive
Current
Situation
1
Situation Assessment
O1
Perceived (state)
Information
Integrate/Comprehend
Situation
2
Integrated
Situation Information
Project
Situation
3
Projected
Situation Information

Figure 5. CRM/A11 Assess Situation

(b) Integrate/Comprehend Situation

This function transforms Perceived Information into Integrated Situation Information subject to Individual Situation Models.

Integrated Situation Information represents the current understanding of the situation. After information is perceived, it is integrated with pre-existing information and the individual actually makes sense of the information or comprehends it.

Once again, the process of integration/comprehension is limited by the person's skills included in Individual Situation Models. Rasmussen (1990) notes that "...skill-based behavior represents sensory-motor performance....depends upon a very flexible and efficient dynamic internal world model." (p. 63). Individual Situation Models is therefore a control to the function Integrate/Comprehend Situation.

(c) Project Situation

This function involves transforming Integrated Situation Information into Projected Situation Information constrained by Individual Situation Models.

Once information is integrated and comprehended, future status is projected, which forms the basis for comparing current state with expected state and deciding on further action. Some of these actions may be involuntary, may involve the action of acquiring further information or may require active planning and decision making. Since they are actions taken by the agent, they are considered under the function Accomplish Technical Tasks discussed in subsequent sections.

A primary purpose of the mental model is to simulate future situations (known as "running" the mental model). Individual Situation Models are therefore a control to Project Situation.

Node CRM/A12 (Figure 6) shows the decomposition of Acquire Information (A12) and is titled "Acquire Information".

Acquire Information (A12) is decomposed into three functions (a) Acquire Information from Environment, (b) Acquire Information from Aircraft, and (c) Acquire Information from Crewmembers. According to the IDEF0 methodology, these functions would be numbered as A121, A122, and A123 respectively. However, since they are not decomposed any further in the analysis, they are simply numbered as 1, 2, and 3 respectively. These functions are described below.

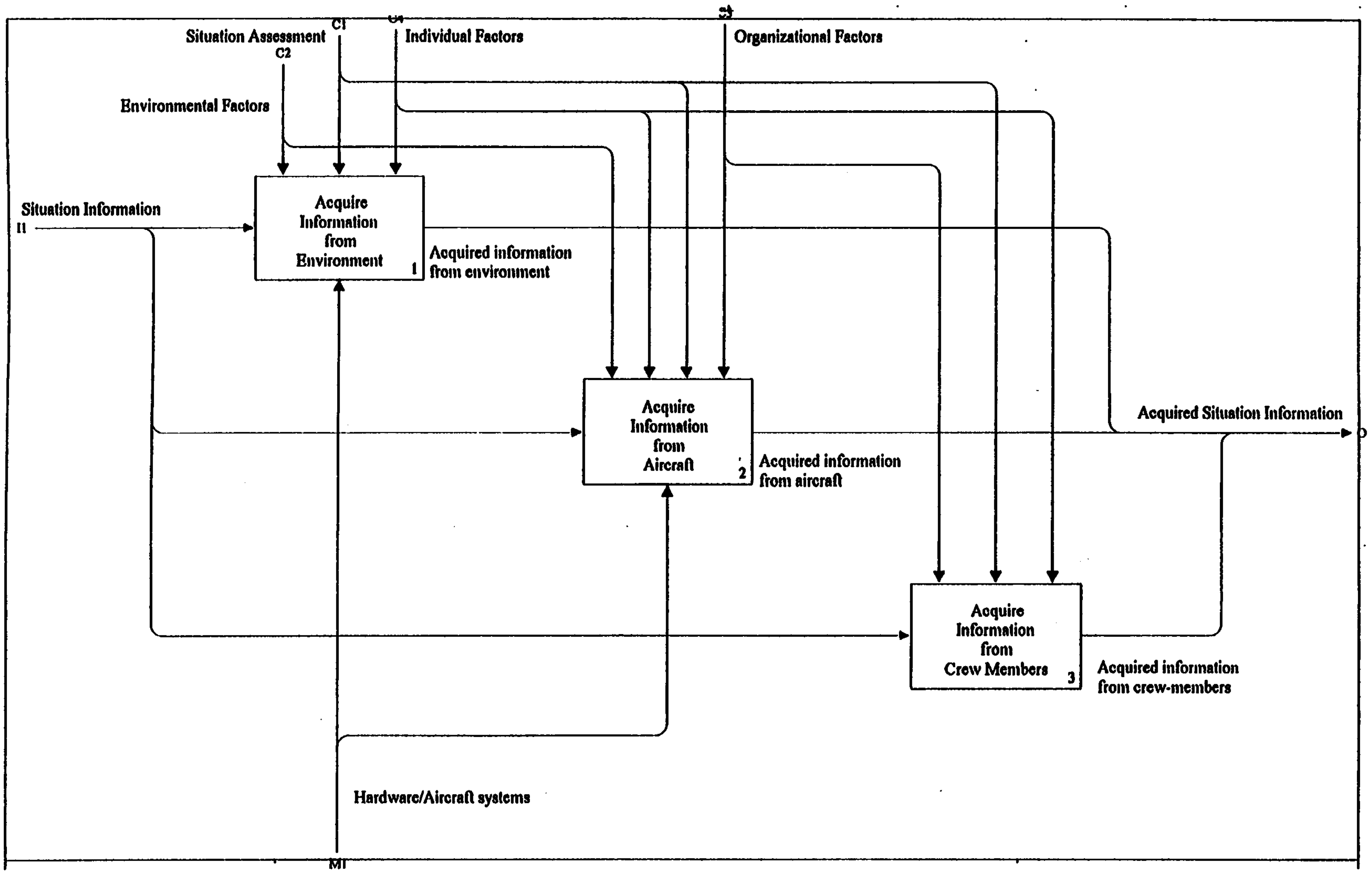

Situation Assessment
C1
C2
Individual Factors
Organizational Factors
Environmental Factors
Situation Information
I1
Acquire Information from Environment
1
Acquired information from environment
Acquire Information from Aircraft
2
Acquired information from aircraft
Acquired Situation Information
O
Acquire Information from Crew Members
3
Acquired information from crew-members
Hardware/Aircraft systems
M1

Figure 6. CRM/A12 Acquire Information

(a) Acquire Information from Environment.

This function transforms Situation Information into Acquired Information from Environment subject to Situation Assessment, Individual Factors, and Environmental Factors with the mechanism Hardware/Aircraft Systems.

Situation Information is the input to this function. Specifically, this refers to all information about the situation potentially available directly from the environment.

Situation Assessment and Individual Factors, controls to this function, have already been discussed while discussing node CRM/A1.

In this case, environment refers to the system environment as distinct from an individual's environment. Based on the situation assessment, information is (actively) acquired from the environment. Information acquired is broadly of three types (a) spatial or navigational information (i.e., knowledge of the aircraft's location in space), (b) information about traffic, and (c) information about abnormal weather conditions.

Acquisition of spatial or navigational information is very important. By looking out of the window, the pilot may be able to tell whether the aircraft is at a high or low altitude, whether it is too close to the ground or in danger of crashing into mountainous terrain. There have been numerous instances when the pilot, either because of weather conditions or 'distractions', allowed the aircraft to collide with terrain. Such accidents have been termed *controlled flight into terrain* or CFIT's. According to Learmount (1993), "the term implies either that the pilot does not know the impact is coming or realizes too late to prevent it" (p. 27). Learmount (1994, p.42) further notes that CFIT's have been "...revealed as the single greatest killer in air accidents..." involving 21 accidents and 706 fatalities in the year 1992 alone (Learmount, 1993).

Due to the possibility of a mid-air collision, the pilot needs to keep a constant watch for other aircraft, particularly so when in the vicinity of airports. Thus, obtaining information about traffic by keeping a vigilant watch outside the aircraft becomes an important component of the pilot's maintaining situation awareness. Abnormal meteorological conditions such as thunderstorms and windshear (changes in wind strength leading to potentially dangerous situations) can have disastrous consequences for aircraft. Although windshear alerting systems are being used in some aircraft, sometimes such situations can be avoided if the crew is alert to warning cues from the environment.

From the above, it is clear that Environmental Factors constrain Acquire Information from Environment.

The cockpit of a modern commercial airliner is designed to maximize the pilot's ability to acquire information from the environment. The cockpit is strategically located at the front of the aircraft thus providing the pilot with a vantage view of the environment. It has a plexi-glass windshield and is fitted with seats with six degrees of freedom, all designed to allow the pilot to get an all round view of the outside environment. Appropriately located lights under the wings and near the wheels enhance the pilot's ability to see during bad weather and at night. Hardware/Aircraft systems are thus a mechanism to Acquire Information from Environment.

(b) Acquire Information from Aircraft.

This function transforms Situation Information into Acquired Information from Aircraft subject to Environmental Factors, Situation Assessment, Individual Factors, and Organizational Factors with the help of the mechanism Hardware/Aircraft Systems.

A primary purpose of automation should be to assist the pilot in maintaining situation awareness. The aircraft, along with its displays and controls provides, or makes available, all kinds of information which the pilot needs to maintain awareness. Hardware/Aircraft Systems are thus the mechanism by which the crewmembers acquire information from the aircraft.

Situation Information is the input to this function. Specifically, this refers to all information about the situation potentially available from the aircraft. Situation information potentially available from the aircraft includes information about the environment and information about aircraft subsystems. Note that some information about the environment is directly acquired from the environment (as in Acquire Information from Environment discussed above) while some information about the environment may be acquired through the aircraft. In order to acquire information from the aircraft and its instruments, the pilot would need to actively monitor them. Also included in this category is information received by the crew over the radio (ATC communications) or via data link (since they are part of the aircraft's Radio-Communications system).

The environment can have an adverse effect on the aircraft and its subsystems. This may result in partial or complete failures of aircraft displays, severely limiting the ability of the crewmembers to acquire information from the aircraft. Despite the reliability of the aircraft and its automation, the aircraft remains a vulnerable piece of equipment. Lightning, thunderstorms, and other electrical activity (even the use of onboard personal computers!) have been known to affect the complex circuitry of onboard navigation displays and controls. Turbulence may limit the crewmember's ability to read displays, again limiting his/her ability to acquire information from the aircraft. Environmental Factors is thus a control to Acquire Information from Aircraft.

Situation Assessment is a control to this function and has already been discussed at the CRM/A1 level.

Physiological factors such as fatigue and vision also constrain the ability of crewmembers to acquire information from the aircraft. Individual Factors are thus a control to Acquire Information from Aircraft (also see discussion of Individual Factors to Acquire Information at CRM/A1 level).

The role of Organizational Factors as controls to Acquiring Information from Aircraft (company policies dictating the use of varying levels of automation) has been discussed at the CRM/A1 level.

c) Acquire information from crewmembers.

This function transforms Situation Information into Acquired Information from Crewmembers subject to Situation Assessment, Individual Factors, and Organizational Factors.

Valuable information regarding the situation can also be obtained from other crewmembers, simply by observing the other's actions. Wiener (1993) provides further insight into the challenges posed by advanced automated cockpits with regards to this aspect of crew coordination. He notes that in the cockpit of advanced aircraft, "...it is physically difficult for one pilot to see what the other is doing....it is more difficult for the captain to monitor the work of the first officer and to understand what he is doing, and vice-versa" (p. 209-210).

The controls to the function have all been discussed at the CRM/A1 level.

5.7.4 CRM/A2

Node CRM/A2 (Figure 7) shows the decomposition of parent box A2 and is titled "Build and Maintain Team".

The forming of shared mental models and their development is essential to team effectiveness. Build and Maintain Team (A2) is thus decomposed into three functions (a) Develop Shared Task Model, (b) Develop Shared Team-interaction Model, and (c) Develop Shared Team-personal Model.

In the section on Team Building and Maintenance (Chapter 4) Hackman and Walton (1986) were cited to define group effectiveness along three dimensions. These dimensions were referred to as the task dimension, social dimension, and the personal dimension.

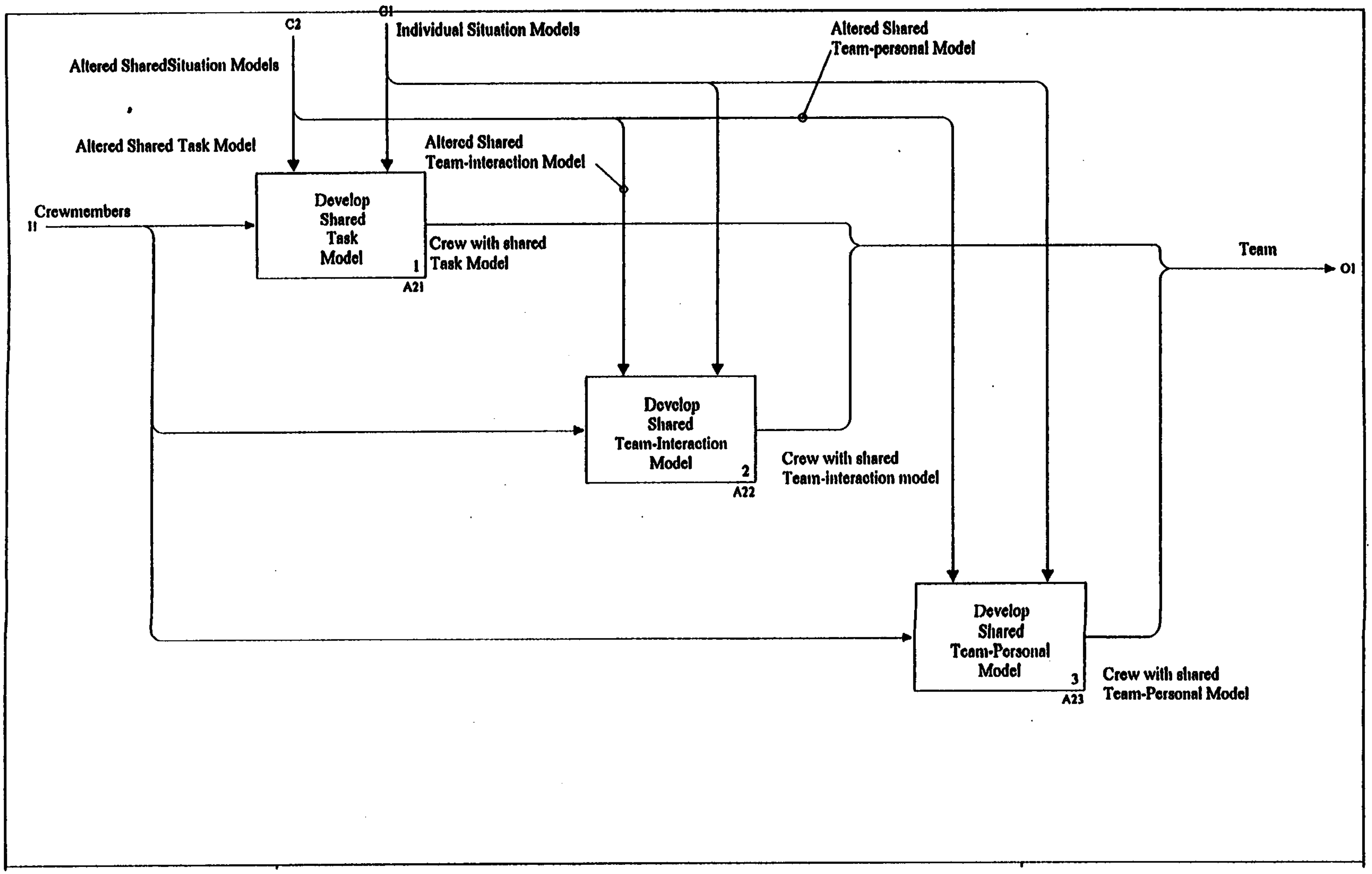

C1
C2
Individual Situation Models
Altered SharedSituation Models
Altered Shared Task Model
Altered Shared Team-personal Model
Altered Shared Team-interaction Model
Crewmembers
I1
Develop Shared Task Model
1
A21
Crew with shared Task Model
Team
O1
Develop Shared Team-Interaction Model
2
A22
Crew with shared Team-interaction model
Develop Shared Team-Personal Model
3
A23
Crew with shared Team-Personal Model

Figure 7. CRM/A2 Build and Maintain Team

Further, they noted that the relative weights that would be assigned to these dimensions would vary as a matter of circumstances, they state, "...it appears that one of the most powerful ways to help a team on the latter two dimensions [social and personal] is to foster its standing on the first" (p. 79). Interpreting this to denote functional dominance, the functions are numbered A21, A22, and A23, respectively. These functions are described below.

Individual Situation Models and Altered Shared Situation Model are the two controls that constrain these three functions. Both of these controls have been discussed at the CRM/A0 level.

(a) Develop Shared Task Model (A21).

This function transforms Crewmembers into a Crew with Shared Task Model and is constrained by Individual Situation Models and Altered Shared Task Model, a component of Altered Shared Situation Models.

It is important to note that individual crewmembers are transformed into a crew - a group which is more than just a collection of individual crewmembers (see 'Groups and Crews' - Chapter 4).

A Shared Task model would include knowledge about each other's tasks, task procedures, and task strategies. According to Cannon-Bowers et al. (1993), it creates expectations "...about how events are likely to unfold and how the team is likely to respond to task demands..." (p. 234).

The Shared Task Model of an airline crew would contain shared knowledge and understanding of tasks that need to be accomplished. Kanki and Palmer (1993) note that "communication processes are of central importance to group activities that rely on verbal exchanges" (p. 109). Development of a shared task model is a group activity. Shared mental models are a result of effective communication (see discussion on 'Team Building and Shared Mental Models').

(b) Develop Shared Team-Interaction Model (A22).

This function transforms crewmembers into a Crew with a Shared Team-interaction Model and is constrained by Individual Situation Models and the Altered Shared Team-interaction Model, a component of the Altered Shared Situation Model.

A Shared Team-interaction Model is developed through the sharing of individual team-interaction models. A Shared Team-interaction Model would include knowledge about how each team member must interact with each other. Shared Team-interaction Model implies a shared understanding and acceptance of group roles, norms and the authority gradient.

(c) Develop Shared Team-Personal Model (A23).

This function transforms Crewmembers into a Crew with a Shared Team-personal Model and is constrained by Individual Situation Models and the Altered Shared Team-personal Model, a component of the Altered Shared Situation Model.

As noted previously, the Shared Team-personal Model would include information regarding the knowledge, skills, abilities, preferences, and tendencies of particular teammates so that behavior can be tailored accordingly.

It is important to note the distinction between the Shared Team-interaction Model and the Shared Team-personal Model. The Shared Team-interaction Model includes a shared understanding of emergent group properties such as roles, norms, and authority status, while the Shared Team-personal Model provides for an understanding of each other's personal likes, dislikes, and tendencies. While the Shared Team-interaction Model is representative of group properties, the Shared Team-personal Model is representative of an understanding of characteristics of the specific individuals involved.

Node CRM/A21 (Figure 8) shows the decomposition of parent box A21 and is titled Develop Shared Task Model.

Develop Shared Task Model (A21) is decomposed into four functions (a) Assess Shared Task Model, (b) Clarify Goals, (c) Discuss Contingencies/Plans, and (d) Discuss Task Strategies. According to the IDEF0 methodology, these functions would be numbered as A211, A212, A213, and A214 respectively. However, since they are not decomposed any further in the analysis, they are simply numbered as 1, 2, 3, and 4, respectively. These functions are described below.

(a) Assess Shared Task Model

This function has no inputs but generates the output, Task Model Assessments (analogous to Situation Assessments) subject to Individual Situation Models and Altered Shared Task Model. The Altered Shared Task Model represents the "current" Shared Task Model which has been changed as a result of Accomplish Technical Tasks. It is this current model that is assessed by this function.

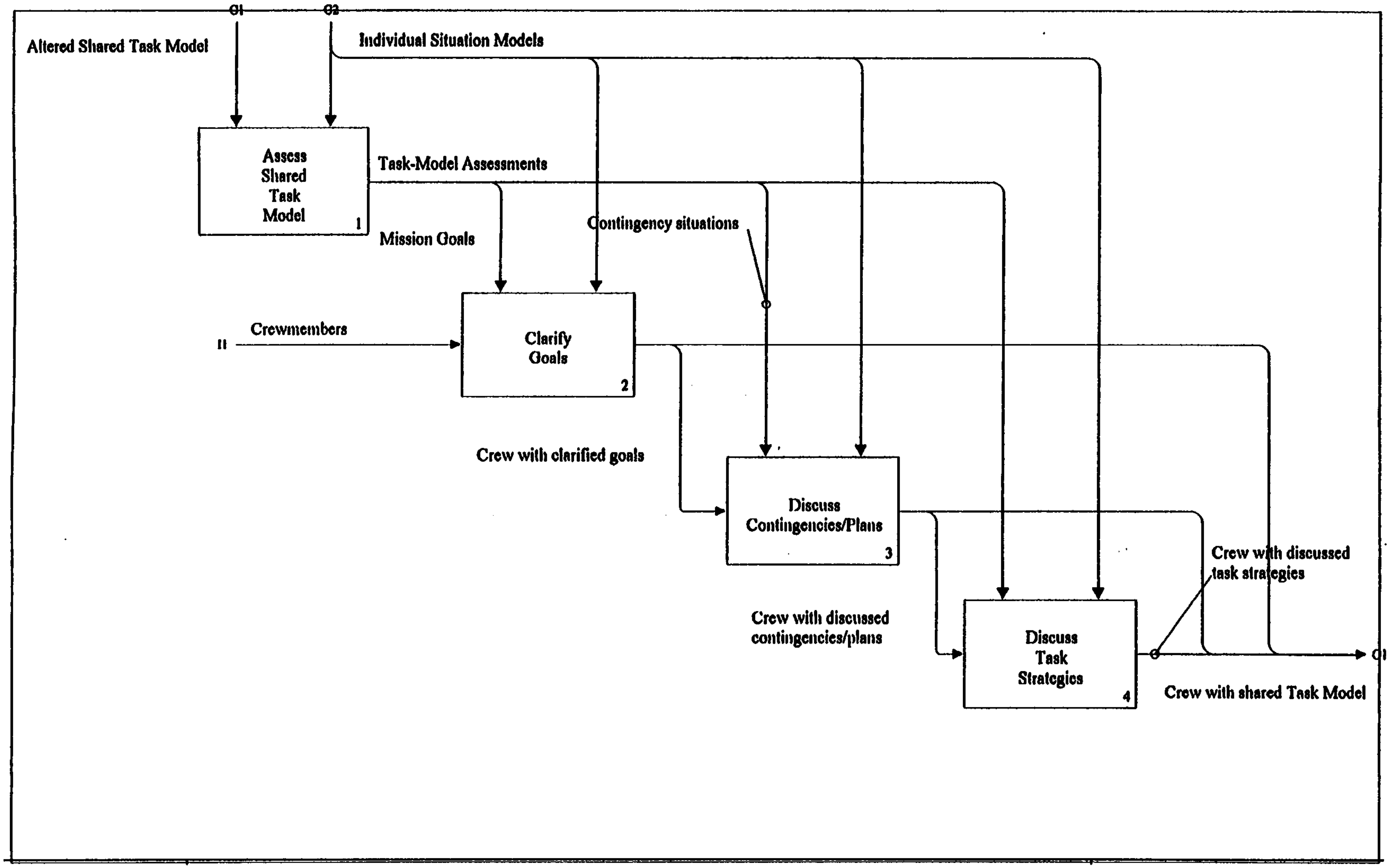

C1
C2
Altered Shared Task Model
Individual Situation Models
Assess Shared Task Model
1
Task-Model Assessments
Mission Goals
Contingency situations
I1
Crewmembers
Clarify Goals
2
Crew with clarified goals
Discuss Contingencies/Plans
3
Crew with discussed contingencies/plans
Crew with discussed task strategies
Discuss Task Strategies
4
O1
Crew with shared Task Model

Figure 8. CRM/A21 Develop Shared Task Model

Assessing the current shared mental model is a fundamental part of developing a shared mental model, just as situation assessment is fundamental to the updating of an individual mental model which leads to situation awareness.

