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PROCEDURES IN COMPLEX SYSTEMS: THE AIRLINE COCKPIT

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ABSTRACT

In complex human-machine systems, successful operations depend on a elaborate set of procedures which are specified by the operational management of the organization. These procedures indicate to the human operator (in this case the pilot) the manner in which operational management intends to have various tasks performed. The intent is to provide guidance to the pilots and to ensure a safe, logical, efficient, and predictable (standardized) means of carrying out the objectives of the job. However, procedures can become a hodge-podge. Inconsistent or illogical procedures may lead to non-compliance by operators. Based on a field study with three major airlines, the authors propose a model for procedure development which we call “The Four P's:” philosophy, policies, procedures, and practices. The various factors, both external and internal to the cockpit, that must be considered for procedure design are presented. In particular, the paper addresses the development of procedures for automated cockpits—a decade-long, and highly controversial issue in commercial aviation. Although this paper is based on airline operations, we believe that the principles discussed are also applicable to other high-risk supervisory control systems, such as space flight, manufacturing process control, nuclear power production, and military operations.

I. INTRODUCTION

A complex human-machine system consists of more than merely one or more human operators and a collection of hardware components. In order to operate a complex system successfully, the human-machine system must be supported by an organizational infrastructure of operating concepts, rules, guidelines, and documents. The coherency of such operating concepts, in terms of consistency and logic, is vitally important for the efficiency and safety of any complex system. In high-risk endeavors such as aircraft operations, space flight, nuclear power production, manufacturing process control, and military operations, it is essential that such support be flawless, as the price of operational error can be unacceptable. When operating rules are not adhered to, or the rules are inadequate for the task at hand, not only will the system's goals be thwarted, but there may also be tragic human and material consequences.

To ensure safe and predictable operations, support to the operators, in this case flight crews, often comes in the form of standard operating procedures (SOP). These provide the crew with step-by-step guidance for carrying out their operations. Standard procedures do indeed promote uniformity, but they do so at the risk of reducing the role of human operators to a lower level. Management, therefore, must recognize the danger of over-procedurization, which fails to exploit one of the most valuable assets in the system, the intelligent operator who is “on the scene.” The alert system designer and operations manager recognize that there cannot be a procedure for everything, and the time will come in which the operators of a complex system will face a situation for which there is no written procedure. Procedures, whether executed by humans or machines, have their place, but so does human cognition.

A dramatic example was provided by an accident at Sioux City. A United Airlines DC-10 suffered a total loss of hydraulic systems, and hence aircraft control, due to a disintegration of the center engine fan disk [11]. When the captain had sized up the situation, he turned to the flight engineer and asked what the procedure was for controlling the aircraft. The reply is worth noting: “There is none.” Human ingenuity and resource management were required: the crew used unorthodox methods to control the aircraft. This resulted in a crash landing in which well over half of the passengers survived.

A. Procedural Deviation: Its Influence on Safety

In 1987 Lautman and Gallimore [8] conducted a study of jet transport aircraft accident reports in order to “better understand accident cause factors.” They analyzed 93 hull-loss accidents that occurred between 1977-1984. The leading crew-caused factor in their study was “pilot deviation from basic operational procedures” (Figure 1). Converging evidence was reported by the National Transportation Safety Board (NTSB) study of 37 recent airline accidents: procedural error accounted for 24 percent of all crew errors—by far the most dominant factor [14]. Similar statistics, showing that procedural deviation is the highest ranking category in crew or operator caused accidents, can also be found in the nuclear industry [20], and in the maritime industry [15].

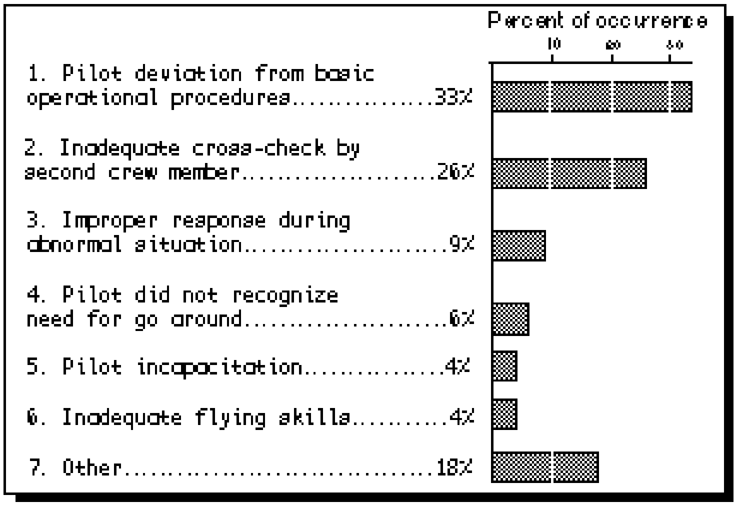


Figure 1. Significant crew-caused factors in 93 hull loss accidents.
Source: reference [8]