Two factors affect the development of an adequate shared task model. Firstly, individual task models must be complete and correct. These are a result of maintaining individual situation awareness discussed previously. Further, developing a shared task model requires effective communication. Effective communication depends on factors such as individual communication skills (a part of individual mental models). Secondly, an adequate shared task model depends on an accurate assessment of the current shared task model. Thus, Individual Situation Models and Altered Shared Task Model are the two constraints to this function.

The assessment of the Shared Task Model results in Task-model Assessments which drives the development or refinement of the Shared Task Model. Typically, such development takes place through explicit and effective communication in the form of verbal exchanges. In such cases, Individual Situation Models, which include crewmembers' models of the task and equipment, play an important role. In the process of development, they are shared to varying degrees and lead to a shared task-model. In this sense, they are themselves transformed, however the IDEF0 methodology recommends that they be treated as controls instead of inputs. Thus, Individual Situation Models are shown as controls to all these three functions. Task-Model Assessments are the other control to each of these three functions

(b) Clarify Goals.

The function Clarify Goals transforms crewmembers into a Crew (group) with Clarified Goals subject to Task-Model Assessments and Individual Situation Models. Depending on the assessment of the shared task-model, the crew may see a need to clarify goals. The Crew with Clarified Goals becomes an input to the function Discuss Contingencies/Plans.

(c) Discuss Contingencies/Plans.

The function Discuss Contingencies/Plans transforms the Crew with Clarified Goals into a Crew with Discussed Contingencies/Plans subject to Task-Model Assessments and Individual Situation Models.

Only when a crew has clarified its goals can it discuss plans and contingency situations, essential for the development of a shared task-model. The output of this function, Crew with Discussed Contingencies/Plans, is an input to the function Discuss Task Strategies.

(d) Discuss Task Strategies.

The function Discuss Task Strategies transforms Crew with Discussed Contingencies/Plans into Crew with Discussed Task Strategies subject to Task-Model Assessments and Individual Situation Models. Through the discussion of contingency situations and the making of plans, task strategies are discussed.

The combination of the outputs of all the above functions leads to a Crew with Shared Task Model, the output of the function Develop Shared Task Model. Crew with Shared Task Model is thus defined as the combination of a Crew with Clarified Goals, a Crew with Discussed Contingencies/Plans and a Crew with Discussed Task Strategies.

Node CRM/A22 (Figure 9) shows the decomposition of parent box A22 and is titled Develop Shared Team-interaction Model.

Develop Shared Team-interaction Model (A22) is decomposed into four functions (a) Assess Shared Team-interaction model, (b) Expand Group Boundaries (c) Refine Group Norms, and (d) Establish Appropriate Authority Dynamic. According to the IDEF0 methodology, these functions would be numbered as A221, A222, A223, and A224 respectively. However, since they are not decomposed any further in the analysis, they are simply numbered as 1, 2, 3, and 4, respectively. These functions are described below.

(a) Assess Shared Team-interaction Model.

This function has no inputs but generates the output, Team-interaction Model Assessments (analogous to Situation Assessments) subject to Individual Situation Models and Altered Shared Team-interaction Model. The Altered Shared Team-interaction Model represents the "current" Shared Task Model which has been changed as a result of Accomplish Technical Tasks. It is this current model that is assessed by this function.

The justification for Individual Situation Models and Altered Shared Team-interaction Model as controls to this function is along the lines for the function Assess Shared Task Model discussed above.

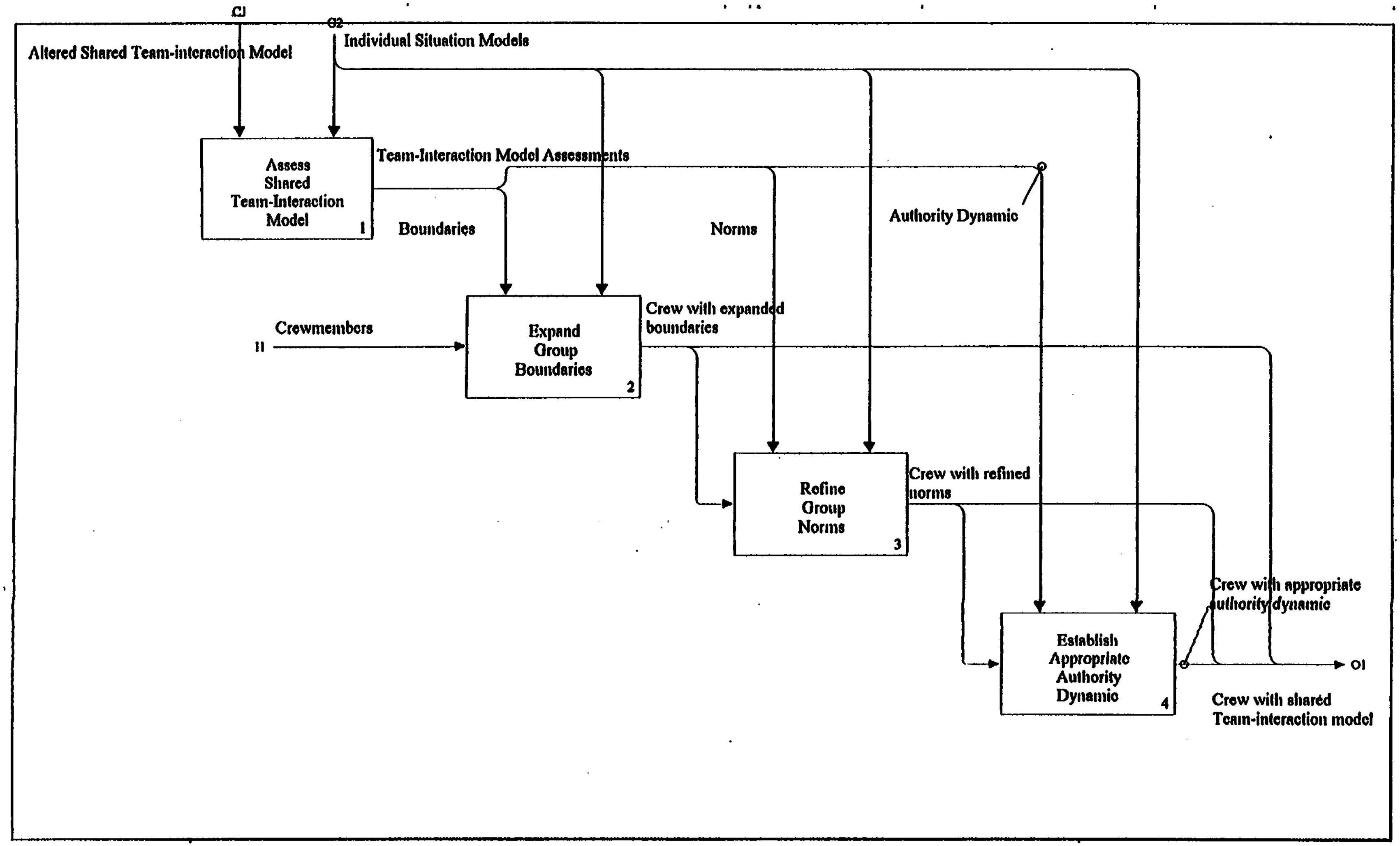

C1
C2
Altered Shared Team-interaction Model
Individual Situation Models
Assess Shared Team-Interaction Model
1
Team-Interaction Model Assessments
Boundaries
Norms
Authority Dynamic
Crewmembers
I1
Expand Group Boundaries
2
Crew with expanded boundaries
Refine Group Norms
3
Crew with refined norms
Crew with appropriate authority dynamic
Establish Appropriate Authority Dynamic
4
O1
Crew with shared Team-interaction model

Figure 9. CRM/A22 Develop Shared Team-Interaction Model

The assessment of the Shared Team-interaction Model drives its further development or refinement. Characteristic group properties such as boundaries and norms are rarely explicitly communicated. The development of the Shared Team-interaction Model thus typically takes place through implicit, non-verbal communication. In such cases, individual situation models, which include crewmembers' models of the self and of interaction play an important role. In the process of development, they are shared and lead to a shared team-interaction model. Individual Situation Models are shown as controls to all these three functions for the same reasons as explained above (see Assess Shared Task Model). Team-interaction Model Assessments are also a control to each of these three functions.

(b) Expand Group Boundaries.

The function Expand Group Boundaries transforms Crewmembers into a Crew with Expanded Boundaries (see Boundaries under Groups and Crews, Chapter 4), subject to Team-Interaction Model Assessments and Individual Situation Models. Depending on the Team-Interaction Model Assessments, the group may see a need to expand its boundaries, as was the case noticed by Ginnett (1993). The output of this function, Crew with Expanded Boundaries, becomes an input to the function Refine Group Norms.

(c) Refine Group Norms.

The function Refine Group Norms transforms the input Crew with Expanded Group Boundaries into a Crew with Refined Norms subject to Team-interaction Model Assessments and Individual Situation Models. The output of this function, Crew with Refined Norms, becomes an input to the function Establish Appropriate Authority Dynamic.

Perhaps the importance of this function is best illustrated by means of an ASRS incident report as cited by Kanki and Palmer (1993). The incident is reported by the F/O who recalls how the aircraft was off course by about 10 miles before ATC had to remind them they were drifting. According to the report, the F/O did notice the problem and tried to draw the Captain's attention to it, but each time the captain tried to reply to the F/O's query, the Captain was interrupted by the flight attendant who was in the cockpit at the time, insisting that the Captain radio ahead about connections since they were behind schedule. The exasperation of the F/O is best captured by the following remark made in the report as:

> It was no problem, just embarrassing to have Center [ATC] tell you that you are starting to go off in the wrong direction. We should have handled it by not being nice guys and telling the flight attendant in a loud voice to "shut up, we are trying to fly the plane".
> (p. 111)

In this case, had the group refined its norms, either one of the crewmembers might have assertively cut short the flight attendant and dealt with the important business of correcting their course.

(d) Establish Appropriate Authority Dynamic.

The function Establish Appropriate Authority Dynamic transforms Crew with Refined Norms into a Crew with Appropriate Authority Dynamic subject to Team-Interaction Model Assessments and Individual Situation Models.

The importance of this function is highlighted by another ASRS incident report, one which has been cited by many in the literature as an example of the negative effects of a high TAG (see Kanki and Palmer, 1993). Ginnett (1993) cites the report as follows:

> I was the first officer on an airline flight into Chicago O'Hare. The captain was flying, we were on approach to 4R [particular runway] getting radar vectors and moving along at 250 knots. On our approach, Approach Control told us to slow to 180 knots. I acknowledged and waited for the captain to slow down. He did nothing, so I figured he didn't hear the clearance. So I repeated, "Approach said slow to 180," and his reply was something to the effect of, "I'll do what I want." I told him at least twice more and received the same kind of answer. Approach Control asked us why we had not slowed down yet. I told them we were doing the best job we could and their reply was, "You almost hit another aircraft." They then asked us to turn east. I told them we would rather not because of the weather and we were given present heading and to maintain 3000 ft. The captain descended to 3000 ft. and kept going to 2500 ft. even though I told him our altitude was 3000 ft. His comment was, "You just look out the damn window". (p. 74)

The combination of the outputs of the above three functions leads to a Crew with Shared Team-interaction Model, the output of the function Develop Shared Team-interaction Model. Crew with Shared Team-interaction Model is thus defined as the combination of a Crew with Expanded Group Boundaries, a Crew with Refined Norms, and a Crew with Appropriate Authority Dynamic.

Node CRM/A23 (Figure 10) shows the decomposition of parent box A23 and is titled Develop Shared Team-personal Model.

Develop Shared Team-personal Model (A23) is decomposed into three functions (a) Assess Shared Team-personal model, (b) Share Knowledge about Selves, and (c) Express Selves. According to the IDEF0 methodology, these functions would be numbered as A231, A232, and A233, respectively. However, since they are not decomposed any further in the analysis, they are only numbered as 1, 2, and 3, respectively. These functions are described below.

(a) Assess Shared Team-personal Model.

This function has no inputs but generates the output, Team-personal Model Assessments (analogous to Situation Assessments) subject to Individual Situation Models and Altered Shared Team-personal Model. The Altered Shared Team-personal Model represents the "current" Shared Team-personal Model which has been changed as a result of Accomplish Technical Tasks. It is this current model that is assessed by this function.

The justification for Individual Situation Models and Altered Shared Team-personal Model as controls to this function is along the lines for the function Assess Shared Task Model discussed above. Development of the Shared Team-personal Model would include both verbal as well as non-verbal exchanges between crewmembers. In such cases, Individual Situation Models, which include crewmembers' models of the self and of interaction play an important role and are thus shown as controls to all three functions for the same reasons as explained above (see Assess Shared Task Model).

The assessment of the Shared Team-personal Model drives its further development or refinement. The Shared Team-personal model essentially is formed by sharing of individual models of the self. Development of the Shared Team-personal Model takes place as a result of crewmembers sharing information about themselves, their knowledge, skills, and past experiences as related to flying, as well as their likes, dislikes and tendencies. This kind of sharing would be expected during the initial briefings and during low workload phases such as cruise, but would not be expected to occur in high workload conditions. In common parlance, such sharing would be referred to as "getting to know you" conversation.

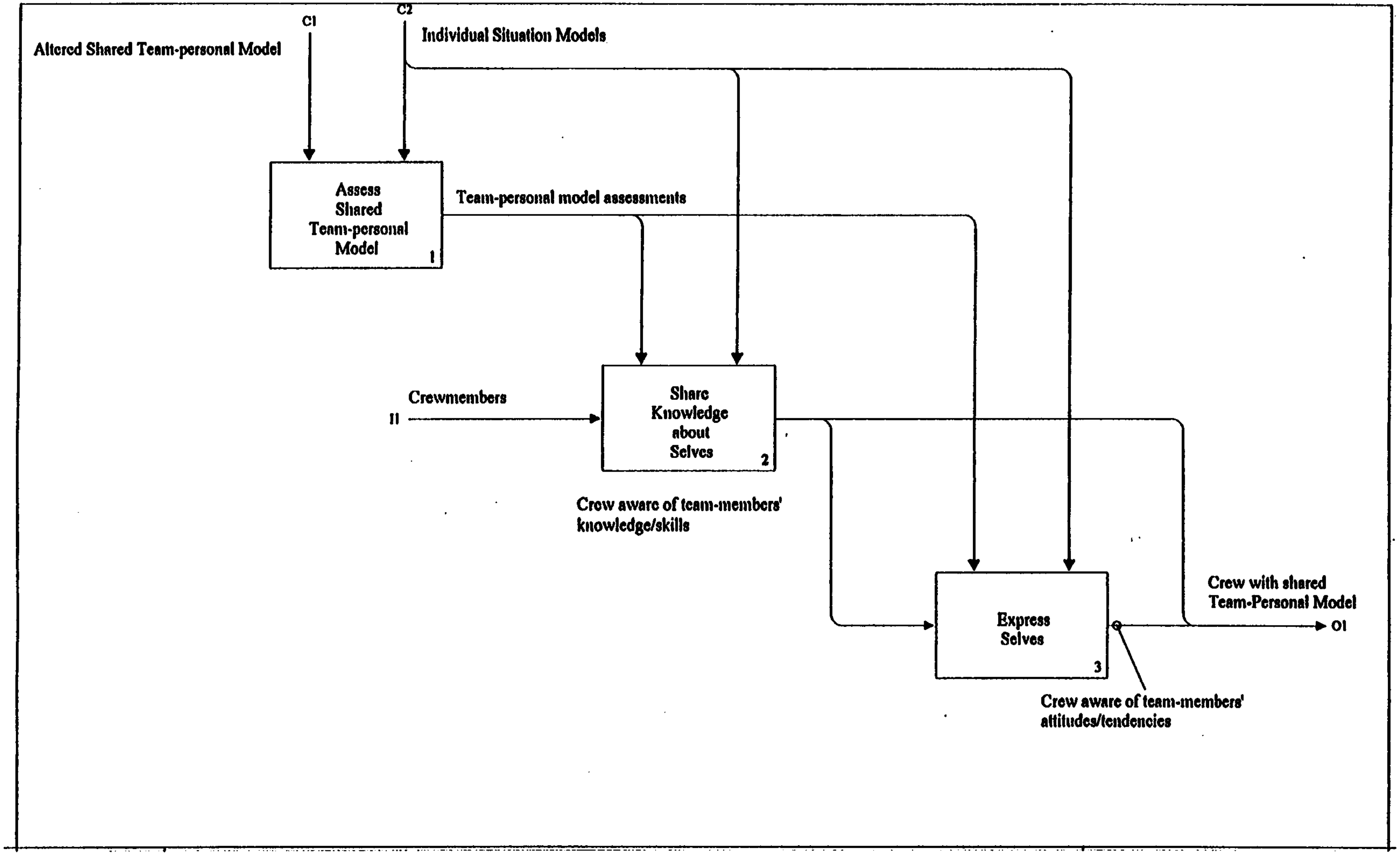

C1
C2
Altered Shared Team-personal Model
Individual Situation Models
Assess Shared Team-personal Model
1
Team-personal model assessments
Crewmembers
I1
Share Knowledge about Selves
2
Crew aware of team-members' knowledge/skills
Express Selves
3
Crew with shared Team-Personal Model
O1
Crew aware of team-members' attitudes/tendencies

Figure 10. CRM/A23 Develop Shared Team-Personal Model

(b) Share Knowledge about Selves.

The function Shared Knowledge about Selves transforms Crewmembers into a Crew aware of team-members' Knowledge/Skills subject to Team-personal Model Assessments and Individual Situation Models. The output becomes an input to the function Express Selves.

(c) Express Selves.

The function Express Selves transforms Crewmembers into a Crew aware of team-members' Attitudes/Tendencies subject to Team-personal Model Assessments and Individual Situation Models.

The combination of the outputs of the above three functions leads to a Crew with Shared Team-personal Model, the output of the function Develop Shared Team-interaction Model. Crew with Shared Team-personal Model is thus defined as the combination of a Crew aware of team-members' Knowledge/Skills, and a Crew aware of team-members' attitudes/tendencies.

5.7.5 CRM/A3

Node CRM/A3 (Figure 11) shows the decomposition of parent box A3 and is titled Accomplish Technical Tasks.

Accomplish Technical Tasks (A3) is decomposed into four functions (a) Prioritize Tasks, (b) Allocate Resources, (c) Share Task Information, and (d) Execute Tasks. According to the IDEF0 methodology, these functions would be numbered as A31, A32, A33, and A34 respectively. However, since they are not decomposed any further in the analysis, they are only numbered as 1, 2, 3, and 4 respectively. These functions are described below.

The decomposition of Accomplish Technical Tasks is based upon Funk's (1991) theory of Cockpit Task Management (CTM).

In discussing the development of the Shared Task Model, it was noted that the crew clarifies goals, discusses contingencies/plans and task strategies. Clarification of goals lead to the definition of tasks. Funk (1990) defines a task as "...a process completed to cause a system to achieve a goal" (p. 229).

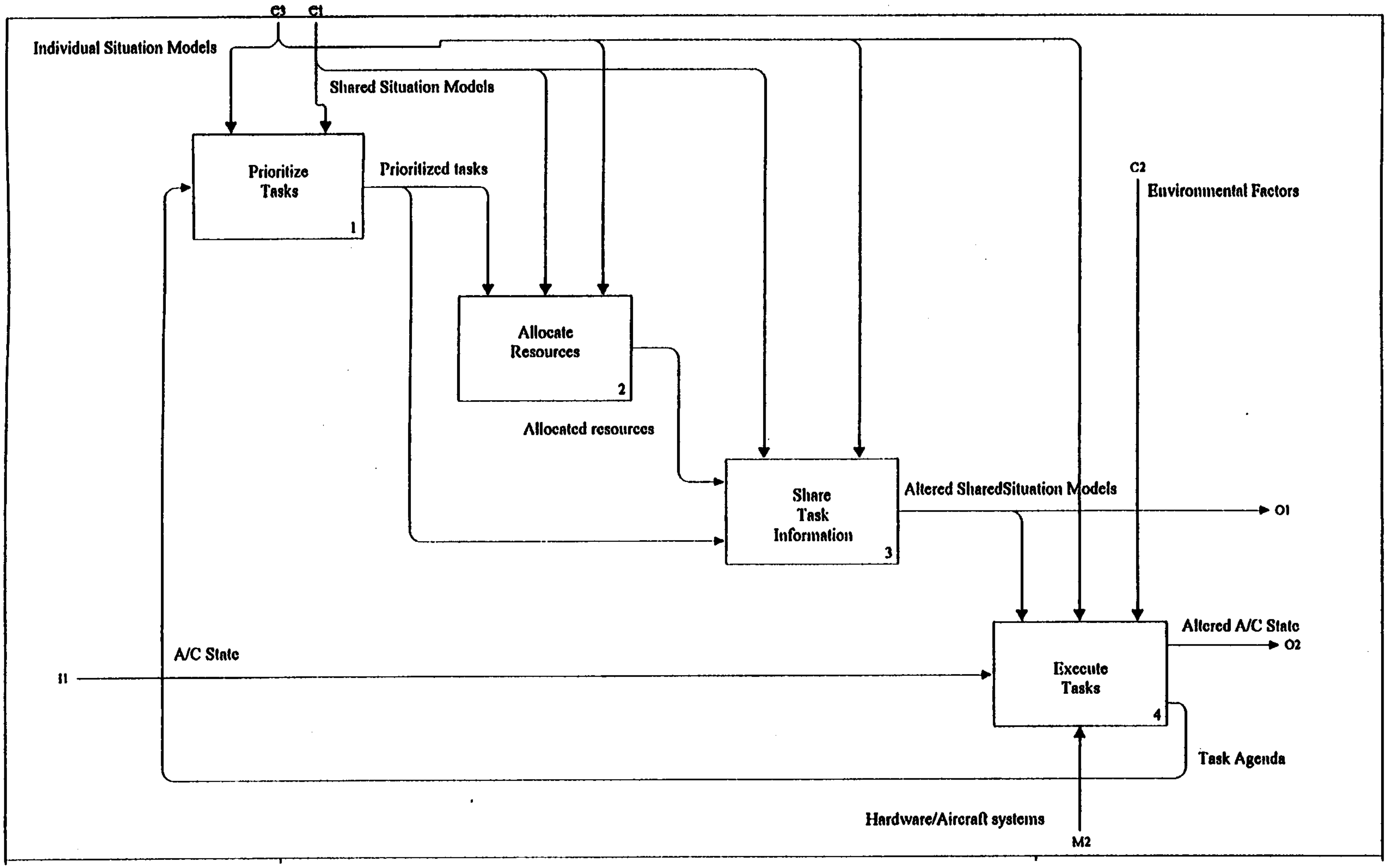

C3
C1
Individual Situation Models
Shared Situation Models
Prioritize Tasks
1
Prioritized tasks
Allocate Resources
2
Allocated resources
Share Task Information
3
Altered SharedSituation Models
O1
C2
Environmental Factors
Execute Tasks
4
Altered A/C State
O2
A/C State
I1
Task Agenda
Hardware/Aircraft systems
M2

Figure 11. CRM/A3 Accomplish Technical Tasks

Since flying an airplane is a dynamic multi-tasking environment, Accomplish Technical Tasks implies that there are many goals to be achieved simultaneously, which means there are many tasks to be defined and executed. This leads to the notion of a hierarchy of tasks and the creation of an agenda of tasks. Funk (1991) defines an agenda as "...a hierarchy of tasks to be completed during a mission" (p. 275). Further, Funk (1990) notes that the process of creating the agenda of tasks "...involves the selection and specification of a suitable task to achieve each goal and the definition of an event to initiate that task" (p. 229).

(a) Prioritize Tasks.

This function transforms the Task Agenda (output of Execute Tasks) into a set of Prioritized Tasks (a prioritized agenda of tasks) subject to Individual Situation Models, and Shared Situation Models.

The Task Agenda needs to be prioritized depending upon the situation. Although there may be a number of tasks to be simultaneously accomplished, each task can be assigned a weight in terms of importance and urgency, thereby allowing for the agenda to be ordered or prioritized.

Task prioritization requires a shared understanding of the situation. Shared Situation Models are thus a control to this task. A variety of decision-making and judgment skills are involved in task prioritization. Individual Situation Models is thus the other control to this function. The Prioritized Tasks then become an input to the function Allocate Resources.

(b) Allocate Resources.

This function generates Allocated Resources subject to Prioritized Tasks, Shared Situation Models, and Individual Situation Models.

Once tasks are prioritized, resources need to be allocated for their execution. Resources are allocated to tasks on the basis of the urgency and importance assigned to them (Prioritized Tasks). Resource allocation in terms of the crew system essentially involves assignment of tasks to crewmembers. These task assignments depend upon a shared understanding of who is currently doing what (Shared Situation Models), and upon cognitive skills involving decision-making (Individual Situation Models). Thus, Prioritized Tasks, Shared Situation Models, and Individual Situation Models are controls to this function.

(c) Share Task Information.

The function of sharing task information transforms the inputs which are Prioritized Tasks and Allocated Resources into an Altered Shared Situation Model subject to Shared Situation Models and Individual Situation Models.

The Shared Situation Model, especially the Shared Team-interaction Model will influence how well the information about the prioritized tasks and team assignments (allocated resources) is communicated to each other. This sharing of task information changes the Shared Situation Model to result in the Altered Shared Situation Model, which is what controls Execute Tasks. The Altered Shared Situation Model is now the current Shared Situation Model which is what is assessed in the Build and Maintain Team function described previously.

(d) Execute Tasks

This function transforms Aircraft State into Altered Aircraft State and Task Agenda, subject to Shared Situation Models, Individual Situation Models, and Altered Shared Situation Models, with the help of Hardware/Aircraft Systems.

Aircraft State and Altered Altered Aircraft State have been defined previously. The function Execute Tasks includes the "physical" execution of tasks, which leads to a change in the Aircraft State, as well as the creation of the agenda of tasks. Hence the outputs of the function are Task Agenda and Altered Aircraft State. Task Agenda becomes an input to Prioritize Tasks.

The Altered Shared Situation Model along with the Individual Situation Models control Execute Tasks. In addition to these, Environmental Factors also control this function. After all, it is the environment over which the crew has minimal control over.

This concludes the description of the model of crew performance. This also concludes the chapter on Modeling Crew Performance. Chapter 6 discusses Model Application.

6. MODEL APPLICATION

Chapter 5 described the model of crew performance developed using the SADT/IDEF0 methodology. The primary purpose of the model is to model crew performance and describe the activities or functions involved in crew performance. Since the model is supposed to be a description of performance, it should also be able to explain breakdowns in crew performance. An example of a breakdown in crew performance is an aircrash. However, an accident represents the harshest example of such breakdowns; not all breakdowns in performance may result in accidents. For example, unsatisfactory accomplishment of activity A22 (Develop Shared Team-Interaction Model) results in an inadequately developed shared team-interaction model, and ultimately in a less effective team. However, not all aircraft flown by less effective teams will crash. Likewise, accidents can occur in cases where the team might have performed well by all standards, yet, the situation was beyond human control because of say, limiting environmental factors.

The crew performance model is useful because it can provide valuable insight into these interactions. It goes beyond helping to identify which activities were not accomplished. It helps the analyst to pose important questions such as: why was a particular activity not accomplished? If it was limited in some way, how so? Through controls or inputs? If so, where did the control or the input come from? Were they boundary inputs or controls or were they the output of another activity? By posing such questions, the analyst is forced to look "deeper" into the accident, thereby gaining insight beyond the superficial causes. Such insight is valuable not just to the accident investigator interested in determining the cause of the accident, but also to those interested in the design of aircraft and crew systems. In the following sections, the utility of the model is demonstrated by applying it to analyze two aircraft accidents.

Accidents occur because of a number of reasons, but since the model was developed with an emphasis on crew coordination related activities, the demonstration of the model is restricted to applying it to those accidents that are supposedly CRM related. Prior to 1979, the NTSB made no mention of CRM in its accident reports. As was mentioned in Chapter 3, the NTSB's first explicit mention of 'poor CRM' was in its report after the crash of a United Airlines flight, in 1978 in Portland, Oregon. Since then, there have been several accidents and incidents in which "good CRM" and "bad CRM" have been implicated, both by the NTSB as well as the operational community.

6.1 Bad CRM

On December 29, 1972, an Eastern Airlines, Lockheed Tristar L-1011 plane (an L-1011 has three jet engines - one each under a wing and one mounted on the tail) crashed into the Florida Everglades primarily because the crew was distracted by two burnt out light bulbs of the nose landing gear position indicating system. Although this accident occurred much before the concept of CRM, as Kayten (1993) writes, "This accident has come to represent the classic *CRM accident* [italics added]" (p. 291). The entire aviation community has come to recognize this accident as a typical example of bad CRM as is evident from the numerous references to it in the literature. This view is even shared by the airline industry (P. Russo, personal communication, 1993). Because of its significance, this is one of the accidents that will be analyzed.

6.2 Good CRM

On July 19, 1989, a United Airlines, McDonnell Douglas DC-10 (also a three engined aircraft with engines mounted in a configuration similar to the L-1011) attempted a landing at Gateway Airport in Sioux City, Iowa after almost 45 minutes of a complete hydraulic system failure following a mid-air explosion in the aircraft's tail section. This accident has been recognized by the aviation community as an example of good CRM, a fact documented by NTSB's (1990) explicit commendation of the crew that "...greatly exceeded reasonable expectations....indicative of the value of cockpit resource management training, which has been in existence at UAL [United Airlines] for a decade" (p. 76). The surviving captain, Al Haynes, himself has attributed the success of the crew's preparation to United's CRM training program known as Command Leadership Resource Training or CLR (Haynes, 1991). This is the other accident that will be analyzed in this chapter.

6.3 Analysis Strategy

The primary source of information about an aircraft accident is that provided by the NTSB accident report following the crash. Consequently, the analysis of the two CRM examples mentioned above will be based upon the respective NTSB accident reports. Communications play an important part in team performance and are hence important for an analysis. Some accident reports provide a detailed transcript of the CVR recordings, while some provide only pertinent communications. The information provided in the accident report along with the transcript of CVR recordings will be the sole basis of data or information for the analysis.

The general format for the analysis will follow one of questions and answers. Madhavan (1993), in his analysis of aircraft incident reports cites the use of Crouch's (1992) 'Five Whys Deep' concept as being "Central to the theme of going beyond 'pilot error' as a causal factor for error committal..." (p. 27). The approach used in this analysis is akin to his approach. However, instead of the use of an error taxonomy, this analysis makes use of the crew performance model which is based on a functional approach.

6.4 Analysis: Example of Bad CRM

The synopsis of the Eastern 401 crash as taken from the NTSB (1973) accident report (NTSB-AAR-73-14) is as follows:

> An Eastern Air Lines [EAL] Lockheed L-1011 crashed at 2342 eastern standard time, December 29, 1972, approximately 18 miles west-northwest of Miami International Airport, Miami, Florida. The aircraft was destroyed. There were 163 passengers and a crew of 13 aboard the aircraft; 94 passengers and 5 crewmembers received fatal injuries. All other occupants received injuries which ranged in severity from minor to critical.
>
> The flight diverted from its approach to Miami International Airport because the landing gear position indicating system of the aircraft did not indicate that the nose gear was locked in the down position. The aircraft climbed to 2,000 feet mean sea level and followed a clearance to proceed west from the airport at that altitude. During this time, the crew attempted to correct the malfunction and to determine whether or not the nose landing gear was extended.
>
> The aircraft crashed into the Everglades shortly after being cleared by Miami Approach Control for a left turn back to Miami International Airport. Surviving passengers and crewmembers states that the flight was routine and operated normally before impact with the ground.
>
> The National Transportation Safety Board determines that the probable cause of this accident was the failure of the flight crew to monitor the flight instruments during the 4 final minutes of flight, and to detect an unexpected descent soon enough to prevent impact with the ground. Preoccupation with a malfunction of the nose landing gear position indicating system distracted the crew's attention from the instruments and allowed the descent to go unnoticed.
>
> As a result of the investigation of this accident, the Safety Board has made recommendations to the Administrator of the Federal Aviation Administration. (p. 1-2)

A graph of the CVR recordings of the last 10 minutes of communications prior to impact, plotted against an altitude trace derived from the DFDR is provided in Appendix D of the NTSB accident report. These communications are illustrated in very fine print on the graph. For the sake of legibility, the transcribed communications from the graph were re-typed into standard text format without the altitude trace. This verbatim transcript is shown in Appendix 1 and was used for the analysis.

A condensed version of the sequence of events along with some transcriptions of the recording of the events during the crucial last six minutes before impact is included below.

The cockpit crew consisted of a Captain, a First Officer, and a Second Officer. Also present was an Eastern Airlines Maintenance specialist who happened to be in the forward observer seat in the cockpit. The F/O was flying the aircraft which had reached an altitude of 2,000 feet

2336:04 Captain directs F/O to engage autopilot.

F/O removes nose gear light lens assembly, attempts to replace it but it jams.

2337:08 Captain instructs Second Officer (S/O) to enter 'forward electronics bay' to check visually the alignment of the nose gear indices.

(Proper nose gear extension is indicated by the physical alignment of two rods on the landing gear linkage that can be observed by means of an optical sight when the nose wheelwell light is illuminated. This observation is done from the forward electronics bay, an area below the cockpit and just forward of the nose wheelwell.)

Flightcrew continues attempts to free nose gear position light lens from retainer without success (since it is jammed)

2338:34 Captain again instructs S/O to descend to forward electronic bay to check the alignment.

2338:56 Captain and F/O discuss faulty nose gear position light lens to and how it might have been reinserted incorrectly.

2341:05	At 2340:38 - half second C-chord sounds (to indicate a deviation of +/-250 feet from selected altitude. No comment by any of flightcrew on sounding of C-chord. No pitch change to correct loss of altitude.
After 2341	S/O comes up to cockpit to say he couldn't see it since it was pitch dark. Flightcrew and EAL maintenance specialist occupying forward observer seat discuss operation of nose wheelwell light. Maintenance specialist goes to help S/O into electronics bay.
2341:40	Tower asks EAL 401 "how are things comin' along out there?" Controller notes 900 feet alphanumeric display on radar screen, but does not think flight is in danger - momentary deviations in altitude information on the radar display were not uncommon and more than one scan on display is required to verify a deviation requiring controller action.
2342:05	F/O " We did something to the altitude" Capt. "What?"
2342:07	F/O "We're still at 2000 feet, right?" Capt. "Hey, what's happening here?"
2342:10	First of six altimeter warning "beep" sounds begin. Cease immediately before sound of initial ground impact.
2342:12	Aircraft crashes into everglades.

In the conclusions made by the NTSB, four of the seventeen findings are very relevant to their determination of the probable cause. These four are listed below:

1. The three flight crewmembers were preoccupied in an attempt to ascertain the position of the nose landing gear. [no. 10]
2. The flightcrew did not hear the aural altitude alert which sounded as the aircraft descended through 1,750 feet m.s.l. [no. 13]
3. The flightcrew did not monitor the flight instruments during the final descent until seconds before impact. [no. 16]

4. The captain failed to assure that a pilot was monitoring the progress of the aircraft at all time. [no. 17] (p. 23).

The probable cause of the accident is cited in the latter half of the synopsis above. The fact that the aircraft crashed implies that somewhere along the line there was a failure or breakdown of the function Accomplish Technical Tasks (A3 on node CRM/A0, Figure 3). Why was there a breakdown? The answer to this lies in a closer look at this function, or its decomposition as shown on node CRM/A3 (Figure 11).

Finding 1 above provides some insight into what happened during accomplishing the technical tasks. It states that "the three flight crewmembers were preoccupied in an attempt to ascertain the position of the nose landing gear" (p. 23). This coupled with finding 4 (the captain failed to assure that a pilot was monitoring the progress of the aircraft at all time) leads to two important inferences (a) tasks were misprioritized and (b) resources were improperly allocated. At 2,000 feet, the most important task that needs to be paid attention to is to fly the airplane. And nobody was flying the airplane. Although the autopilot was engaged, the NTSB report notes that "...good pilot practices and company training dictate that one pilot will monitor the progress of the aircraft at all times and under all circumstances" (p. 21). The non-illumination of the nose landing gear position indicating system should indeed have been a matter of concern. Nevertheless, all three pilots need not have been involved in diagnosing the problem. Thus, the two functions that were inadequately accomplished were (a) Prioritize tasks and (b) Allocate Resources.

Why was there a misprioritization of tasks? The Prioritize Tasks function is controlled by Individual Situation Models and Shared Situation Models. It can thus be inferred that these models were either incorrect or inadequate given the demands of the situation. The same can be said about Allocate Resources. Even if the problem of burnt out light bulbs was assigned a higher priority, all the crewmembers need not have attempted to solve it. By taking a closer look at the functions that generated these models, it may be possible to infer what was lacking. Individual Situation Models are the output of Maintain Individual Situation Awareness (A1) while Shared Situation Models are the output of Build and Maintain Team (A2). The performance of both these functions is therefore analyzed.

Maintain Individual Situation Awareness is decomposed into Assess Situation, Acquire Information, and Update Situation Models (node CRM/A1, Figure 4). Finding 3 states that the flightcrew did not monitor the flight instruments during the final descent until seconds before impact. The crew thus failed to Acquire Information (A12). A closer look is taken at the function Acquire Information (node CRM/A12, Figure 6).

Acquire Information (A12) has Individual Factors, Environmental Factors, Organizational Factors, and Situation Assessment as controls and Hardware/Aircraft Systems as a mechanism. It is decomposed into Acquire Information from the Environment, Acquire Information from the Aircraft, and Acquire Information from Crewmembers.

The accident occurred at night (close to midnight); the outside environment was not illuminated. Although the aircraft was at 2,000 feet it is not clear from the report if the pilots could have acquired valuable information from the outside (e.g., runway landing lights, other landmarks). The plane descended into the Everglades; it is thus probable that very few visual cues could have been acquired from outside the cockpit. Acquire Information from Environment is therefore ruled out. Acquire information from Crewmembers is also irrelevant in this case; the crew appeared to all be working together trying to fix the light bulb problem. What was lacking was the acquisition of information from the aircraft instruments. A closer look is thus taken at Acquire Information from Aircraft.

One of the findings of the NTSB was, "There was no failure or malfunction of the structure, powerplants, systems, or components of the aircraft before impact, except that both bulbs in the nose landing gear position indicating system were burned out" (p. 22). Thus, there was no problem with the mechanism, Hardware/Aircraft Systems. All pilots were well experienced and possessed the requisite skills and knowledge. In fact, the Captain in his most recent flight check had received the comments, "Good knowledge of aircraft and procedures" (p. 27). Although a post-mortem discovered a tumor in the brain of the captain, the NTSB concluded that this had no effect on the pilot's motor skills. In any case, motor skills were irrelevant to the unfolding of the circumstances. Organizational factors are not indicative of having any effect on this function. The weather conditions were normal, there was no windshear or other abnormal meteorological conditions that could have affected the crew's ability to acquire information from the aircraft. The only other control that affected the acquisition of information was thus Situation Assessment, which resulted in inadequate Acquired Situation Information. Situation Assessment is an output of Assess Situation (A11). A closer look is therefore taken at this function (see node CRM/A11, Figure 5).

Assess Situation has Acquired Situation Information as the input and Individual Situation Models as the control. It was concluded in the above paragraph that the Acquired Situation Information was inadequate. Preoccupation with the light bulbs led the flightcrew to ignore important aspects of the situation. The pilots' focus of the situation centered around the light bulbs; other aspects of the situation, such as the aircraft instruments, were ignored. As a result, their perception of the situation might have been correct, but it was inadequate since the pilots did not even notice that the aircraft had started on an unintentional descent. They comprehended the "narrow view" of the situation correctly, but only to the extent that their individual situation models suggested based on the perceived situation. As far as they were concerned, removing the bulb was the problem and they proceeded to determine how it could be taken care of. But this comprehension lacked integration of all aspects of the situation, therefore their projections of the situation were also inadequate. Individual Situation Models are the only control to Assess Situation, hence it is inferred that these were inadequate. Thus, the combination of inadequate Individual Situation Models with inadequate Acquired Situation Information resulted in inadequate Situation Assessment which in turn controlled the Acquire Information function and Update Situation Models function, resulting in inadequate or incorrect Individual Situation Models.

Shared Situation Models are an output of the function Build and Maintain Team (A2). A closer look is taken at its decomposition (see node CRM/A2, Figure 7). Build and Maintain Team has three functions (a) Develop Shared Task Model, (b) Develop Shared Team-interaction Model, and (c) Develop Shared Team-personal Model.

There is insufficient information available to make any inferences about the Shared Team-interaction Model and the Shared Team-personal model (only the last 10 minutes of communications are available). In any case, from the last 10 minutes of data, there is no indication that these limited performance in any way. The remaining function is Develop Shared Task Model (A21). A closer look is thus taken at this function (see node CRM/A21, Figure 8).

Crewmembers are an input to A21; its controls are Altered Shared Task Model and Individual Situation Models, and its output is a Crew with Shared Task Model. Sharing of mental models requires effective communication. The effectiveness of the communication is however, irrelevant if the "content" that is being shared is deficient. In this case, the Individual Situation Models themselves were inadequate, which was the primary reason why the crew had an inadequate Shared Task Model. An inadequate Shared Task Model resulted in an inadequate Shared Situation Model, which adversely affected the Accomplish Technical Task function as examined previously. From this it can be inferred that inadequate Individual Situation Models were the primary cause that led to a breakdown in the function Accomplish Technical Tasks.

6.5 Analysis: Example of Good CRM

A portion of the Executive Summary of the United Airlines crash as cited in the NTSB (1990) accident report (NTSB-AAR-90-06) is as follows:

> On July 19, 1989, at 1516, a DC-10-10, N1819U, operated by United Airlines as flight 232, experienced a catastrophic failure of the No. 2 tail-mounted engine during cruise flight. The separation, fragmentation and forceful discharge of stage 1 fan rotor assembly parts from the No. 2 engine led to the loss of the three hydraulic systems that powered the airplane's flight controls. The flightcrew experienced severe difficulties controlling the airplane, which subsequently crashed during an attempted landing at Sioux Gateway Airport, Iowa. There were 285 passengers and 11 crewmembers onboard. One flight attendant and 110 passengers were fatally injured.
>
> The National Transportation Safety Board determines that the probable cause of this accident was the inadequate consideration given to human factors limitations in the inspection and quality control procedures used by United Airlines' engine overhaul facility which resulted in the failure to detect a fatigue crack originating from a previously undetected metallurgical defect located in a critical area of the stage 1 fan disk that was manufactured by General Electric Aircraft Engines. The subsequent catastrophic disintegration of the disk resulted in the liberation of debris in a pattern of distribution and with energy levels that exceeded the level of protection provided by design features of the hydraulic systems that operate the DC-10's flight controls.

Unlike the Eastern Airlines report, this accident report does not provide a complete transcript of the CVR recordings as a single appendix. Instead, details of communications including paraphrased versions interspersed with actual transcriptions are provided in different sections of the report. For example, details of communications between the aircraft and United Airlines' San Francisco Maintenance facility are included under section 1.9.1 while details of cockpit communications are included under section 1.11.1 (p. 19-23). For the purposes of this analysis, a summary of events compiled by combining the communications provided under different sections of the report was prepared. This summary is as follows:

[Aircraft cruising at 37,000 feet - F/O flying aircraft]

1516:10 Loud bang/explosion is heard, followed by vibration and shuddering of airframe.

Crew checks instruments and determines the No. 2 (tail-mounted) engine to have failed.

Captain (Capt.) asks for engine shutdown checklist.

S/O observes airplane's normal systems hydraulic pressure and quantity gages are indicating zero.

F/O reports he cannot control airplane; airplane enters right descending turn.

Capt. takes control but the aircraft does not respond to control inputs.

Capt. reduces thrust on No.1 engine (mounted under left wing) and aircraft rolls to level attitude.

Crew deploys air driven generator (ADG) as backup to restore auxiliary hydraulic power, but the attempt is in vain.

1520 Crew contacts Minnesota Air Route Traffic Control Center (ARTCC) and requests emergency assistance and vectors to nearest airport. ARTCC suggests Des Moines airport.

1521 Crew sends Aircraft Communications and Reporting Systems (ACARS) message to UAL Central Dispatch - requesting a call on frequency 129.45. No contact yet.

1522 ARTCC informs UA 232 they were proceeding towards Sioux City, and if they would prefer vectors to Sioux City - crew responds "affirmative."

1523 UAL dispatch initiates contact with UA 232.

1525 UA 232 requests dispatch connect flight with UAL's San Francisco Maintenance (SAM) "...immediately, its a MAYDAY"

1526:42 CVR recording begins - Capt. talking to ARTCC (probably confirming vectors to Sioux city)

1527 Crew contacts SAM - advises SAM of loss of all hydraulic systems and quantities and requested whatever assistance SAM could provide - SAM unable to provide any new instructions. (see 1530:35 -- crew here implies S/O)

Meanwhile (shortly after no. 2 engine failure) passengers informed of no. 2 engine failure, senior flight attendant called to cockpit - was told to prepare for a "quick and dirty" (i.e., an emergency landing).