The potential for procedural deviations to results in fatal accidents can be seen from three airline accidents that occurred during a three-year period. In the first, Northwest Airlines Flight 255, an MD-82, crashed at Detroit Metropolitan Airport following a no-flap/no-slat takeoff [9]. In the second, Delta Air Lines Flight 1141, a B-727, crashed shortly after lifting off from Dallas-Fort Worth International Airport, following a no-flap/no-slat takeoff [10]. In the third, USAir Flight 5050, a B-737, ran off the runway at La Guardia Airport and dropped into adjacent waters, following a mis-set rudder trim and several other problems [12].

B. Objectives of the Study

The intent of this work was to examine the use and design of cockpit procedures from a broad perspective; and in particular, with respect to cockpit automation. The objectives were:

1. Understand what procedures are.
2. Document how procedures are actually used by pilots
3. Propose a model of procedure development and usage.
4. Understand the interaction between procedure and automation.
5. Identify the factors that affect procedure usage and design.

II. METHODOLOGY

Three major U.S. airlines agreed to participate in this research study. The research approach was naturalistic: we collected data on each of the three airlines in order to obtain information regarding procedural concepts, usage, and design. We focused our research on procedures for automated cockpits (Airbus A-320, Boeing B-757/767, and B-737-300).

A. Interviews with Management and Pilots

The underlying rationale was that if we wanted to examine how the organization directs flight operations, we must first have a clear understanding of how flight operation concepts are perceived at each level within the organization. At each of the participating airlines, we started with the vice-president for flight operations, and followed with interviews through the ranks of flight management. In cooperation with the pilot representative group, we conducted interviews with pilots who were currently flying an advanced technology aircraft.

B. Procedure Design Meetings

We also wanted a view-port into the process itself; that is, how flight management actually designs or modifies procedures. We attended meetings in which procedural changes were addressed, debated, and resolved.

C. Cockpit Observations

Consistent with the naturalistic approach, we conducted cockpit observations. We flew 200 flights, mostly on advanced technology aircraft, and observed first hand how flight crews use procedures in routine operations. This also allowed us to informally discuss procedural concepts in the context of a flight operation. Flight crews explained and pointed out procedural problems as they occurred.

D. Interviews with Personnel at one Manufacturer

We visited one airframe manufacturer in order to understand its concepts for designing procedures. We conducted discussions with a group of managers and engineers responsible for procedure design. Our main objective was to understand the manufacturer’s concepts and the process of specifying procedures for automated aircraft.

E. Accident and Incident Databases

In order to gain insight into the influence of procedures on incidents and accidents we analyzed reports from two databases: (1) the accident database of the National Transportation Safety Board, and (2) the incident database of NASA’s Aviation Safety Reporting System (ASRS). The NTSB database reports are the result of formal investigations. The ASRS, however, is a voluntary reporting system in which pilots can submit subjective accounts about safety-related aviation incidents [2].

III. A MODEL FOR PROCEDURE DEVELOPMENT

Procedures do not fall from the sky. Nor are they inherent in the equipment. The manufacturer provides a set of procedures, but each airline tailors them to its own style of operations. Thus the same piece of equipment may have very different operating procedures [5]. But just what is the basis for designing procedures? What makes one set of procedures better in terms of compatibility, consistency, and compliance?

Based on our study with the three airlines, we identified a link between the organization’s *philosophy*, *policies*, and the standard operating *procedures* supplied to the pilots. We called this link the “Three P’s” of cockpit operations. We shall now explore how an orderly, consistent path can be constructed from the company’s philosophy of operation to the actual conduct of any given procedure. Figure 2 depicts this model. The fourth P, "practices," will be introduced later.

A. Philosophy

The cornerstone of the "Three P's" model is an organization's philosophy of operations. By philosophy we mean that the airline management determines an over-arching view of how they will conduct the business of the airline, including flight operations. A company's philosophy is largely influenced by the individual philosophies of the top decision makers on how to conduct operations. It is also influenced by the company's culture, a term that has come into favor in recent years to explain broad-scale differences between corporations.