1529:15 A flight attendant relays a message to the Capt. - advising the Capt. that a UAL DC-10 training check airman who was off duty and seated in the first-class cabin section, had volunteered his assistance.

Capt. responds "Okay, let'em come up" to flightdeck.

1529:35 Check Airman (CA) arrives on deck.

1529:41 Capt. (to CA) "We don't have any controls"

1529:55 Capt. directs CA to return to cabin to assess external damage.

1530:32 F/O "What's the hydraulic quantity?"
S/O reports zero.
F/O "on all of them?"
S/O confirms the status.
Capt. "quantity is gone?"
1530:35 Capt. to S/O "you got a hold of SAM?"
S/O "he's not telling me anything"

Capt. " We're not gonna make the runway fellas"

[Believed that CA returns to the deck at this juncture]

Capt. "We have no hydraulic fluid, that's part of our main problem."
CA "Okay both your inboard ailerons are sticking up that's as far as I can tell. I don't know"

CA asks Capt. for instructions.
Capt. tells him which throttle to manipulate.

1532:02 CA reports that the flight attendants were slowly securing the cabin.
Capt. reports that "they better hurry we're gonna have to ditch I think"

1532:16 Capt. reports to approach controller that the flight had no hydraulic fluid and therefore no elevator control and that the flight might have to make a forced landing.

1532:18 CA states "get this thing down we're in trouble"

1533 SAM informs UA 232 it was making contact with UAL flight operations.

1534:27 Capt. decides to attempt a landing at Sioux City.
Capt. asks S/O for information to make a no-flap, no-slat landing.
Capt. also asks controller for ILS frequency heading to runway and length of runway.
Controller provides frequency and reports runway 31 to be 9,000 feet long.

[Airplane is now 35 miles northeast of the airport]

1535:36 Capt. instructs S/O to start dumping fuel by using the quick dump.

1537:55 Capt. asks CA if he could manipulate the throttles to maintain a 10 to 15 degree turn.
CA replies that he "would try"

1538:55 One of the pilots says that 200 Knots would be the "clean maneuvering airspeed"
F/O responds "two hundred and one eighty five on your [speed]bugs Al"

1540 SAM advises UA 232 that 'Operational Engineering' department had been contacted to lend assistance.

1540:39 Capt. asks senior flight attendant if everyone in the cabin was ready.
Capt. explains to the flight attendant that they had very little control of the airplane because of the loss of hydraulic flight controls and that they were going to attempt to land at Sioux City, Iowa. He mentions that it would be a difficult landing and that he had doubts about the outcome and the crew's ability to carry out a successful evacuation. He also mentions that there would be the signal "brace, brace, brace" made over the P.A. system to alert the cabin occupants to prepare for the landing.

1541:09 Approach controller informs UA 232 that emergency equipment would be standing by.

1541:52 S/O reports that a flight attendant said she observed damage on one wing.
S/O asks if he should go aft and look.
Capt. authorizes S/O's absence from flightdeck to investigate.

1543 S/O returns to report damage to tail of airplane.
Capt. reports "...that's what I thought"

1545 SAM informs UA 232 that "engineering is assembling right now and they're listening to us."
Crew advises SAM that the flight was at 9,000 feet and that they were planning to land at Sioux City.

1548:43 Landing gear is extended (by means of the alternate gear extension procedure)

1549:11 Capt. directs flightcrew to lock their shoulder harnesses and to put everything away.

UA 232 informs SAM that they has just completed the alternate gear extension procedure. (last communication recorded between UA 232 and SAM)

1551:04 ATC reports flight was 21 miles north of the airport.
Controller requests flight to widen its turn slightly to the left in order to make a turn onto its final approach and keep airplane away from the city.

Capt. responds "whatever you do, keep us away from the city"
Controller gives flight a heading of 180 degrees.

1552:19 Controller alerts crewmembers to a 3,400 ft tower 5 miles to right.
F/O acknowledges alert.
Capt. responds they were trying to make a 30 degree. bank.
A crewmember comments "I can't handle that steep of bank...can't handle that steep of bank."

1553:35 F/O states "...we're gonna have to try it straight ahead Al"

1553:37 Controller advises crew that if they could hold altitude, their right turn to 180 degree would put flight 10 miles east of airport.
Capt. states "that's what we're tryin' to do"
F/O recommends they try to establish a shallow descent.

1553:57 Captain states he wants to get as close to airport as possible.
Captain (few seconds later) states "get on the air and tell them we got about 4 minutes to go"
F/O so advises the controller.
Capt. corrects him "tell the passengers"
A crewmember (presumably the Captain) makes a PA announcement.

1555:44 Capt. reports a heading of 180 degrees.
Controller reports that if the altitude could be maintained, the heading, "will work fine for about oh 7 miles"

1557:07 Controller reports that the airport was "...twelve o'clock and one three miles."

1558:11 Capt. reports the runway in sight and thanks controller for his help.
Capt. instructs the S/O to make a PA announcement which was believed to be a 2-minute warning.
Controller reports winds as 360 degrees at 11 knots and cleared flight to land on any runway.
Crew attempts to turn airplane to the left slightly.

1558:59 Capt. reports "we're pretty well lined up on this one here...think we will be..."
Controller states that the runway the flight was lined up on was runway 22, which was closed, but added "that'll work sir, we're gettin' the equipment off the runway, they'll line up for that one."
Capt. asks its length - controller reports it as 6,600 ft long

1559:11 Controller states that there was an open field at the end of runway and that the winds would not be a problem.

[Crew's attention is directed to manipulating the throttles]

1559:29 One of the crewmembers makes announcement to brace for the landing.

1559:44 First of several Ground Proximity Warning Signal (GPWS) alerts begin.

1559:52 GPWS warnings end.

1559:58 Capt. states "close the throttles"

1600:01 CA states "nah I can't pull'em off or we'll lose it, that's what's turnin' ya"

1600:05 F/O "left Al" "left throttle" "left" (repeated several times)

1600:09 Second series of GPWS alerts.
F/O "we're turning" or "we're tryin'"

1600:16 Impact.

United 232 crashed killing 110 of 285 passengers and one crewmember. Yet, it is considered to be an exemplar of good crew coordination. Breakdowns in crew performance may lead to accidents. However, not all accidents may be caused by a breakdown in crew performance. The performance of the crew of United 232 serves to highlight this fact.

This fact is also clarified by a look at the A0 node of the crew performance model developed. The controls to the function Accomplish Technical Task include Shared Situation Models, Individual Situation Models, and Environmental Factors. The mechanism to the function is Hardware/Aircraft systems. In the Eastern Airlines case, Individual Situation Models were determined to have been the limiting factor. In the case of United 232, it is clear that the mechanism, rather its partial loss, was responsible for affecting the Accomplish Technical Tasks function. Despite this, crew performance was better than what could be expected under such conditions. The NTSB complimented the crew for saving the lives of more than half the people on board the aircraft. A lot more lives could have been lost were it not for the crew of United 232. The focus of this analysis is thus different from Eastern Airlines. Instead of bad performance, the crew performance model will serve to show how the crew performed in a manner commended by the NTSB to have "...greatly exceeded reasonable expectations" (p. 76).

When the explosion occurred in the tail of the DC-10, the aircraft lost all three hydraulic systems. In the absence of hydraulic power, the plane did not respond to the control inputs made by the crew; the plane was out of control. As the crew soon discovered, they could have a minimal degree of control on the aircraft's attitude and heading by manipulating the thrust on the remaining two engines. There were a number of things the crew could have done wrong soon thereafter. Instead, the Captain immediately took charge and prioritized tasks and allocated resources.

The most important task was to try to keep the plane under control. After assessing the situation, the crew determined that the aircraft was not responding to any control inputs (A11 - Assess Situation). Based on the Situation Assessment, they decided that they needed more information (see node CRM/A1, Figure 4). Based on the prioritization of tasks, (see node CRM/A3, Figure 11) the Capt. and the F/O took charge of the task of controlling the airplane while the Capt. assigned the task of contacting Minneapolis

ARTCC to (Allocate Resources) the S/O to acquire information (Acquire Information) about alternate landing sites. Barely minutes after the explosion, the Captain accurately assessed the situation and based on the projection of its future status (Project Situation - see node CRM/A11, Figure 5), the crew contacted United Airlines Central Dispatch for further assistance and declared an emergency.

Through explicit sharing of information, the Captain proceeded to build and maintain his team. Perhaps the most obvious of these functions was the crew's development of a Shared Task and Team-interaction Model (see nodes CRM/A21- Figure 8, CRM/A22 - Figure 9). An emergency situation is not the time to be developing a Shared Team-personal Model, although it could be inferred that the crew already had a fairly well developed Shared Team-personal Model given the fact that "The accident occurred on the third day of a 4-day scheduled trip sequence" and that they "...had flown together six times in the previous 90 days" (p. 11).

An assessment of the Shared Team-interaction Model determined the need to further expand the group's boundaries. The Captain informed the senior flight attendant of the criticality of the situation, while asking the S/O to get any information he could from San Francisco Maintenance and UAL Central Dispatch. Making the cabin crew aware of the emergency, led to the refinement of the norm, "yes, we are in this together and we can use your help". When a cabin crew member informed the captain of the United Airlines Check Airman seated in the first-class section, the Captain did not hesitate to invite him into the cockpit. He knew the crew could need all the help it could get. The Check Airman proved to be of invaluable help.

Once the Check Airman arrived in the cockpit, the Captain briefly apprised him of the situation (see details of communications above - Check Airman arrives at 1529:35, at 1529:41 Captain informs him "We don't have any controls") and the crew thus developed a Shared Task Model. Meanwhile, the Captain had already assigned the S/O with the task of maintaining communications with San Francisco Maintenance, while the F/O tried to maintain control of the airplane. Having an extra person in the cockpit, the Captain immediately made use of this resource by asking the Check Airman to return to the cabin to assess external damage (Acquire Information from Environment). By assigning this task to the Check Airman, who was a Captain himself, the Captain clearly established the authority dynamic between them (Develop Team-interaction Model).

During the time the CA went into the cabin and returned, the Captain discussed the situation with the F/O and the S/O (Develop Shared Task Model). As soon as the Check Airman returned to the cockpit, the Captain once again apprised him of the situation (1530:35 - Capt. "We have no hydraulic fluid, that's part of our main problem"). He then assigned the difficult task of trying to manipulate the throttles to the Check Airman (1537:55) who by standing between the Captain and F/O's seats and using both hands, was able to manipulate the throttles so as to maintain the aircraft's attitude (Allocate Resources). Having thus assigned the task of controlling the airplane to the Check Airman and the F/O, the Captain freed himself for further decision making tasks. All along, the Captain apprised the cabin crew about what was going on, and despite the critical situation took the time to make announcements over the Public Address system to inform the passengers.

It is clear from the above that all along, the crew maintained a level of group situation awareness by maintaining adequate levels of individual situation awareness, through explicit and effective sharing of information leading to the development of shared task and team-interaction models. The adequate Individual and Shared Situation Models thus formed were helpful in Accomplishing Technical Tasks.

The model of crew performance has been demonstrated to be applicable towards analyzing two salient examples of crew coordination. In the "Bad CRM" case, the model by posing questions such as "Why was there a misprioritization of tasks?" leads to the conclusion that the crew made an incorrect or inadequate assessment of the situation which was largely a consequence of their holding inadequate situation models, which were again because they failed to maintain individual situation awareness. In the "Good CRM" case, the model is able to highlight aspects of performance that led to the crew being able to effectively manage their resources through proper allocation and good coordination. By doing so, the model has been demonstrated to provide a useful framework for understanding crew performance from a CRM perspective.

7. DISCUSSION

The primary objective of this research has been to gain a better understanding of crew performance. In order to meet this objective, a framework for understanding crew performance was developed with an emphasis on crew coordination related activities. Chapter 4 laid the foundation for the development of the framework, while Chapter 5 described the modeling methodology used to develop the framework. In addition to the model's primary purpose of being a descriptor of crew processes, its ability to be applicable to the analysis of accidents was demonstrated in Chapter 6.

The discussion in this chapter pertains to the research as a whole. First, the overall research approach is discussed; the problems encountered, solutions adopted, and their limitations. This is followed by a discussion of the modeling methodology adopted for the purpose of modeling the crew system. The model is then discussed with an emphasis on its strengths and weaknesses. Finally, the usefulness of the model, and its validity is discussed.

7.1 Overall Approach

For more than a decade, the aviation industry has recognized, at least conceptually, the need for CRM. Presently, the industry is in the process of validating the effectiveness of CRM training. Meanwhile the challenge to regulatory agencies like the FAA is the development of objective measures of CRM evaluation, which was the vision goal of this research. It was believed that the development of a coherent framework for understanding the issues involved in CRM would lead to their better definition, thereby setting the stage for the development of objective performance measures. This led to the formulation of this research's primary objective: The development of a coherent framework for understanding crew performance with an emphasis on crew coordination.

The research proceeded with the hypothesis that the application of systems engineering principles to crew performance may result in a better understanding of crew coordination, an integral component of crew performance. The concepts underlying systems engineering may seem intuitive, yet because of their rigor, they force the analyst to think about issues in a logical and consistent manner. As a result, the principles of systems engineering have been traditionally applied in various domains, ranging from manufacturing systems to social systems (Wymore, 1976). This was the rationale behind applying systems theory to analyze crew performance.

Two ingredients are essential for a successful systems analysis: (a) a firm grasp of the concepts underlying systems engineering, and (b) domain knowledge or information about the system being modeled. One of the goals that this research accomplished was to gain an understanding of systems theory and of the SADT/IDEF0 modeling methodology used to analyze crew performance (this is further discussed in the following section, Modeling Methodology). This was then applied to the domain of crew performance.

A couple of points with regards to domain knowledge in general, and specifically with regards to crew performance are worth mentioning. While it is important to have a consistent viewpoint in the modeling of a system, it is always beneficial to have a wider perspective during the acquisition of domain knowledge. It is for this reason that modern, large-scale, complex systems are modeled not by a single individual but by a team of interdisciplinary professionals who provide input all along the modeling process (Wymore, 1976). Domain knowledge about crew performance can be acquired through the available research literature, or it can be acquired through the systematic study of crews and airline operations. A systematic study of actual operations would involve observations of either "line" crews (i.e., crews actually conducting a real-life transport mission), or simulator studies such as those conducted in LOFT sessions. However, access to airline crew operations is restricted, particularly within the United States. Firstly, it requires the establishment of a rapport with an airline that is open to an outside researcher. There are stringent FAA regulations regarding the observation of line crews in operation; even the casual ride in the "jumpseat" (an extra seat in the cockpit, usually to accommodate a check airman or technician) by unauthorized personnel is forbidden. Obtaining permission to observe simulator training sessions if also very difficult, partly because of the competitiveness among industry, and for reasons of confidentiality.

For the purpose of this research, initial contact was established with Evergreen Airlines of McMinnville, Oregon. At the time, Evergreen was in the process of developing an in-house CRM training program, and I am grateful for having had the opportunity to be present for at least one of their CRM sessions. Through my interactions with Evergreen, I gained valuable insight into line-based CRM, however, for reasons discussed above, I was unable to ride jumpseat and observe actual line operations or full-mission simulator training. Consequently, most of my domain knowledge about crew performance was acquired through available research literature in aviation psychology and related disciplines. It is thus possible that inadequate knowledge from operational sources could have diminished the quality or "richness" of the crew performance model developed.

7.2 Modeling Methodology

As previously noted, systems engineering is a very broad discipline. Although rigorous in principle, there isn't any one prescribed methodology that can be universally applied to all domains. There are many methods by which one can go about describing a system. Yet, the underlying principles of systematic and consistent analysis are paramount. Perhaps it is this intrinsic flexibility that accounts for the versatility of systems engineering.

One approach to designing or analyzing a system is the functional approach which focuses on system activities instead of system elements. Such an approach is especially useful in the design of human-machine systems, in which functions are to be allocated between human and automation based on the relative capabilities and limitations of these resources. A functional approach is useful because it does not restrict the analyst, at least initially, to prescribing specific methods of performing system activities and thereby accomplishing system goals. Such an approach is not restricted to any particular kind of system. For instance, in talking about the application of the functional approach to analyzing leadership performance (social systems), Hackman and Walton (1986) write, "Because the functional approach leaves room for an indefinite number of specific ways to get a critical function accomplished, it avoids the need to delineate the specific behaviors that a leader should exhibit in given circumstances..." (p. 77).

SADT is one such structured analysis technique which utilizes the functional approach for analyzing and designing systems. Because of its proven applicability in various domains, SADT/IDEF0 was adopted to analyze the crew system.

IDEF0's uniqueness and strength lies in the fact that it forces the analyst to identify the activities and the transformations involved in the system. In addition to doing so, it also forces the analyst to think about what limits these activities; the controls. Further, IDEF0 allows for the identification of mechanisms to perform these activities. In the design of human-machine systems, this facilitates the crucial task of function allocation; the assignment of system tasks to either the human or the machine. Another important feature which is unique to IDEF0 modeling is the Author/Reader cycle in which the model being developed by the Author (typically a team of analysts) is iteratively reviewed by the Reader (typically a team of reviewers). The validity of the model is thus continuously checked at all stages of model development (Marca & McGowan, 1988). More is said about this in the section on Model Application. Because of these features, the IDEF0 methodology has repeatedly proven to be useful in modeling systems, particularly in the design of manufacturing systems where task allocation decisions significantly influence the economics of design.

Despite its strengths, the IDEF0 modeling methodology has its limitations. Although based on a rigorous framework of analysis based on the concepts of inputs, outputs, controls and mechanisms, the IDEF0 methodology lacks formalization on several issues. For example, there are no well-defined rules for defining mechanisms, for distinguishing between inputs and controls, or for the use of tunneled arrows. A detailed discussion on some of these relevant issues as based on the work of Williamson (1991) has already been presented in the section, More on Boxes and Arrows, in Chapter 5, and is not further belabored. Some of these limitations led to conceptual problems in modeling crew performance. These are discussed in the following section.

7.3 The Crew Performance Model

In my opinion, there are four factors that significantly influenced the development of the model. These are (a) my lack of prior expertise in IDEF0 modeling, (b) the fact that domain knowledge about crew performance was acquired primarily through available research literature, (c) the lack of formalization of some issues in IDEF0, and (d) disagreement among the different disciplines about fundamental issues underlying human behavior.

The overall objective or goal of the research is to provide a better understanding of crew performance. The purpose of the model thus was to provide a framework for the better understanding of crew performance with an emphasis on crew coordination. The fact that domain knowledge about crew performance was acquired through research literature on aviation psychology certainly influenced its viewpoint. Since the model was developed from the perspective of an aviation researcher, it quite understandably reflects contemporary views about crew performance amongst aviation researchers. However, as noted above, the model was developed with an inadequate emphasis on knowledge acquired from an operational perspective. Consequently, the model might lack the operational emphasis, and subsequently affect its "usefulness" to the operational community.

Chapter 4 presented an overview of the theory underlying human performance. It drew upon various disciplines such as psychology, sociology, and human factors engineering to present an understanding of contemporary psychological constructs such as mental models, situation awareness, personality, groups, teams, and shared mental models. As might have been apparent, many of these issues remain fuzzy, each attempting to explain a particular aspect of human performance from their own perspective; their own view of reality. One of the objectives of the review of the literature was to integrate these perspectives in a logical and consistent manner. When it was not possible to do any more than present the different views, it was not attempted to resolve the dilemma per se, but the discussion was concluded by recognizing the fact that there may be disagreement over its representation. By doing so, concepts and terms were better defined, thus allowing for the development of a consistent model, which sets the stage for a coherent theory of crew performance.

The difficulty in the development of the model due to different perspectives was only exacerbated by the inherent limitations of IDEF0. For instance, IDEF0 lacks formalization on the distinction between an input, a control, and a mechanism. The only broad distinction offered is the fact that inputs are transformed by functions while controls are generally not transformed; they remain unchanged. This is obviously contradicted when a function has no inputs and only a control. Consider the case of mental models and maintaining individual situation awareness. The process of maintaining situation awareness is an iterative process of continuous adaptation, one which constantly results in an updating of the mental model. But the mental model also influences situation awareness. Should the mental model be a control or an input? It is true that part of this dilemma stems from the fuzziness surrounding the very concept of situation awareness and mental models. Obviously, there is a lot of room for further research in these areas, and a need for the further refinement of these concepts, a point made in the preceding section. But it may also be that the IDEF0 methodology is not adequate for modeling human performance; an inherent limitation of the modeling process. Indeed, as some sociologists would argue, it may not be possible to model human behavior, particularly group behavior, on the basis of systems concepts such as inputs and outputs (Richard Mitchell, personal communication, May 1994). In other words, they would argue that the hypothesis, that the application of systems engineering principles to crew performance can result in a better understanding of crew coordination, is in essence incorrect! However, I do not subscribe to this view. I maintain that the model of crew performance developed bears testimony to the fact that it is possible to apply systems theory to establish a framework for understanding crew performance.

7.4 Model Application

Chapter 6 described the application of the crew performance model to the analysis of two aircraft accidents. Since the model is a descriptor of the normative process of crew performance, it was supposed that it should be able to identify breakdowns in performance.

Accident reports were used as the source of information for demonstrating the applicability of the crew performance model as a descriptor of crew processes. However, there are a number of drawbacks with using accident reports, some of which were mentioned earlier. Firstly, an accident is a 'harsh' example of a breakdown in crew performance. Not all accidents are caused due to inadequate accomplishment of CRM related activities, and not all breakdowns in CRM necessarily lead to an accident. For example, developing a Shared Team-interaction Model is one of the activities necessary to build a team that safely carries out the mission. However, a crew with a poorly developed Shared Team-interaction Model, may also manage to safely accomplish a mission. But, given a contingency situation, there is a good chance that a crew with a well-developed Shared Team-interaction Model will perform better than a crew with a poorly developed Shared Model.

Many crew coordination activities are not directly observable. In most cases, they have to be inferred from other directly observable activities. Accident reports, however, do not provide adequate information about these subtle, non-observable processes. They focus on providing information about recorded verbal communications and behavior has to be inferred only on the basis of those communications. For example, it is difficult enough to infer if a crew has a well developed Shared Team-interaction Model. It becomes almost impossible to do so, given the limited information, if any, about team-building activities provided in an accident report. An accident report only provides CVR recordings of verbal communication. Yet, group processes, such as sharing of norms and the establishment of an authority dynamic, are communicated subtly, and in many cases, non-verbally. In other words, an accident report is not the best source of information to be using to authenticate or demonstrate the utility of a model of crew performance that has been developed with an emphasis on CRM related activities. A far better source would undeniably have been direct observation, either from the jumpseat or in a simulator. However, because of the difficulties involves in obtaining access to better sources of information, such as video taped recordings of LOFT training scenarios, I used accident reports as the primary source of information.

The crew performance model was used to analyze one good, and one bad example of CRM. "Bad CRM" implied that a breakdown in crew coordination resulted in a breakdown in performance, which resulted in the accident. The demonstrations in both cases proceeded along different lines. In the case of the bad CRM example, a "bottom-up" approach was used to demonstrate the model. Bottom-up means that the analysis began at a lower-level (more easily observable) activity, and proceeded upwards to higher level activities. In this case, the accident report specifically mentioned the mis-prioritization of tasks to be a contributing factor to the accident. The function Prioritize Tasks thus served as an easy "starting-point" to begin the demonstration of the process.

In the case of the good CRM example, there was no breakdown in crew coordination. In fact, the performance was considered to be exemplary. In this accident, the crew was faced with known contingency situation. Given a situation of good performance, the analysis proceeded in a "top-down" manner. Top-down means that the analysis started at the highest level of activities, and proceeded to lower levels of decomposition. The feasibility of using both approaches to analyze crew performance may be a testimony to the strength of the model.

7.5 Model Utility and Validity

Referring to an SADT/IDEF0 model, Williamson (1991) writes, "...model utility is comprised of two factors: model validity and model quality" (p. 3). Model quality is concerned with level of detail, expressiveness, and syntactic and semantic compliance. Of the two, "...model validity takes precedence over model quality..." because "...an invalid model is useless, regardless of its quality" (p. 3). The focus of this discussion will therefore be model utility and validity.

By definition, model utility and model validity are inextricably linked with each other. Merriam-Webster's (1993) defines valid as, "well grounded or justifiable: being at once relevant and meaningful...logically correct...appropriate to the end in view" (p. 1304). This meaning is reflected in Marca and McGowan's (1988) definition of an SADT model as, "M is a model of a system S if M can be used to answer questions about S..." (p. 8). With reference to purpose or utility, Weinberg (1975) was earlier cited to have stated that "The main role of models is not so much to explain and to predict - though ultimately these are the main functions of science - as to polarize thinking and to pose sharp questions" (p. 43). The utility and validity of the IDEF0 crew performance model is discussed on the basis of these meanings.

The primary purpose of the crew performance model is to describe crew performance with an emphasis on crew coordination or CRM related activities. The IDEF0 model is a subset of SADT, a logical, structured analysis and design technique. The model was developed on the basis of knowledge acquired from multiple sources of research literature (limitations of this have been discussed in the preceding sections). Further, as stated previously, the model was intended to answer questions pertaining to what limits or constrains the execution of activities and thus provide a framework for better understanding crew performance. As was demonstrated in the application of the model to the accidents, the model does assist in posing questions and seeking answers to the limits of crew performance. By doing so, I believe that the model serves its purpose and therefore fulfills the criteria of model utility, thereby laying the basis for its validity.

Creswell (1994) in discussing verification steps for results of qualitative research notes that there is "...no single stance or consensus on addressing the traditional topics such as validity and reliability in qualitative studies" (p. 157). Further, Creswell cites several methods for determining the issue of "...internal validity, the accuracy of the information and whether it matches reality..." (p. 158) based on Merriam (1988). These include discussing "...plans to triangulate, or find convergence among sources of information...", and discussing "...plans to receive feedback from informants..." (p. 158).

Earlier, it was acknowledged that the failure to have acquired knowledge from the operational community (i.e., airlines) may have resulted in limitations to the applicability or usefulness of the model. However, the review of the research literature did comprise the consideration of a multitude of information sources. It is thus claimed that the resulting model which represents an integration of different views represents a convergence among these different sources of information.

Previously, the SADT Author/Reader cycle was mentioned. The cycle is so designed as to ensure the checking of model validity at all stages of the development process. During the course of the crew performance model, every attempt was made to adhere to this cycle, albeit the author and the reader (Kenneth Funk, personal communication, 1992-1994) were both individuals as against a team of analysts and a team of readers.

Despite the case being made that the SADT methodology as well as the actual modeling process followed tends to ensure the validity of the model, it could always be argued that the model is merely the analyst's representation of the system, which is but a perspective of reality. Because each individual's perception of reality differs, each person's representation of reality will also be different. Determining the accuracy or legitimacy of a model thus translates into asking, "how can one be certain that the model developed is an accurate representation of reality?" This is not an easy question to answer, and can easily lead to a philosophical argument about the very purpose or futility of modeling a system. The matter is particularly difficult when dealing with qualitative representations of a system such as the crew performance model developed. In the case of quantitative models, it may be possible to simulate the model on a computer and contrast the results of the simulation with actual observations of the system. If the results agree, the model is considered valid. It is possible to attempt to validate a qualitative model by way of simulations too, but this would involve the development of another model of the model, so as to be possible to simulate on a computer. Because of the scope of this research, I did not pursue the validation of the crew performance model by any such technique(s).

Another way of determining the accuracy or legitimacy of the model is, as noted above, through feedback from key informants. Since a model is essentially an individual's view of reality, the question of accuracy boils down to one of determining if that view of reality is shared among others in a population. Evidently, this is a debatable method and has obvious drawbacks. Firstly, it is important to ensure that the reviewers belong to the end-user population from whose viewpoint the model was developed. Secondly, individuals vary in their perception of reality; consequently, their representations of the world may not be similar. Despite these inherent drawbacks, the accuracy of the crew performance model was validated by having it reviewed by an expert, Kathy Mosier, Senior Research Scientist at NASA-Ames Research Center. In evaluating the model from the perspective of an aviation researcher, Mosier concludes that, "...it seems to reflect all of the facets of excellent crew performance in a logical, coherent form..." (K. Mosier, personal communication, August 3, 1994). The model was also sent to Beth Lyall of America West Airlines for evaluation. In evaluating the model from an operational perspective, Lyall comments, "I don't have any problems with the model as it is presented. I think the real test of its viability is going to be its utility in assessing situations for an evaluation of CRM effectiveness" (B. Lyall, personal communication, August 10, 1994).

By providing a useful and coherent framework for understanding performance, I believe that the Crew Performance model developed is a significant step towards better understanding crew coordination. Hopefully, this model can be refined and in some way be more useful towards establishing measures of performance, leading to the establishment of CRM standards. This concludes the discussions. In Chapter 8, a summary of the research is provided, conclusions are drawn, and recommendations for further research are made.

8. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8.1 Summary

When the airline industry realized that most errors made by airline crews could be traced to breakdowns in communication and coordination, a concept called Crew Resource Management soon evolved. CRM implies a paradigm shift from a focus on the individual pilot to the crew as a team that flies the airplane. CRM has been conceptually accepted by most of the airline industry, although the issue of evaluation remains unsolved. An evaluation of performance implies a means to measure it. Before CRM training can be made mandatory, it becomes necessary to arrive at objective criteria by which crew coordination behavior can be measured. Once objective performance measures are arrived at, standards of performance can be established.

Presently, one of the primary objectives of the airline industry is to come up with objective measures of crew performance, particularly the crew coordination aspects of performance. This research was based on the premise that objective criteria of measuring crew coordination aspects of crew performance cannot be reached unless there exists a clear understanding of the issues surrounding crew coordination. Crew coordination is one aspect of crew performance. This research proceeded with the conviction that a good understanding of crew coordination or CRM could only be achieved through a good understanding of crew performance. In other words, it is infeasible to think of determining performance measures to evaluate CRM related behavior without thoroughly understanding the broad context of performance in which CRM is observed.

The primary goal of this research was to provide a better understanding of crew coordination or CRM by providing a framework to better understand crew performance. It was believed that the application of systems engineering to crew performance would result in its better understanding.

Chapter 4 discussed the theory underlying crew performance. Concepts underlying crew performance such as (a) mental models, (b) situation awareness, (c) individual factors, and (d) groups and teams were analyzed in detail. A broad perspective was ensured by drawing upon various sources of research literature.

In Chapter 5, key concepts of systems engineering were discussed. This chapter also included an overview of the SADT/IDEF0 methodology adopted for the systematic analysis of crew performance. The result of this analysis was the formal IDEF0 model of crew performance. Essentially, this model is a framework which is the result of a functional analysis of crew performance. The development of the model resulted in a concrete definition of the issues surrounding the concept of CRM.

The IDEF0 model is the result of an analysis of normative crew performance. To the extent that the model adequately describes the process of crew performance, it has served its purpose. The application of the model to analyze two accidents, examples of good and bad CRM, served to further demonstrate the utility of the model in serving as a descriptor of crew processes. This was discussed in Chapter 6.

Chapter 7 discussed the strengths and weaknesses of various aspects of the research.

8.2 Conclusions

A conclusion of this research is that it is possible to systematically analyze crew performance through the application of systems engineering. Through such an application, valuable insight into the process of crew coordination is gained. The model of crew performance developed bears testimony to this conclusion. The research concludes that although the application of systems theory to the domain of crew performance may pose some conceptual problems, it is possible to overcome these through the refinement of the methodology as well as through further research aimed at better understanding the cognitive and interpersonal aspects of human behavior.

8.3 Recommendations

Previously, in the discussion on Model Utility and Validity, some of the limitations of the model were discussed. Although the model is a descriptor of crew processes, and grounded in contemporary theory of aviation psychology, the model as it exists may be limited in its applicability to the operational domain. Although this is understandable, given the aviation researcher's viewpoint, a recommendation would be that the model be refined so as to be directly useful as an instructional system tool. The most obvious way of ensuring this would be to incorporate an operational viewpoint along with the current researcher's viewpoint. Further, it was acknowledged that the limited applicability may be a result of the limited perspective adopted at the knowledge acquisition stage. A recommendation would thus be to ensure knowledge acquisition from the operational community as well. To ensure this, a desirable pre-requisite would be the establishment of appropriate contacts in the aviation community.

With regard to model validation, it was noted that there have been attempts made to validate qualitative models by modifying them so as to be able to simulate them on a computer. Mosier informs me that such an approach is currently underway at NASA-Ames. It would indeed be prudent to explore this avenue in the future.

With regard to the SADT/IDEF0 methodology, it was noted that IDEF0 lacks formalization on certain important issues. This was partially responsible for some of the conceptual problems encountered. Further research into formalization of SADT concepts would be an obvious recommendation. Given the possibility that the IDEF0 modeling lacks rigor required for the modeling of complex human behavior, it was acknowledged that perhaps its not the best methodology to have adopted for such modeling. A recommendation would be the exploration of other systems methodologies that would enable a rigorous, systematic treatment of the issues involved in crew coordination.

Almost all of the concepts studied in Chapter 4 remain poorly defined. Clearly, there is a need for more research into those concepts. However, if the industry aims to develop objective measures of performance, it should focus more on developing theories of human performance which can be empirically verified. The research community has to gear its efforts to go beyond the development of theoretical measures of performance to more practical, operational measures.

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APPENDICES

APPENDIX I

Eastern Airlines Transcript (NTSB-AAR-73-14)

Flight: Eastern Airlines flight 401
Lockheed L-1011 (3-engined Tristar)

From: JFK to Miami International Airport, Florida.

Date: December 29, 1972

Crash: Crashed at 2342 hrs (11.42pm) in the Everglades.

Pax: 94/163 passengers and 5/13 crewmembers fatally injured.

Complete transcript (Appendix D)

CAM- Cockpit Area Microphone voice or sound source

RDO- Radio transmission from

1- Captain
2- F/O
3- S/O
4- Observer seat occupant

MIA AAPR - Miami approach control

MIA TWR - Miami control tower
****

2332:19 MIA APP
Eastern Four-oh-one, left heading one zero three from the marker cleared to *** nine left approach, tower one one eight point three, good morning.

2332:26 RDO-1
One one eight point three, eastern four oh one, so long.

2332:35 CAM
Sound of warning horn (sound similar to 180-knot gear warning horn approximately one second duration.)

2332:39 RDO-1
Miami Tower Eastern four oh one just turned on final

2332:45 MIA TWR
Who else called ?

2332:48 CAM-1
Go ahead and throw'em out

2332:52	RDO-1	Miami Tower, do you read eastern four oh one ? Just turned on final.
2332:56	MIA TWR	Eastern four oh one heavy, continue approach to one nine left.
2333:00	RDO-1	Continue approach, roger
2333:00.5	CAM-3	Continuous ignition
	CAM-3	**smoke
	CAM-1	Coming on
	CAM-3	Brake system
	CAM-1	Okay
	CAM-3	Radar
	CAM-1	Up off
	CAM	*Sound of click*
	CAM-3	Hydraulic panels checked
	CAM-2	Thirty-five thirty three
	CAM-1	(immediatetly after 'thirty-three') Bert, is that handle in?
	CAM	****
	CAM-3	Engine crossfields are open
2333:22	CAM-?	Gear down
	CAM-?	***
	CAM-1	I gotta.
	CAM-2	No nose gear.
2333:25	CAM-1	I gotta raise it back up
2333:26	CAM	Sound of flap position warning horn begins
	CAM-1	**** it.
2333:47	CAM-1	Now I'm gonna try it down one more time.
	CAM-2	All right
2333:58.5	CAM	Sound of altitude alert horn.
2333:59.5	CAM	Sound of flap position warning horn ceases.
	CAM-2	(Right) gear.
	CAM-2	Well, want to tell'em we'll take it around and circle around and around ?
2334:05	RDO-1	Well, ah, tower this is eastern, ah, four zero one, it looks like we're gonna have to circle, we don't have a light on our nose gear yet.
2334:14	MIA TWR	Eastern four oh one heavy, roger, pull up, climb straight ahead to two thousand. Go back to approach control, one twenty eight six.

2334:10	CAM-2	Twenty-two degrees
	CAM-2	Twenty-two degrees, gear up
	CAM-1	Put power on it first Bert thata boy.
	CAM-1	Leave the *** gear down til we found out what we got.
	CAM-2	All right.
	CAM-3	You want me to test the lights or not?
	CAM-1	Yeah.
	CAM-?	**** Seat back
	CAM-1	Check it.
	CAM-2	Uh Bob, it might be the light, could you jiggle tha, the light?
	CAM-2	(or CAM-3) It's gotta, gotta come out a little bit and then snap in.
	CAM-2	I'll put'em on
2334:21	RDO-1	Okay doing up two thousand, one twenty eight six
2334:58	CAM-2	We're up two thousand...
	CAM-2	You want me to fly it Bob ?
	CAM-1	What frequency did he want us on Bert ?
	CAM-2	One twenty eight six
	CAM-1	I'll talk to 'em.
	CAM-3	Its right above that, ah, red one, is it not?
	CAM-1	Yeah, oh, I can't get it from here
	CAM-3	I can't make it pull out either
	CAM-1	We got pressure?
	CAM-3	Yes sir, all systems
	CAM-1	***
2335:09	RDO-1	All right, ah approach control, eastern four zero one , we're right above the airport here and climbing to two thousand feet, in fact, we've just reached two thousand feet and we've got to get a green light on our nose gear.
2335:20	MIA APPR	Eastern four oh one, roger, turn left heading three six zero. Maintain two thousand, vectors to nine left final.
2335:28	RDO-1	Left three six zero

****

2336:04	CAM-1	Put the **** on autopilot here.
	CAM-2	All right
	CAM-1	See if you can get that light out
	CAM-2	All right
	CAM-1	Now push the switches just a *** forward.
	CAM-?	***
	CAM-1	You gotta turn it one quarter turn to the left
2336:27	MIA APPR	Eastern four oh one, turn left heading three zero zero.
	RDO-1	Okay.
2336:37	RDO-1	Three zero zero eastern four oh one.

2337:08	CAM-1	Hey hey get down there and see if that *** nose wheel's down.
	CAM-1	You better do that.
	CAM-2	You got a handkerchief or something so I can get a little better grip on this. anything I can do with.
	CAM-3	Then pull down and turn to your right. Now turn to your left one time.
	CAM-2	It hangs out and sticks.
	CAM-1	*** get down there and see if that, if that thing...
	CAM-?	Try my way
	CAM-1	What ?
	CAM-?	Try my way
	CAM-1	Okay
	CAM-2	This won't come out Bob
	CAM-2	If I had a pair of pliers, I could cushion it with that kleenex.
	CAM-3	I can give you pliers but if you force it, you'll break it, just believe me.
	CAM-2	Yeah, I'll cushion it with the kleenex.
	CAM-3	Oh we can give you pliers.
2337:48	MIA APPR	Eastern, uh, four oh one, turn left heading two seven zero.
2337:53	RDO-1	Left two seven zero, roger. *[selection of the new heading would have required action by the first officer]*
2338:34	CAM	To *** with it, to *** with this, go down and see if its lined up with that red line. Thats all we care. *** around with that *** twenty cent piece of light equipment we got on this ***.
	CAM	Ha ha ha
2338:46	RDO-1	Eastern four oh one'll go ah, out west just a little bit further if we can here and ah see if we can get this light to come on here.
2338:54	MIA APPR	All right, uh we got you headed westbound there now eastern four oh one.
2338:56	RDO-1	All right.
	CAM-1	How much fuel we got on this ***
	CAM-2	Fifty two five
	CAM-2	It won't come out no way.
2339:37	CAM-1	Did you ever take it out of there?
	CAM-2	Huh?
	CAM-1	Have you ever took it out of there?
	CAM-2	Hadn't till now.
	CAM-1	Put it in the wrong way huh?
	CAM-?	In there looks square to me
	CAM-4	Can't you get the hole lined up?

	CAM-?	* * *
	CAM-?	Whatever's wrong?
	CAM-1	What is that?
2340:05	CAM-2	I think thats over the training field
	CAM-?	West heading. You wanna go left or * ?
	CAM-2	Naw thats right, we're about to cross Krome Avenue right now.
2340:17	CAM	Sound of click
	CAM-2	I don't know what the * holding that *** in.
	CAM-2	Always something, we coulda make schedule.
2340:38	CAM	**Sound of altitude alert** (0.5 second C-chord to indicate deviation of +/- 25o feet)
	CAM-1	We can tell if that *** is down by looking down at our indices
	CAM-1	I'm sure its down, there's no way it couldn't help but be.
	CAM-2	I'm sure it is.
	CAM-1	It free falls down.
	CAM-2	The tests didn't show that the lights worked anyway.
	CAM-1	Thats right.
	CAM-2	Its a faulty light.
2341:05	CAM-2	Boy, this *** just wont come out.
	CAM-1	All right, leave it there.
	CAM-3	I don't see it down there.
	CAM-1	Huh?
	CAM-3	I don't see it.
	CAM-1	You cant see that indi**** for the nose wheel ah, there's a place in there you can look and see if they're lined up.
	CAM-3	I know, a little like a telescope.
	CAM-1	Yeah.
	CAM-3	Well...
	CAM-1	It's not lined up?
	CAM-3	I can't see it. It's pitch dark and I throw the little light I get, ah, nothing.
2341:31	CAM-4	Wheel light's on?
	CAM-3	Pardon?
	CAM-4	Wheel light's on?
	CAM-3	Yeah wheel lights always on if the gears down.
	CAM-1	Now try it.
2341:40	MIA APPR	Eastern ah four oh one how are things comin' along out there (begins simultaneously with "now" above)
2341:44	RDO-1	Okay, we'd like to turn around and come, come back in.
	CAM-1	Clear on left.
	CAM-2	Okay

2341:47	MIA APPR	Eastern four oh one turn left heading one eight zero.
2341:50	CAM-1	Huh?
2341:51	RDO-1	One eighty
2342:05	CAM-2	We did something to the altitude
2342:06	CAM-1	What?
2342:07	CAM-2	We're still at two thousand right?
2342:09	CAM-1	Hey, what's happening here?
	CAM	(Sound of click simultaneous with "what's")
2342:10	CAM	Sound of six beeps similar to radio altimeter (increasing in rate)
2342:12	CAM	Sound of initial impact.

APPENDIX II

USED AT:

AUTHOR: Cherag Sukhia

PROJECT: Crew Performance

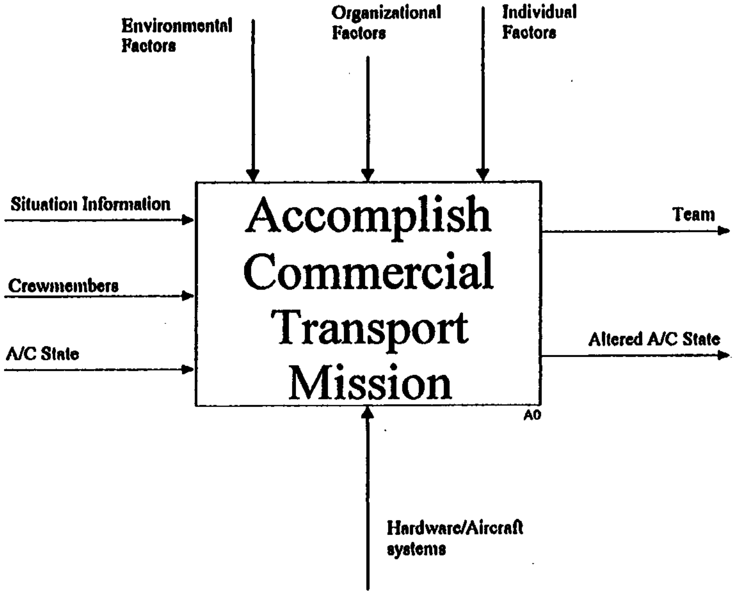
NOTES: 1 2 3 4 5 6 7 8 9 10

DATE: 06/12/94

REV: 11/10/94

X	WORKING	READER	DATE
	DRAFT		
	RECOMMENDED		
	PUBLICATION		

CONTEXT: NONE


Environmental Factors
Organizational Factors
Individual Factors
Situation Information
Crewmembers
A/C State
Accomplish Commercial Transport Mission
A0
Team
Altered A/C State
Hardware/Aircraft systems

Purpose: To describe crew performance with an emphasis on crew coordination or CRM related activities

Viewpoint: Aviation human factors researcher

NODE: CRM/A-0

TITLE: Accomplish Commercial Transport Mission

NUMBER:

Figure 12. Model of Crew Performance

USED AT:	AUTHOR: Cherag Sukhia	DATE: 06/12/94	X	WORKING	READER DATE	CONTEXT:
	PROJECT: Crew Performance	REV: 11/10/94		DRAFT		NONE
	NOTES: 1 2 3 4 5 6 7 8 9 10			RECOMMENDED		
				PUBLICATION		

A/C State
Refers to the current, actual state of the aircraft. Examples include aircraft position, altitude, airspeed, fuel level, and position of flaps.

Accomplish Commercial Transport Mission
This function transforms the inputs Situation Information, Crewmembers, and Aircraft (A/C) state into the outputs Team, and Altered A/C State subject to the constraints Environmental Factors, Organizational Factors, and Individual Factors with the help of the mechanism Hardware/Aircraft Systems.

Altered A/C State
(See Aircraft State)
Accomplishing the commercial transport mission results in transforming the values of the parameters (e.g., altitude, fuel level, flap position), resulting in the output Altered Aircraft State.

Crewmembers
Refers to cockpit crewmembers which typically ranges from two to three: Captain, First Officer (F/O), and Second Officer (S/O).

Environmental Factors
These include temperature, humidity, pressure, wind direction and velocity, visibility, runway conditions, and other meteorological conditions liable to affect or constrain the accomplishment of the overall missio.

Hardware/Aircraft systems
The entire aircraft, incorporating all its subsystems, aid the accomplishment of the commercial transport mission and are hence "mechanisms".

Individual Factors
These refer to those characteristics of the individual crewmembers that potentially constrain the function of accomplishing the mission. These include individual knowledge, skills, attitudes, fatigue, and personality.

Organizational Factors
These refer to all factors related to the organization that can affect crew performance such as company policies, rules and regulations, and special requirements. These are also considered to include the designated flight plan for a particular mission, local operating procedures, federal aviation regulations (FAR's), and advisory circular.

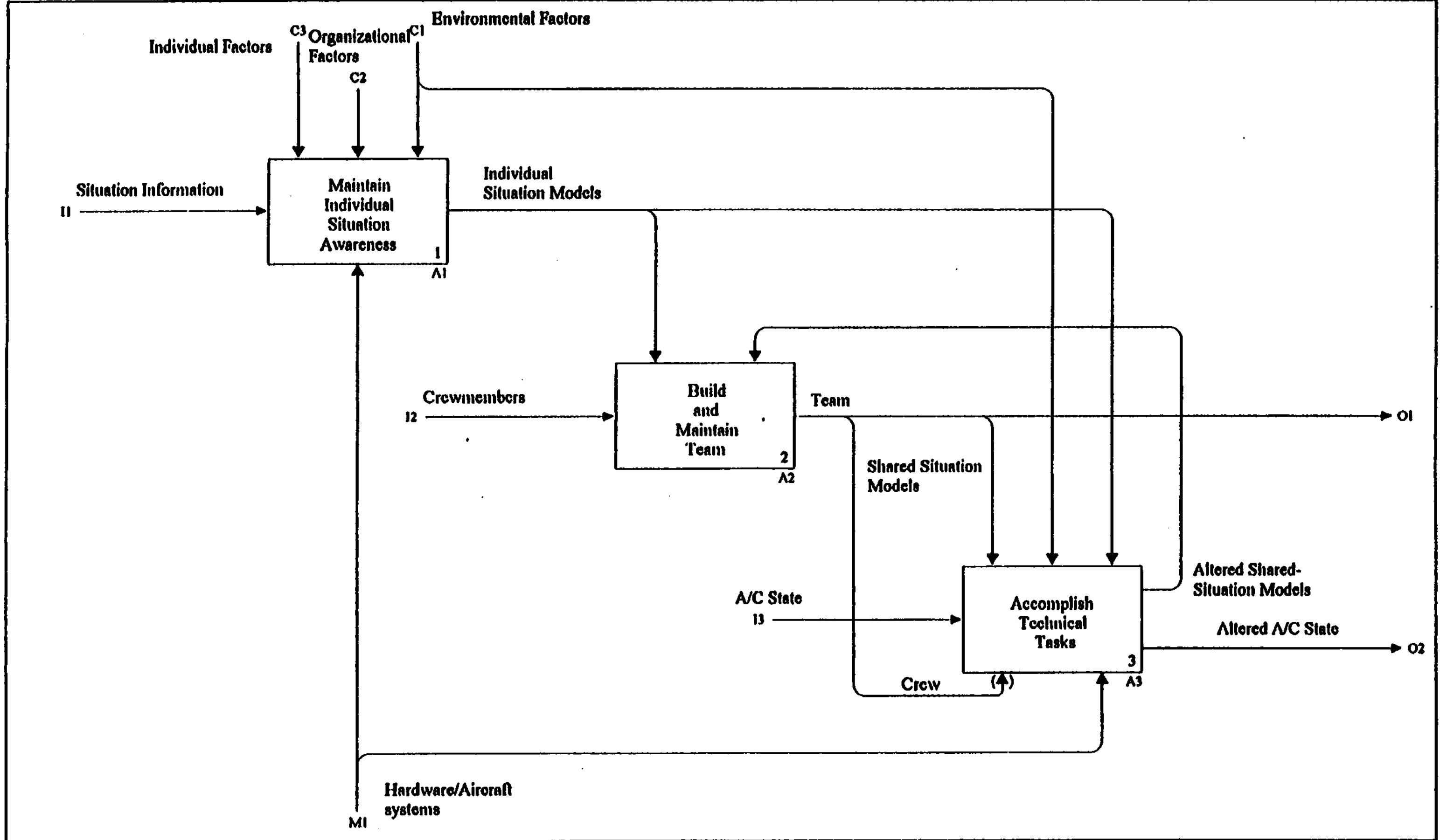
Situation Information
This refers to all information about the situation that is potentially available for the accomplishment of the mission. Includes information about the environment, information about the aircraft, and information about crewmembers.

Team
Team is the output of the function Accomplish Commercial Transport Mission. It represents the transformation of (individual) Crewmembers into an emergent whole (see definition at node CRM/A0 level).

NODE: CRM/A-0G1	TITLE: Accomplish Commercial Transport Mission	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia	DATE: 06/12/94	X	WORKING	READER DATE	CONTEXT:
	PROJECT: Crew Performance	REV: 11/12/94		DRAFT		TOP
	NOTES: 1 2 3 4 5 6 7 8 9 10			RECOMMENDED		
				PUBLICATION		



Individual Factors
C3
Organizational Factors
C2
C1
Environmental Factors
Situation Information
I1
Maintain Individual Situation Awareness
1
A1
Individual Situation Models
Crewmembers
I2
Build and Maintain Team
2
A2
Team
O1
Shared Situation Models
A/C State
I3
Accomplish Technical Tasks
3
A3
Altered Shared-Situation Models
Altered A/C State
O2
Crew
(A)
Hardware/Aircraft systems
M1

NODE: CRM/A0	TITLE: Accomplish Commercial Transport Mission	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR:	Cherag Sukhia	DATE:	06/12/94	X	WORKING	READER	DATE	CONTEXT:
	PROJECT:	Crew Performance	REV:	11/12/94		DRAFT			TOP
	NOTES:	1 2 3 4 5 6 7 8 9 10				RECOMMENDED			
						PUBLICATION			

A/C State

Refers to the current, actual state of the aircraft. Examples include aircraft position, altitude, airspeed, fuel level, and position of flaps.

Accomplish Technical Tasks

This function transforms A/C state into Altered A/C state and Altered Shared Situation Models subject to Shared Situation Models, Environmental Factors, and Individual Situation Models with the help of the mechanisms Crew and Hardware/Aircraft Systems.

Altered A/C State

(See Aircraft State)

Accomplishing the commercial transport mission results in transforming the values of the parameters (e.g., altitude, fuel level, flap position), resulting in the output Altered Aircraft State.

Altered SharedSituation Models

(Also see Shared Situation Models)

Communication between Crewmembers as a part of the function Accomplish Technical Tasks, results in an altering of the (existing) Shared Situation Models, resulting in Altered Shared Situation Models.

Build and Maintain Team

This function transforms the input Crewmembers into the output Team, subject to the constraint Individual Situation Models and Altered Shared Situation Models.

Crew

Crew represents the members of the group working together as a team. It is shown as a tunneled mechanism merely to highlight the significance of the fact that ultimately, it is the Crew that performs the function Accomplish Technical Tasks.

Crewmembers

Refers to cockpit crewmembers which typically ranges from two to three: Captain, First Officer (F/O), and Second Officer (S/O).

Environmental Factors

These include temperature, humidity, pressure, wind direction and velocity, visibility, runway conditions, and other meteorological conditions liable to affect or constrain the accomplishment of the overall missio.

Hardware/Aircraft systems

The aircraft, along with all its subsystems, aid the accomplishment of the commercial transport mission and are hence "mechanisms".

Individual Factors

These refer to those characteristics of the individual crewmembers that potentially constrain the function of accomplishing the mission. These include individual knowledge, skills, attitudes, fatigue, and personality.

Individual Situation Models

Individual Situation Models are 'Mental Models' of the Situation held by individual crewmembers.

Wilson & Rutherford (1989) define a mental model as "...a representation formed by a user of a system and/or task, based on previous experiences as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance" (p. 619).

Maintain Individual Situation Awareness

This function transforms Situation Information into Individual Situation Models subject to the constraints Individual Factors, Organizational Factors, and Environmental Factors with the help of the mechanism Hardware/Aircraft Systems.

NODE: CRM/A0G1	TITLE: Accomplish Commercial Transport Mission	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR:	Cherag Sukhia	DATE: 06/12/94	X	WORKING	READER	DATE	CONTEXT:
	PROJECT:	Crew Performance	REV: 11/12/94		DRAFT			TOP
	NOTES:	1 2 3 4 5 6 7 8 9 10			RECOMMENDED			
					PUBLICATION			

Organizational Factors

These refer to all factors related to the organization that can affect crew performance such as company policies, rules and regulations, and special requirements. These are also considered to include the designated flight plan for a particular mission, local operating procedures, federal aviation regulations (FAR's), and advisory circulars.

Shared Situation Models

(Also see Individual Situation Models)

These are formed through specialized communication; a result of explicit sharing of information or patterns of communication. They refer to the current or existing shared situation models, versus the Altered Shared Situation Models.

Situation Information

This refers to all information about the situation that is potentially available for the accomplishment of the mission. Includes information about the environment, information about the aircraft, and information about crewmembers.

Team

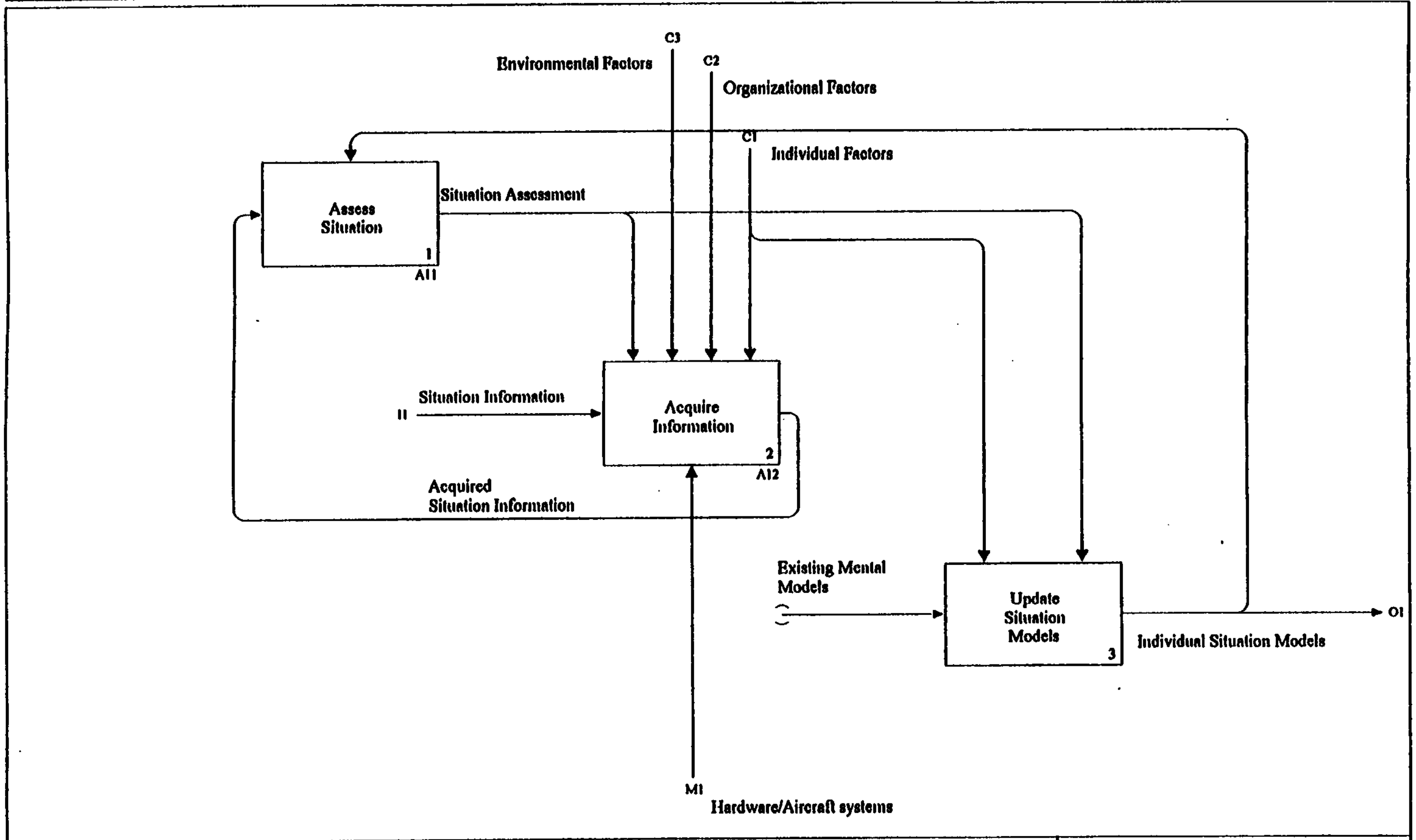
Team is the output of the function Build and Maintain Team. It represents the transformation of (individual) Crewmembers into an emergent whole.

It is defined by this function as: A crew with shared task model, a shared team-interaction model, and a shared team-personal model.

NODE: CRM/A0G2	TITLE: Accomplish Commercial Transport Mission	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia	DATE: 06/12/94	X	WORKING	READER DATE	CONTEXT:
	PROJECT: Crew Performance	REV: 11/10/94		DRAFT		
	NOTES: 1 2 3 4 5 6 7 8 9 10			RECOMMENDED		
				PUBLICATION		


C3
Environmental Factors
C2
Organizational Factors
C1
Individual Factors
Assess Situation
1
A11
Situation Assessment
Situation Information
I1
Acquire Information
2
A12
Acquired Situation Information
Existing Mental Models
Update Situation Models
3
Individual Situation Models
O1
M1
Hardware/Aircraft systems

NODE: CRM/A1	TITLE: Maintain Individual Situation Awareness	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia PROJECT: Crew Performance NOTES: 1 2 3 4 5 6 7 8 9 10	DATE: 06/12/94 REV: 11/10/94	X	WORKING	READER	DATE	CONTEXT:
				DRAFT			
				RECOMMENDED			
				PUBLICATION			

Acquire Information

This function transforms the Situation Information into Acquired Situation Information subject to Situation Assessment, Environmental Factors, Organizational Factors, and Individual Factors with the mechanism Hardware/Aircraft Systems.

Acquired Situation Information

(Also see Situation Information)

Acquired Situation Information refers to the information that is "actually" available to the pilot as compared to the information "potentially" available (situation information).

Only when the agent becomes "aware" of the information does "potentially" available information become "actually" available to the pilot (Smith & Hancock, 1993).

Assess Situation

This function transforms Acquired Situation Information into Situation Assessment subject to Individual Situation Models.

Environmental Factors

These include temperature, humidity, pressure, wind direction and velocity, visibility, runway conditions, and other meteorological conditions liable to affect or constrain the accomplishment of the overall missio.

Existing Mental Models

(see Individual Situation Models)

Hardware/Aircraft systems

The aircraft, along with all its subsystems, aid the accomplishment of the commercial transport mission and are hence "mechanisms".

Individual Factors

These refer to those characteristics of the individual crewmembers that potentially constrain the function of accomplishing the mission. These include individual knowledge, skills, attitudes, fatigue, and personality.

Individual Situation Models

Individual Situation Models are 'Mental Models' of the Situation held by individual crewmembers.

Wilson & Rutherford (1989) define a mental model as "...a representation formed by a user of a system and/or task, based on previous experiences as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance" (p. 619).

Organizational Factors

These refer to all factors related to the organization that can affect crew performance such as company policies, rules and regulations, and special requirements. These are also considered to include the designated flight plan for a particular mission, local operating procedures, federal aviation regulations (FAR's), and advisory circulars.

Situation Assessment

This is the output of the function Assess Situation. Situation Assessment leads to Situation Awareness.

Sarter and Woods (1991) define Situation Assessment as "a complex process of perception and pattern matching greatly limited by working-memory and attentional capacity" (p.50).

NODE: CRM/A1G1	TITLE: Maintain Individual Situation Awareness	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia	DATE: 06/12/94	X	WORKING	READER	DATE	CONTEXT: ■ □ □
	PROJECT: Crew Performance	REV: 11/10/94		DRAFT			
	NOTES: 1 2 3 4 5 6 7 8 9 10			RECOMMENDED			
				PUBLICATION			

Situation Information

This refers to all information about the situation that is potentially available for the accomplishment of the mission. Includes information about the environment, information about the aircraft, and information about crewmembers.

Update Situation Models

This function transforms the (tunneled) input Existing Situation Models into Individual Situation Models subject to Situation Assessment and Individual Factors. The process of updating a situation model is an unconscious one, which is interpreted as being the internally-directed facet of situation awareness (Smith & Hancock, 1993).

NODE: CRM/A1G2	TITLE: Maintain Individual Situation Awareness	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR:	Cherag Sukhia	DATE: 06/13/94	X	WORKING	READER DATE	CONTEXT:
	PROJECT:	Crew Performance	REV: 11/12/94		DRAFT		
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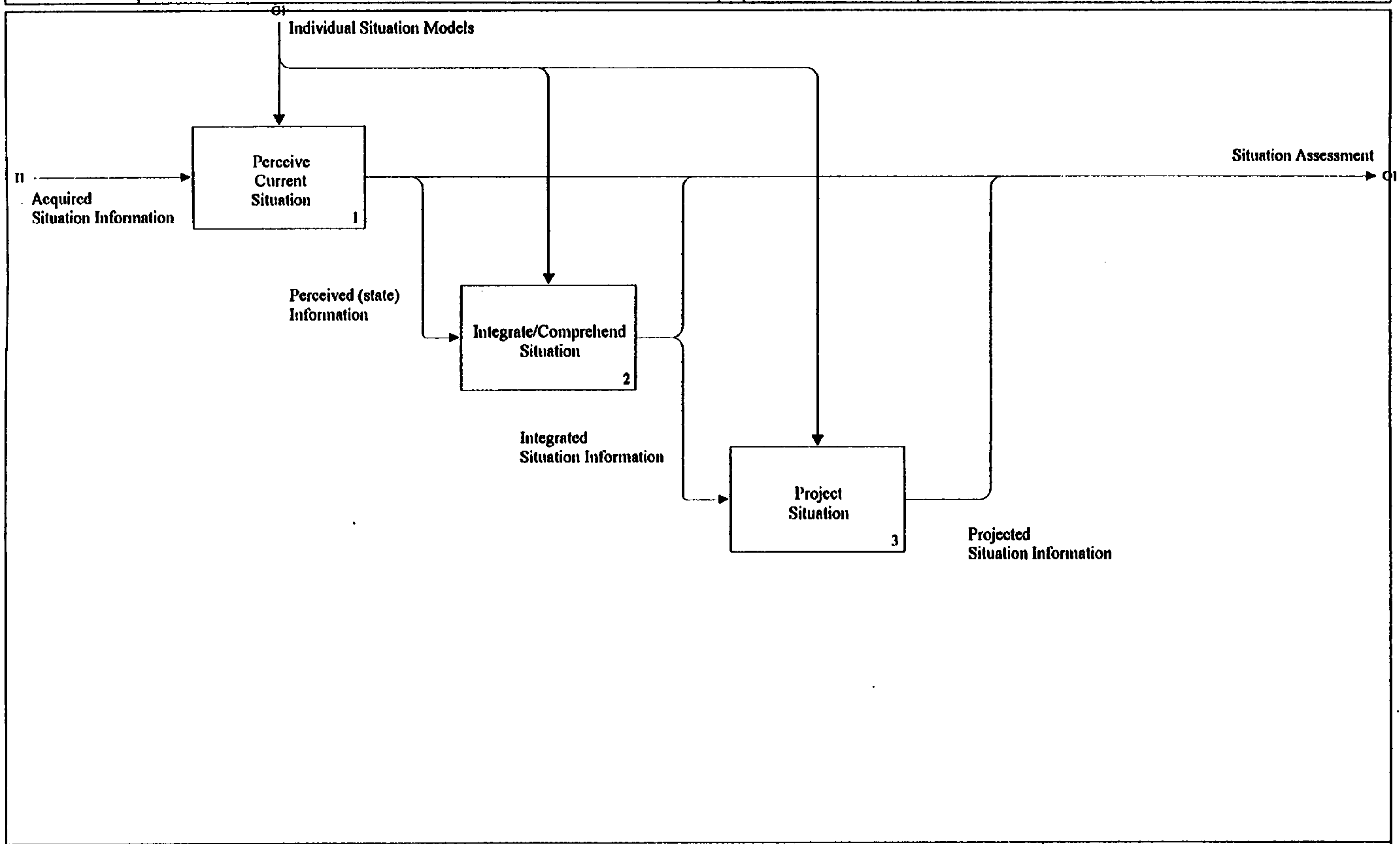
	NOTES:	1 2 3 4 5 6 7 8 9 10			PUBLICATION		


O1
Individual Situation Models
I1
Acquired
Situation Information
Perceive
Current
Situation
1
Situation Assessment
O1
Perceived (state)
Information
Integrate/Comprehend
Situation
2
Integrated
Situation Information
Project
Situation
3
Projected
Situation Information

NODE: CRM/A11	TITLE: Assess Situation	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia PROJECT: Crew Performance NOTES: 1 2 3 4 5 6 7 8 9 10	DATE: 06/13/94 REV: 11/12/94	☒ WORKING ☐ DRAFT ☐ RECOMMENDED ☐ PUBLICATION	READER DATE	CONTEXT: ■ ☐ ☐

Acquired Situation Information

(Also see Situation Information)

Acquired Situation Information refers to the information that is "actually" available to the pilot as compared to the information "potentially" available (situation information).

Only when the agent becomes "aware" of the information does "potentially" available information become "actually" available to the pilot (Smith & Hancock, 1993).

Individual Situation Models

Individual Situation Models are 'Mental Models' of the Situation held by individual crewmembers.

Wilson & Rutherford (1989) define a mental model as "...a representation formed by a user of a system and/or task, based on previous experiences as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance" (p. 619).

Integrate/Comprehend Situation

This function transforms Perceived Information into Integrated Situation Information subject to Individual Situation Models.

Integrated Situation Information

This represents the current understanding of the situation. After information is perceived, it is integrated with pre-existing information and the individual actually makes sense of the information or comprehends it.

Perceive Current Situation

This function transforms Acquired Situation Information into Perceived Information subject to Individual Situation Models.

Perceived (state) Information

Acquired Situation Information is perceived by the individual and results in Perceived (state) Information. This is part of the process of assessing the situation.

Project Situation

This function transforms Integrated Situation Information into Projected Situation Information constrained by Individual Situation Models.

Projected Situation Information

No Glossary Text Provided.

Situation Assessment

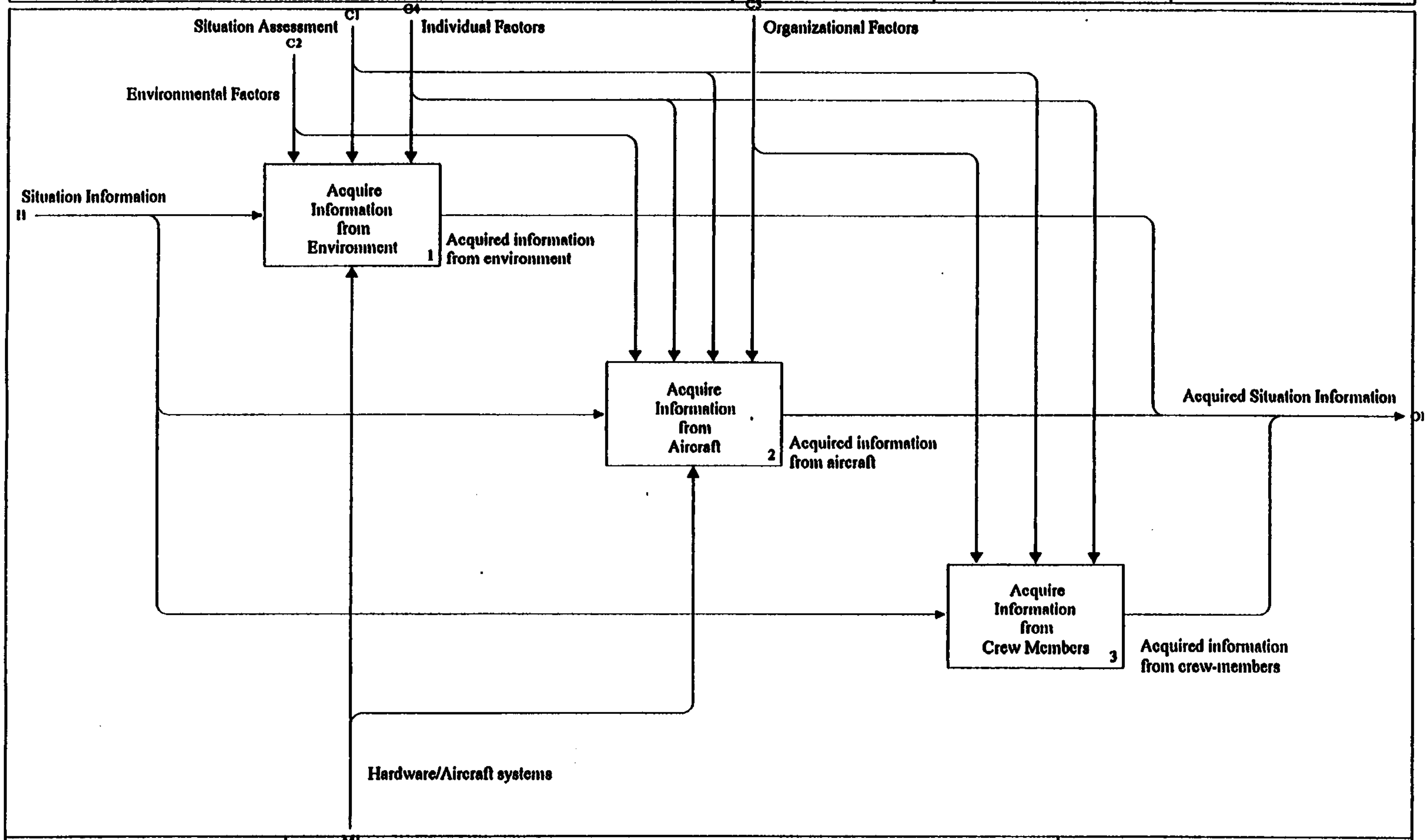
This is the output of the function Assess Situation. Situation Assessment leads to Situation Awareness.

Sarter and Woods (1991) define Situation Assessment as "a complex process of perception and pattern matching greatly limited by working-memory and attentional capacity" (p.50).

NODE: CRM/A11G1	TITLE: Assess Situation	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia	DATE: 06/13/94	X	WORKING	READER	DATE	CONTEXT:
	PROJECT: Crew Performance	REV: 11/10/94		DRAFT			
	NOTES: 1 2 3 4 5 6 7 8 9 10			RECOMMENDED			
				PUBLICATION			



C1
C4
C3
Situation Assessment
C2
Individual Factors
Organizational Factors
Environmental Factors
Situation Information
I1
Acquire Information from Environment
1
Acquired information from environment
Acquire Information from Aircraft
2
Acquired information from aircraft
Acquired Situation Information
O1
Acquire Information from Crew Members
3
Acquired information from crew-members
Hardware/Aircraft systems
M1

NODE: CRM/A12	TITLE: Acquire Information	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia PROJECT: Crew Performance NOTES: 1 2 3 4 5 6 7 8 9 10	DATE: 06/13/94 REV: 11/10/94	☒ WORKING ☐ DRAFT ☐ RECOMMENDED ☐ PUBLICATION	READER DATE	CONTEXT:

Acquire Information from Aircraft
This function transforms Situation Information into Acquired Information from Aircraft subject to Environmental Factors, Situation Assessment, Individual Factors, and Organizational Factors with the help of the mechanism Hardware/Aircraft Subsystems.

Acquire Information from Crew Members
This function transforms Situation Information into Acquired Information from Crewmembers subject to Situation Assessment, Individual Factors, and Organizational Factors.

Acquire Information from Environment
This function transforms Situation Information into Acquired Information from Environment subject to Situation Assessment, Individual Factors, and Environmental Factors with the mechanism Hardware/Aircraft Subsystems.

Acquired information from aircraft
This includes information about the environment that may be acquired through the aircraft, information about the aircraft and its subsystems, as well as information received by the crew over the radio (ATC communications) or via data link.

Acquired information from crew-members
This refers to information about the situation acquired from crew-members, simply by observing the other's actions.

Acquired information from environment
Acquired Information from environment refers broadly to three three types of information that is actively acquired a) spatial or navigational information (i.e., knowledge of the aircraft's location in space), b) information about traffic, and c) information about weather conditions.

Acquired Situation Information
(Also see Situation Information)
Acquired Situation Information refers to the information that is "actually" available to the pilot as compared to the information "potentially" available (situation information).
Only when the agent becomes "aware" of the information does "potentially" available information become "actually" available to the pilot (Smith & Hancock, 1993).

Environmental Factors
These include temperature, humidity, pressure, wind direction and velocity, visibility, runway conditions, and other meteorological conditions liable to affect or constrain the accomplishment of the overall missio.

Hardware/Aircraft systems
The aircraft, along with all its subsystems, aid the accomplishment of the commercial transport mission and are hence "mechanisms".

Individual Factors
These refer to those characteristics of the individual crewmembers that potentially constrain the function of accomplishing the mission. These include individual knowledge, skills, attitudes, fatigue, and personality.

Organizational Factors
These refer to all factors related to the organization that can affect crew performance such as company policies, rules and regulations, and special requirements. These are also considered to include the designated flight plan for a particular mission, local operating procedures, federal aviation regulations (FAR's), and advisory circulars.

NODE: CRM/A12G1	TITLE: Acquire Information	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR:	Cherng Sukhia	DATE:	06/13/94	X	WORKING	READER	DATE	CONTEXT: ☐ ■ ☐
	PROJECT:	Crew Performance	REV:	11/10/94		DRAFT			
	NOTES:	1 2 3 4 5 6 7 8 9 10				RECOMMENDED			
						PUBLICATION			

Situation Assessment

This is the output of the function Assess Situation. Situation Assessment leads to Situation Awareness.

Sarter and Woods (1991) define Situation Assessment as "a complex process of perception and pattern matching greatly limited by working-memory and attentional capacity" (p.50).

Situation Information

This refers to all information about the situation that is potentially available for the accomplishment of the mission. Includes information about the environment, information about the aircraft, and information about crewmembers.

NODE: CRM/A12G2	TITLE: Acquire Information	NUMBER:

Figure 12. (Continued)

USED AT:

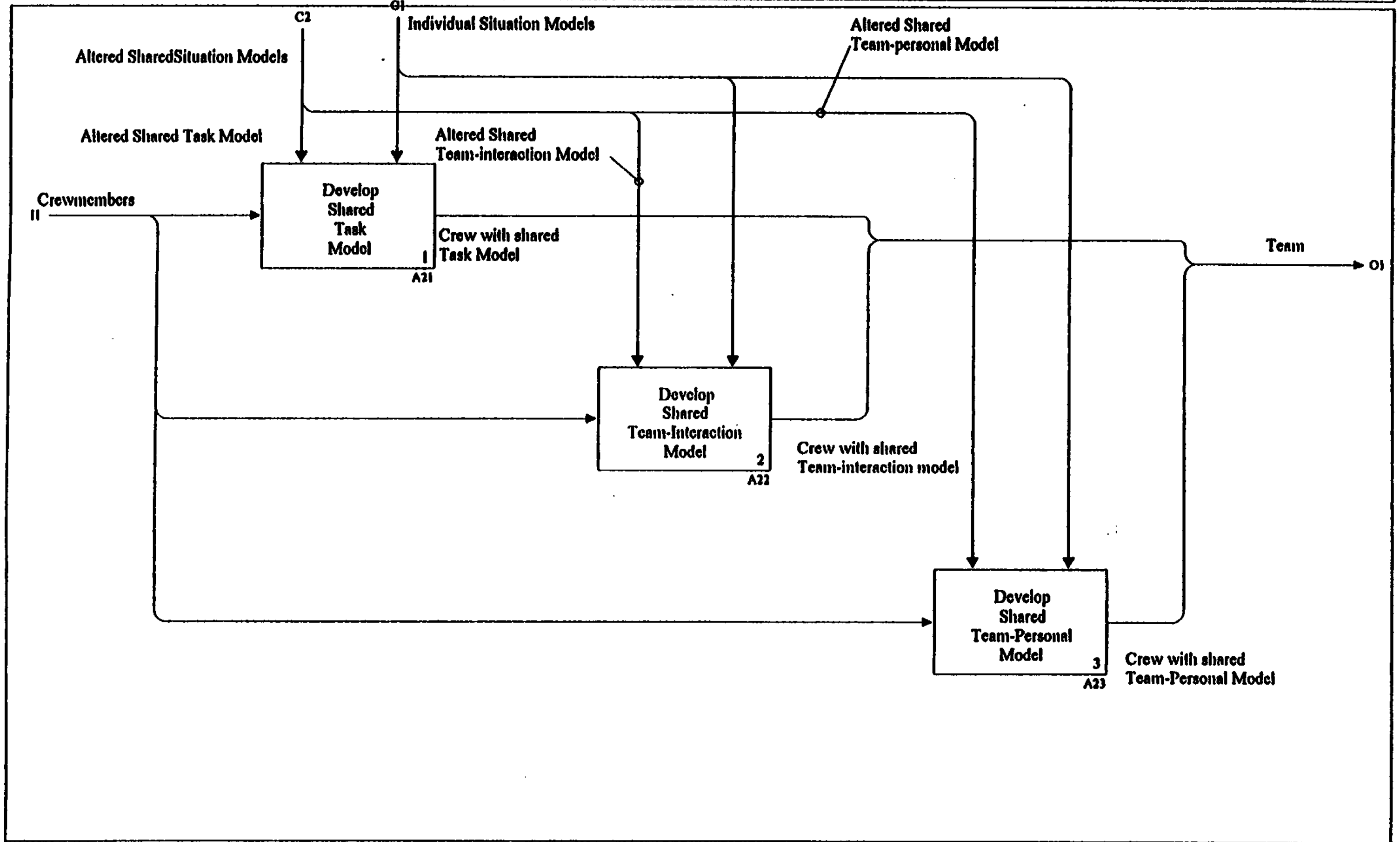
AUTHOR: Cherag Sukhia
PROJECT: Crew Performance
NOTES: 1 2 3 4 5 6 7 8 9 10

DATE: 06/13/94
REV: 11/12/94

☒ WORKING
☐ DRAFT
☐ RECOMMENDED
☐ PUBLICATION

READER DATE

CONTEXT:



C2
O1
Individual Situation Models
Altered SharedSituation Models
Altered Shared Task Model
Altered Shared Team-interaction Model
Altered Shared Team-personal Model
Crewmembers
I1
Develop Shared Task Model
1
A21
Crew with shared Task Model
Team
O1
Develop Shared Team-Interaction Model
2
A22
Crew with shared Team-interaction model
Develop Shared Team-Personal Model
3
A23
Crew with shared Team-Personal Model

NODE: CRM/A2
TITLE: Build and Maintain Team
NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia	DATE: 06/13/94	X	WORKING	READER DATE	CONTEXT:
	PROJECT: Crew Performance	REV: 11/12/94		DRAFT		
				RECOMMENDED		
	NOTES: 1 2 3 4 5 6 7 8 9 10			PUBLICATION		

Altered Shared Task Model
(see Crew with Shared Task Model, and Altered Shared Situation Models) Altered Shared Task Model is a component of Altered Shared Situation Models.

Altered Shared Team-interaction Model
(see Crew with Shared Team-interaction Model, Altered Shared Situation Models) Altered Shared Team-interaction Model is a component of Altered Shared Situation Models.

Altered Shared Team-personal Model
(see Crew with Shared Team-personal Model, Altered Shared Situation Models) Altered Shared Team-personal Model is a component of Altered Shared Situation Models.

Altered SharedSituation Models
(Also see Shared Situation Models)
Communication between Crewmembers as a part of the function Accomplish Technical Tasks, results in an altering of the (existing) Shared Situation Models, resulting in Altered Shared Situation Models.

Crew with shared Task Model
A Shared Task Model includes knowledge about each other's tasks, task procedures, and task strategies. It is formed by a sharing of individual team members' Task Models.

A Shared Task Model creates expectations about how events are likely to unfold and the team's likely response to task demands.

Crew with shared Team-interaction model
A Shared Team-interaction Model is developed through the sharing of individual team-interaction models. A Shared Team-interaction Model would include knowledge about how each team member must interact with each other. A Shared Team-interaction Model implies a shared understanding and acceptance of group roles, norms, and the authority gradient.

Crew with shared Team-Personal Model
A Shared Team-personal Model includes information regarding the knowledge, skills, abilities, preferences, and tendencies of particular teammates so that behavior can be tailored accordingly.

While the Shared Team-interaction Model is representative of group properties, the Shared Team-personal Model is representative of an understanding of the characteristics of the specific individuals involved.

Crewmembers
Refers to cockpit crewmembers which typically ranges from two to three: Captain, First Officer (F/O), and Second Officer (S/O).

Develop Shared Task Model
This function transforms Crewmembers into a Crew with Shared Task Model and is constrained by Individual Situation Models and Altered Shared Task Model.

Develop Shared Team-Interaction Model
This function transforms Crewmembers into a Crew with Shared Team-interaction Model and is constrained by Individual Situation Models and the Altered Shared Team-interaction Model.

The development of a Shared Team-Interaction Model typically takes place through implicit, non-verbal communication.

NODE: CRM/A2G1	TITLE: Build and Maintain Team	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR:	Cherag Sukhia	DATE: 06/13/94	X	WORKING	READER	DATE	CONTEXT:
	PROJECT:	Crew Performance	REV: 11/12/94		DRAFT			
					RECOMMENDED			
	NOTES:	1 2 3 4 5 6 7 8 9 10			PUBLICATION			

Develop Shared Team-Personal Model

This function transforms Crewmembers into a Crew with Shared Team-personal Model and is constrained by Individual Situation Models and Altered Shared Team-personal Model.

Development of the Shared Team-personal Model takes place as a result of crewmembers sharing information about themselves, their knowledge, skills, and past experiences as related to flying, as well as their likes, dislikes and tendencies.

Individual Situation Models

Individual Situation Models are 'Mental Models' of the Situation held by individual crewmembers.

Wilson & Rutherford (1989) define a mental model as "...a representation formed by a user of a system and/or task, based on previous experiences as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance" (p. 619).

Team

Team is the output of the function Build and Maintain Team. It represents the transformation of (individual) Crewmembers into an emergent whole. It is defined by this function as: A crew with shared task model, a shared team-interaction model, and a shared team-personal model.

NODE: CRM/A2G2	TITLE: Build and Maintain Team	NUMBER:

Figure 12. (Continued)

USED AT:

AUTHOR: Cherag Sukhia DATE: 06/15/94

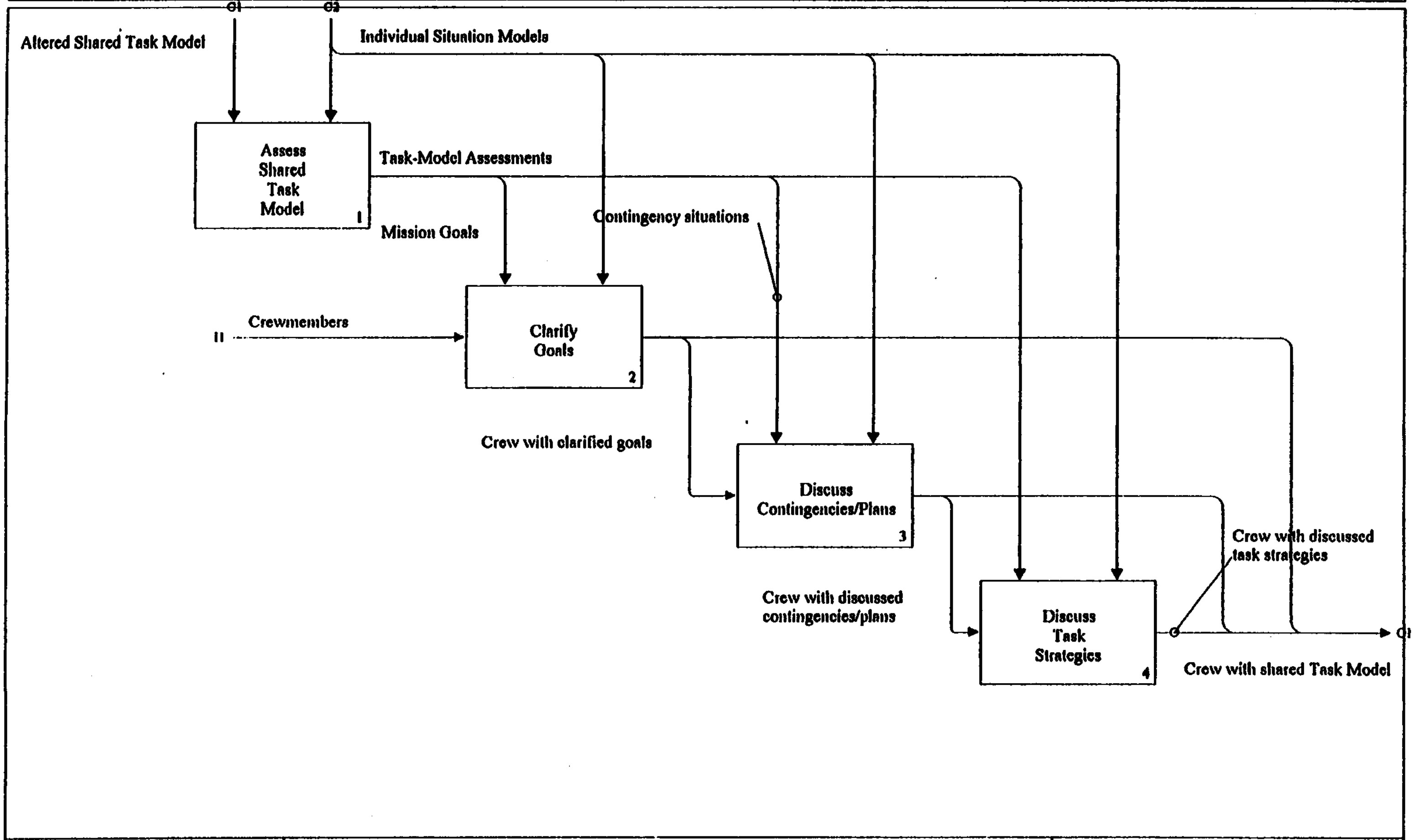
PROJECT: Crew Performance REV: 11/12/94

NOTES: 1 2 3 4 5 6 7 8 9 10

☒ WORKING
☐ DRAFT
☐ RECOMMENDED
☐ PUBLICATION

READER DATE

CONTEXT:


C1
C2
Altered Shared Task Model
Individual Situation Models
Assess Shared Task Model
1
Task-Model Assessments
Mission Goals
Contingency situations
I1
Crewmembers
Clarify Goals
2
Crew with clarified goals
Discuss Contingencies/Plans
3
Crew with discussed contingencies/plans
Discuss Task Strategies
4
Crew with discussed task strategies
O1
Crew with shared Task Model

NODE: CRM/A21 TITLE: Develop Shared Task Model NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia	DATE: 06/15/94	X	WORKING	READER DATE	CONTEXT: ■ ☐ ☐
	PROJECT: Crew Performance	REV: 11/12/94		DRAFT		
				RECOMMENDED		
	NOTES: 1 2 3 4 5 6 7 8 9 10			PUBLICATION		

Altered Shared Task Model
(see Crew with Shared Task Model, and Altered Shared Situation Models) Altered Shared Task Model is a component of Altered Shared Situation Models.

Assess Shared Task Model
This function has no inputs, but generates the output, Task Model Assessments (analogous to Situation Assessments) subject to Individual Situation Models and Altered Shared Task Model [Also see Altered Shared Task Model].

Clarify Goals
This function transforms Crewmembers into a Crew (group) with Clarified Goals subject to Task-Model Assessments and Individual Situation Models.

Contingency situations
Preparing for contingency situations is part of what leads to the development of a Shared Task Model. [Also see Task-Model Assessments]

Crew with clarified goals
Output of the function Clarify Goals [Also see Mission Goals]

Crew with discussed contingencies/plans
Output of the function Discuss Contingencies/Plans [Also see Contingency Situations].

Crew with discussed task strategies
Output of the function Discuss Task Strategies

Crew with shared Task Model
A Shared Task Model includes knowledge about each other's tasks, task procedures, and task strategies. It is formed by a sharing of individual team members' Task Models.

A Shared Task Model creates expectations about how events are likely to unfold and the team's likely response to task demands.

Crewmembers
Refers to cockpit crewmembers which typically ranges from two to three: Captain, First Officer (F/O), and Second Officer (S/O).

Discuss Contingencies/Plans
This function transforms the Crew with Clarified Goals into a Crew with Discussed Contingencies/Plans subject to Contingency Situations (a component of Task-Model Assessments] and Individual Situation Models.

Discuss Task Strategies
This function transforms Crew with Discussed Contingencies/Plans into Crew with Discussed Task Strategies subject to Task-Model Assessments and Individual Situation Models.

Individual Situation Models
Individual Situation Models are 'Mental Models' of the Situation held by individual crewmembers.

Wilson & Rutherford (1989) define a mental model as "...a representation formed by a user of a system and/or task, based on previous experiences as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance" (p. 619).

NODE: CRM/A21G1	TITLE: Develop Shared Task Model	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia	DATE: 06/15/94	X	WORKING	READER	DATE	CONTEXT: ■ ☐ ☐
	PROJECT: Crew Performance	REV: 11/12/94		DRAFT			
	NOTES: 1 2 3 4 5 6 7 8 9 10			RECOMMENDED			
				PUBLICATION			

Mission Goals

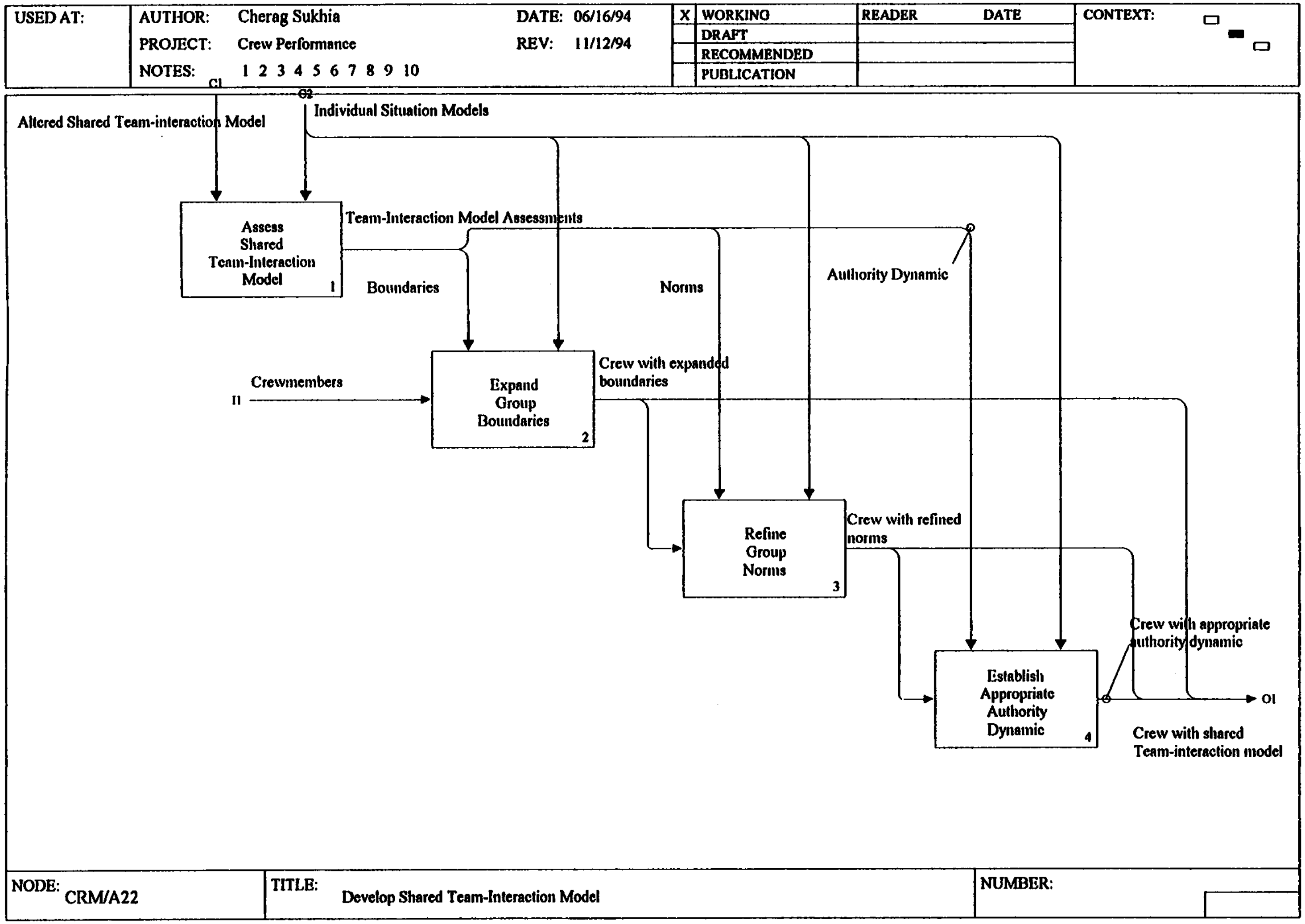
Clear definition of Mission Goals is essential for the development of a Shared Task Model. Mission Goals thus act as a control to the function Clarify Goals.

Task-Model Assessments

Assessing the shared mental model is a fundamental part of developing a shared mental model. The assessment of the Shared Task Model results in Task-Model Assessments which drives the development or refinement of the Shared Task Model.

NODE: CRM/A21G2	TITLE: Develop Shared Task Model	NUMBER:

Figure 12. (Continued)



USED AT:

AUTHOR: Cherag Sukhia

PROJECT: Crew Performance

NOTES: 1 2 3 4 5 6 7 8 9 10

DATE: 06/16/94

REV: 11/12/94

X WORKING

DRAFT

RECOMMENDED

PUBLICATION

READER DATE

CONTEXT:

NODE: CRM/A22

TITLE: Develop Shared Team-Interaction Model

NUMBER:

C1
C2
Altered Shared Team-interaction Model
Individual Situation Models
Assess Shared Team-Interaction Model
1
Team-Interaction Model Assessments
Boundaries
Norms
Authority Dynamic
Crewmembers
I1
Expand Group Boundaries
2
Crew with expanded boundaries
Refine Group Norms
3
Crew with refined norms
Crew with appropriate authority dynamic
Establish Appropriate Authority Dynamic
4
O1
Crew with shared Team-interaction model

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia PROJECT: Crew Performance NOTES: 1 2 3 4 5 6 7 8 9 10	DATE: 06/16/94 REV: 11/12/94	X WORKING DRAFT RECOMMENDED PUBLICATION	READER DATE	CONTEXT:

Altered Shared Team-interaction Model
(see Crew with Shared Team-interaction Model, Altered Shared Situation Models) Altered Shared Team-interaction Model is a component of Altered Shared Situation Models.

Assess Shared Team-Interaction Model
This function has no inputs, but generates the output, Team-Interaction Model Assessments (analogous to Situation Assessments) subject to Individual Situation Models and Altered Shared Team-Interaction Model [Also see Altered Shared Team-Interaction Model].

Authority Dynamic
Ginnett (1993) defines authority as "...the right to use power and influence". Because of differences in authority of crewmembers, there exists a 'trans-cockpit authority gradient' (TAG) (Edwards, 1975) or an 'authority dynamic' (Ginnett, 1993) which needs to be optimized.

Boundaries
Boundaries are emergent, socio-psychological properties of groups. According to Vander Zanden (1977), "Group boundaries act not as physical barriers, but as discontinuities in the flow of interactions". Generally speaking, the more permeable the boundary, the greater are the possibilities of interaction.

Crew with appropriate authority dynamic
Output of the function Establish Appropriate Authority Dynamic (Also see Authority Dynamic].

Crew with expanded boundaries
Output of the function Expand Group Boundaries [Also see Boundaries]

Crew with refined norms
Output of the function Refine Group Norms (Also see Norms].

Crew with shared Team-interaction model
A Shared Team-interaction Model is developed through the sharing of individual team-interaction models. A Shared Team-interaction Model would include knowledge about how each team member must interact with each other. A Shared Team-interaction Model implies a shared understanding and acceptance of group roles, norms, and the authority gradient.

Crewmembers
Refers to cockpit crewmembers which typically ranges from two to three: Captain, First Officer (F/O), and Second Officer (S/O).

Establish Appropriate Authority Dynamic
This function transforms Crew with Refined Norms into a Crew with Appropriate Authority Dynamic subject to Team-Interaction Model Assessments and Individual Situation Models.

Expand Group Boundaries
This function transforms Crewmembers into a Crew with Expanded Boundaries subject to Team-Interaction Model Assessments and Individual Situation Models.

Individual Situation Models
Individual Situation Models are 'Mental Models' of the Situation held by individual crewmembers.

Wilson & Rutherford (1989) define a mental model as "...a representation formed by a user of a system and/or task, based on previous experiences as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance" (p. 619).

NODE: CRM/A22G1	TITLE: Develop Shared Team-Interaction Model	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia	DATE: 06/16/94	X	WORKING	READER	DATE	CONTEXT: ▭ ■ ▭
	PROJECT: Crew Performance	REV: 11/12/94		DRAFT			
	NOTES: 1 2 3 4 5 6 7 8 9 10			RECOMMENDED			
				PUBLICATION			

Norms

Ginnett (1993) defines Norms as "the informal rules that groups adopt to regulate group members' behavior". Norms are an emergent property of groups that regulate many aspects of group life and provide expectations about behavior.

Refine Group Norms

This function transforms the input Crew with Expanded Group Boundaries into a Crew with Refined Norms subject to Team-Interaction Model Assessments and Individual Situation Models.

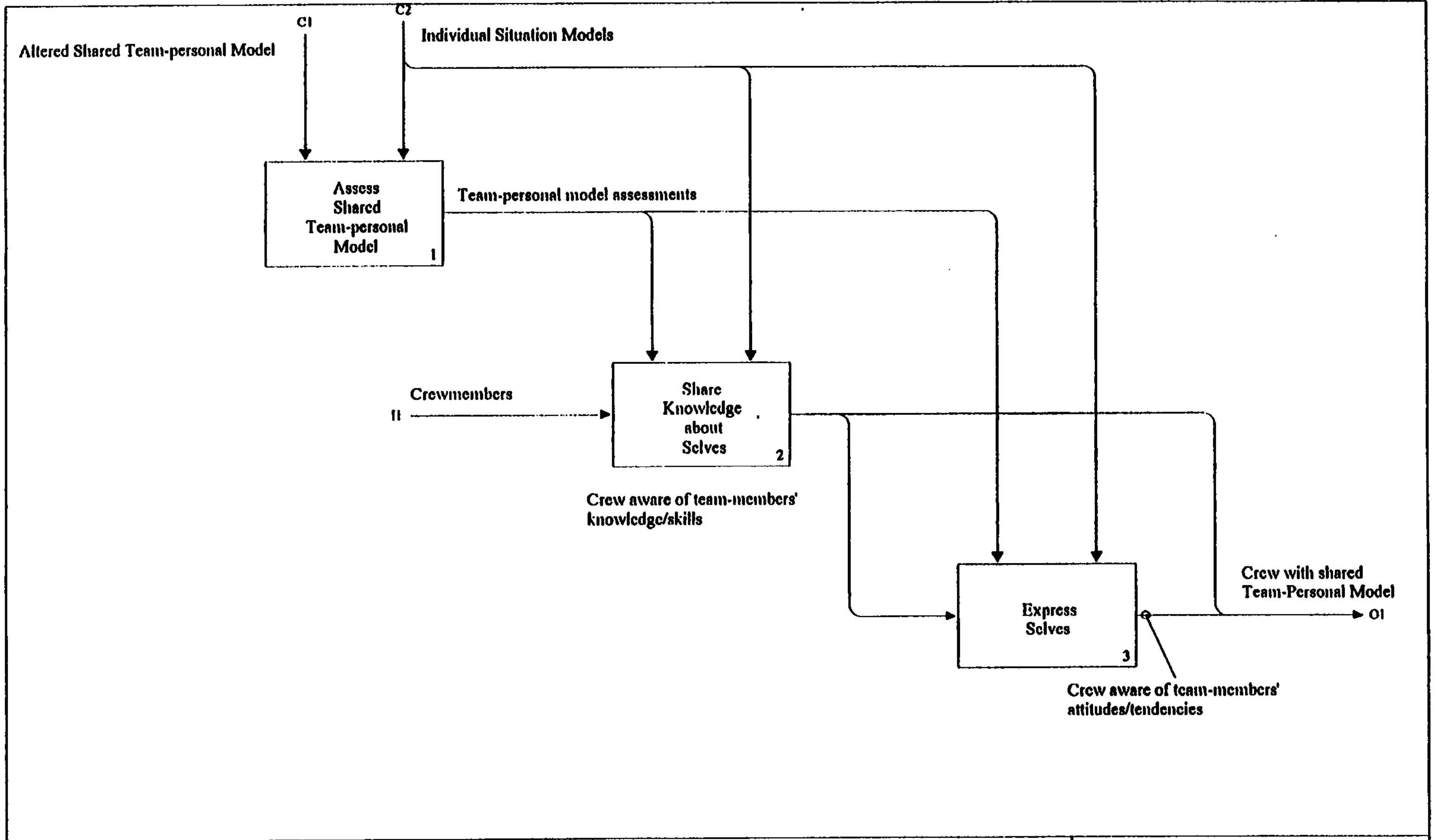
Team-Interaction Model Assessments

Assessing the shared mental model is a fundamental part of developing a shared mental model. The assessment of the Shared Team-Interaction Model results inTeam-Interaction Model Assessments which drives the development or refinement of the Shared Team-Interaction Model.

NODE: CRM/A22G2	TITLE: Develop Shared Team-Interaction Model	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia PROJECT: Crew Performance NOTES: 1 2 3 4 5 6 7 8 9 10	DATE: 06/16/94 REV: 11/12/94	☒ WORKING ☐ DRAFT ☐ RECOMMENDED ☐ PUBLICATION	READER DATE	CONTEXT:


C1
Altered Shared Team-personal Model
C2
Individual Situation Models
Assess Shared Team-personal Model
1
Team-personal model assessments
Crewmembers
I1
Share Knowledge about Selves
2
Crew aware of team-members' knowledge/skills
Express Selves
3
Crew with shared Team-Personal Model
O1
Crew aware of team-members' attitudes/tendencies

NODE: CRM/A23	TITLE: Develop Shared Team-Personal Model	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia	DATE: 06/16/94	X	WORKING	READER	DATE	CONTEXT:
	PROJECT: Crew Performance	REV: 11/12/94		DRAFT			
	NOTES: 1 2 3 4 5 6 7 8 9 10			RECOMMENDED			
				PUBLICATION			

Altered Shared Team-personal Model

(see Crew with Shared Team-personal Model, Altered Shared Situation Models) Altered Shared Team-personal Model is a component of Altered Shared Situation Models.

Assess Shared Team-personal Model

This function has no inputs, but generates the output, Team-personal Model Assessments (analogous to Situation Assessments) subject to Individual Situation Models and Altered Shared Team-personal Model [Also see Altered Shared Team-personal Model].

Crew aware of team-members' attitudes/tendencies

Output of the function Express Selves.

Crew aware of team-members' knowledge/skills

Output of the function Share Knowledge about Selves.

Crew with shared Team-Personal Model

A Shared Team-personal Model includes information regarding the knowledge, skills, abilities, preferences, and tendencies of particular teammates so that behavior can be tailored accordingly.

While the Shared Team-interaction Model is representative of group properties, the Shared Team-personal Model is representative of an understanding of the characteristics of the specific individuals involved.

Crewmembers

Refers to cockpit crewmembers which typically ranges from two to three: Captain, First Officer (F/O), and Second Officer (S/O).

Express Selves

This function transforms Crewmembers into a Crew aware of team-members' Attitudes/Tendencies subject to Team-personal Model Assessments and Individual Situation Models.

Individual Situation Models

Individual Situation Models are 'Mental Models' of the Situation held by individual crewmembers.

Wilson & Rutherford (1989) define a mental model as "...a representation formed by a user of a system and/or task, based on previous experiences as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance" (p. 619).

Not aware of each other's knowledge/skills

No Glossary Text Provided.

Not aware of other's attitudes/tendencies

No Glossary Text Provided.

Share Knowledge about Selves

This function transforms Crewmembers into a Crew (group) aware of team-members' Knowledge/Skills subject to Team-personal Model Assessments and Individual Situation Models.

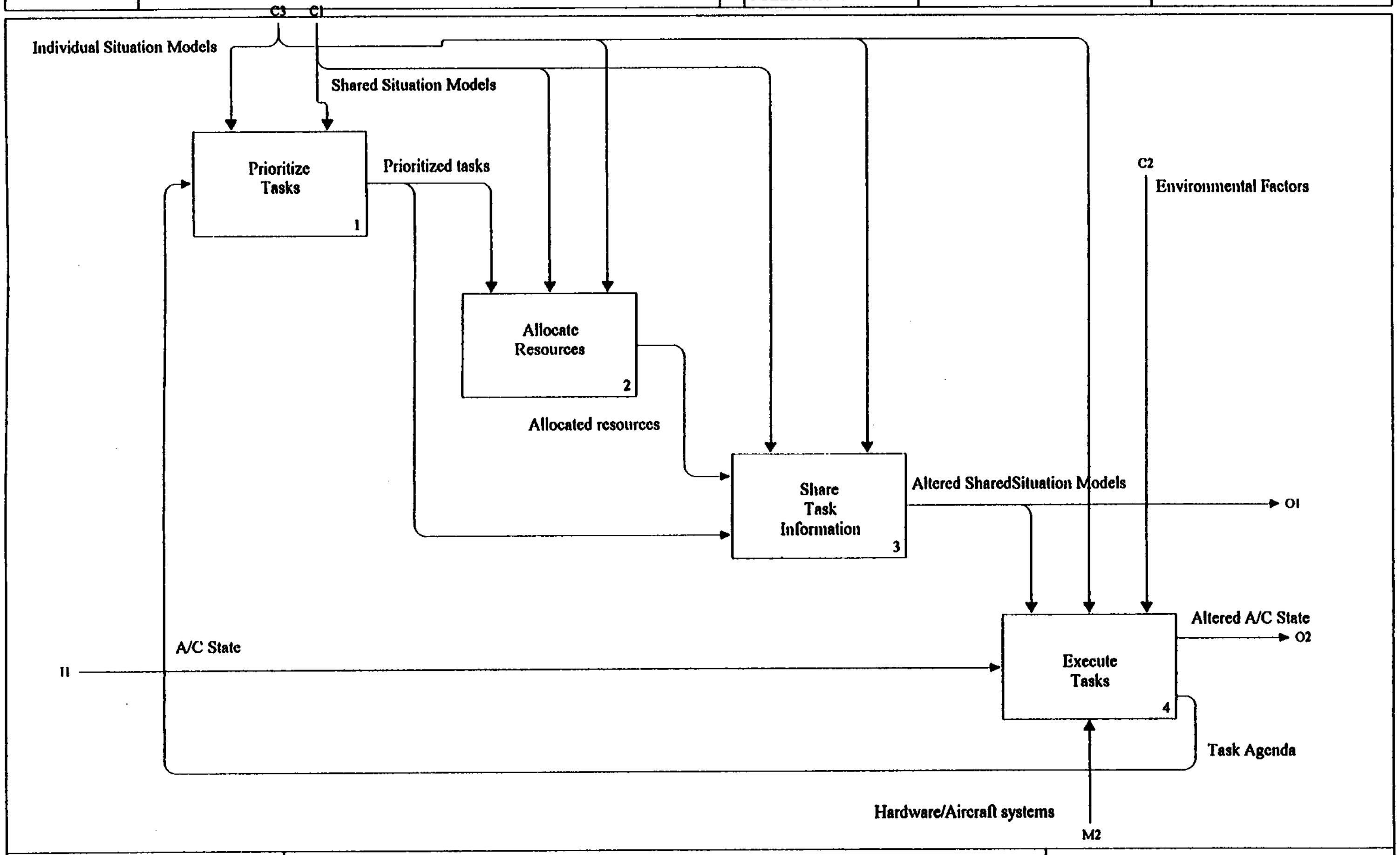
Team-personal model assessments

Assessing the shared mental model is a fundamental part of developing a shared mental model. The assessment of the Shared Team-personal Model results inTeam-personal Model Assessments which drives the development or refinement of the Shared Team-personal Model.

NODE: CRM/A23G1	TITLE: Develop Shared Team-Personal Model	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia PROJECT: Crew Performance NOTES: 1 2 3 4 5 6 7 8 9 10	DATE: 07/13/94 REV: 11/12/94	X WORKING DRAFT RECOMMENDED PUBLICATION	READER DATE	CONTEXT:



C3
C1
Individual Situation Models
Shared Situation Models
Prioritize Tasks
1
Prioritized tasks
Allocate Resources
2
Allocated resources
Share Task Information
3
Altered SharedSituation Models
O1
C2
Environmental Factors
Execute Tasks
4
Altered A/C State
O2
A/C State
I1
Task Agenda
Hardware/Aircraft systems
M2

NODE: CRM/A3	TITLE: Accomplish Technical Tasks	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR: Cherag Sukhia	DATE: 07/13/94	X	WORKING	READER	DATE	CONTEXT: ☐ ☐ ■
	PROJECT: Crew Performance	REV: 11/12/94		DRAFT			
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A/C State

Refers to the current, actual state of the aircraft. Examples include aircraft position, altitude, airspeed, fuel level, and position of flaps.

Allocate Resources

This function has no inputs, but generates the output, Allocated Resources subject to Prioritized Tasks, Shared Situation Models, and Individual Situation Models.

Once tasks are prioritized, resources for the execution can be allocated.

Allocated resources

Output of the function Allocate Resources.

Altered A/C State

(See Aircraft State)
Accomplishing the commercial transport mission results in transforming the values of the parameters (e.g., altitude, fuel level, flap position), resulting in the output Altered Aircraft State.

Altered SharedSituation Model

No Glossary Text Provided.

Altered SharedSituation Models

(Also see Shared Situation Models)
Communication between Crewmembers as a part of the function Accomplish Technical Tasks, results in an altering of the (existing) Shared Situation Models, resulting in Altered Shared Situation Models.

Environmental Factors

These include temperature, humidity, pressure, wind direction and velocity, visibility, runway conditions, and other meteorological conditions liable to affect or constrain the accomplishment of the overall missio.

Execute Tasks

This function transforms Aircraft (A/C) State into Altered Aircraft State and Task Agenda subject to Shared Situation Models, Individual Situation Models, and Altered Shared Situation Models with the help of Hardware/Aircraft Systems.

Hardware/Aircraft systems

The aircraft, along with all its subsystems, aid the accomplishment of the commercial transport mission and are hence "mechanisms".

Individual Situation Models

Individual Situation Models are 'Mental Models' of the Situation held by individual crewmembers.

Wilson & Rutherford (1989) define a mental model as "...a representation formed by a user of a system and/or task, based on previous experiences as well as current observation, which provides most (if not all) of their subsequent system understanding and consequently dictates the level of task performance" (p. 619).

Prioritize Tasks

This function transforms Task Agenda into Prioritized Tasks subject to Individual Situation Models and Shared Situation Models.

The Task Agenda is prioritized depending upon the situation. Each task can be assigned a weight in terms of importance and urgency, thereby allowing for the agenda to be ordered or prioritized.

Prioritized tasks

Output of the function Prioritize Tasks.

NODE: CRM/A3G1	TITLE: Accomplish Technical Tasks	NUMBER:

Figure 12. (Continued)

USED AT:	AUTHOR:	Cherag Sukhia	DATE: 07/13/94	X	WORKING	READER	DATE	CONTEXT:
	PROJECT:	Crew Performance	REV: 11/12/94		DRAFT			
					RECOMMENDED			
	NOTES:	1 2 3 4 5 6 7 8 9 10			PUBLICATION			

Share Task Information

This function transforms Prioritized Tasks and Allocated Resources into an Altered Shared Situation Model subject to Shared Situation Models [existing] and Individual Situation Models.

Shared Situation Models

(Also see Individual Situation Models)

These are formed through specialized communication; a result of explicit sharing of information or patterns of communication. They refer to the current or existing shared situation models, versus the Altered Shared Situation Models.

Task Agenda

Funk (1991) defines an agenda as "...a hierarchy of tasks to be completed during a mission". Further, the process of creating an agenda of tasks "...involves the selection and specification of a suitable task to achieve each goal and the definition of an event to initiate that task".

NODE: CRM/A3G2	TITLE: Accomplish Technical Tasks	NUMBER:

Figure 12. (Continued)