Although most high-ranking managers, when asked, could not clearly state their philosophy of operations, such philosophies do indeed exist within airlines; they can be inferred from working procedures, policies, punitive actions, organizational structure, and training [6]. For example, one company that we surveyed had a flight operation philosophy of granting great discretion (they called it "wide road") to the individual pilot. Pilots were schooled under the concept that they were both qualified and trained to perform all tasks. Consistent with this philosophy, the company allowed the first officer to abort a takeoff, a maneuver which is the captain's absolute prerogative at most airlines.

The emergence of flight-deck automation as an operational problem has recently generated interest in philosophy of operations; partly due to lack of agreement about how and when automatic features are to be used, and who may make that decision [21]. This has led one carrier, Delta Air Lines, to develop a formal statement of automation philosophy. Subsequently other airlines have developed similar statements [23].

B. Policy

The philosophy of operations, in combination with economic factors, public relations campaigns, new aircraft, and major organizational changes, generates policies. Policies are broad specifications of the manner in which management expects things to be done (training, flight operations, maintenance, exercise of authority, personal conduct, etc.). In some cases, policies that are actually remote from flight operations can affect cockpit procedures. For example, one airline's new public relations policy led to a procedure that called for the captain to stand at the cockpit door and make farewells to the passengers as they departed the cabin. In particular, the marketing department wanted the pilot to be in place at the cockpit door in time to greet the disembarking first-class passengers. This dictated a procedural change in that most of the "SHUT-DOWN" checklist had to be done single-handed by the first officer. Thus checklist procedures which would normally be conducted by both pilots had to be significantly changed in deference to public relations imperatives.

C. Procedure

Procedures, then, should be designed to be as much as possible consistent with the policies (which, in turn, should be consistent with the philosophy). But just what are procedures? In general, we argue, a procedure exists in order to specify, unambiguously, the following:

1. What the task is.
2. When the task is conducted (time and sequence).
3. How the task is done (actions).
4. By whom it is conducted.
5. What type of feedback is provided to other crew members

The function of a well-designed procedure is to aid flight crews by dictating and specifying a progression of sub-tasks and actions to ensure that the primary task at hand will be carried out in a manner that is logical, efficient, and also error resistant. Another important function of a cockpit procedure is that it should promote standardization—the application of procedures to promote crew coordination and quality control. In airline operations, standardization of procedures is a critical aspect of flight operations; mainly because flight crews are paired for a particular trip without consideration to whether they know one another; also because operations are conducted remotely, and no direct management supervision can be maintained over every flight. So strong is the airline industry's dependency on SOPs, that it is believed that in a well-standardized operation, a cockpit crew member could be plucked from the cockpit in mid-flight and replaced with another pilot, and the operation would continue safely and smoothly. Nevertheless, any human operator knows that adherence to a particular set of SOPs is not the only way that one can operate equipment; there may be several other ways of doing the same task with a reasonable level of efficiency and safety.

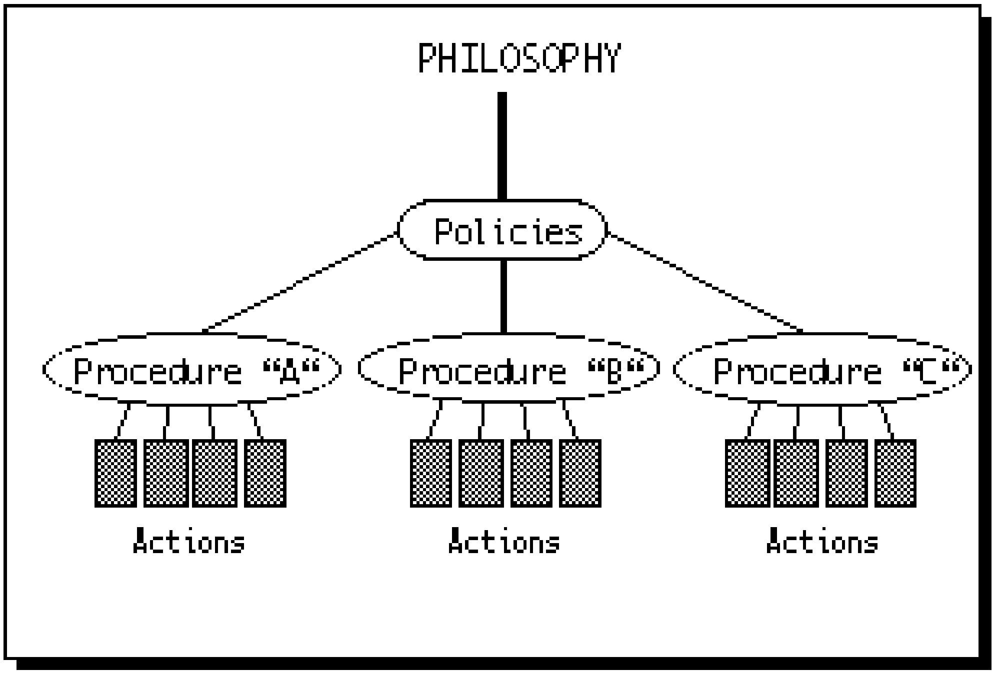


Figure 2. The "Three P's" model

To illustrate the Three P's, let us assume that the task at hand is the configuration of an advanced technology aircraft for an instrument approach:

1. *Philosophy*: Automation is just another tool to help the pilot.
2. *Policy*: Use or non-use of automatic features (within reason) is at the discretion of the crew.
3. *Procedure*: The flight crew will first decide what level of automation to use (manually, manually with computer guidance, semi-automatic, fully automatic), which determines what must be done to configure the cockpit.
4. *Sub-tasks (or actions)*: Follow from procedures (e.g., identify and tune the signal from the landing site, select automation mode, set the altitude criterion for a missed approach, etc.)

We argue that if philosophies and policies are articulated, then (1) a logical and consistent set of cockpit procedures that are in accord with the policies and philosophy can be generated, (2) discrepancies and conflicting procedures will be easily detected, and (3) flight crews will notice and understand the logic behind SOPs. We believe that adherence to the Three P's model will also lead to a higher degree of conformity to procedures during line operations.

D. The fourth P: Practices

The model up to this point provides a framework for procedure development. Yet it is incomplete. It overlooks the person for whom procedures are designed. To correct this, we have added an additional component—*practices*. The term "practice" encompasses every activity conducted on the flight deck. While a procedure may be mandatory, it is the pilot who will either conform to it or deviate from it. *Ideally, procedures and practices should be the same*. The high prevalence of the "pilot deviations from SOP" in accidents, as documented by Lautman and Gallimore [8], indicates a breakdown of the link between procedures and practices.

The goal of flight management is to promote "good" practices by specifying coherent procedures. But we must also recognize that this is not always the case: procedures may be poorly designed. The crew can either conform to a procedure or deviate from it. The deviation may be trivial (e.g., superimposing some non-standard language on a procedural callout), or it may be significant (e.g., not setting the auto-brakes according to the takeoff procedures). For example, we once observed a captain who, in response to the first officer's question regarding the conduct of a *mandatory* taxi procedure, replied "I just don't do that procedure." That captain, unequivocally, elected to deviate from the procedure. The immediate consequences of the failure to conform to a procedure can be seen in the following report submitted to the NASA's Aviation Safety Reporting System (ASRS):

> Our flight departed late in the afternoon for San Francisco. During the flight we discussed the necessity to request lower altitudes from air traffic control (ATC), when approaching the San Francisco Airport, due to tendency to be "caught high" on arrival in this aircraft type. Area arrival progressed smoothly and we were cleared for the approach to the runway. When changing radio frequency from approach to tower (head down), the First Officer selected "open descent" to 400 feet. The autopilot was off, both flight directors were engaged, and

> autothrust was on. After contacting San Francisco tower, I became aware that we were below the glideslope, that airspeed was decaying, and that we were in an "open descent" mode. I instructed the first officer to engage the “Vertical Speed” mode in order to stop our descent, restore the speed mode for the autothrottles, and continue the approach visually. Company procedures explicitly prohibit selecting an altitude below 1500 feet for engaging the “Open Descent” mode, since this places the aircraft close to the ground with engines at idle. It is suspected that this was the cause of a recent aircraft accident in Asia. “Highly automated” aircraft demand explicit following of established procedures. Unfortunately it is possible to fly the aircraft in numerous ways that will degrade your safety margin rapidly. Adherence to procedures would’ve prevented this incident. (ASRS Report No. 149672)

IV. THE INFLUENCE OF AUTOMATION

Our study suggest that increased automation reduces the number of procedures on the fight deck. In a highly automated aircraft, large number of tasks are “bundled” into a single action on part of the pilot. Thus a single procedure may replace many. For example, consider the task of rolling out of a turn. When manually flying an aircraft, a useful procedure is to start leveling the wings several degrees prior to the assigned heading. The time-honored rule of thumb is to lead the rollout to the specified heading by the number of degrees equal to half of the angle of bank (e.g., while turning right to a heading of 090 at a bank angle of 10 degrees, the rollout will be initiated at 085). On the other hand, when the autopilot is engaged, the flight crew will dial 090 in the heading window and the plane will initiate the rollout and level the wings by itself. Again, it is not that the procedure has vanished, but it is simply concealed in the autopilot computer code (in a more precise control algorithm, of course).

Conversely, in those cases where some function of the automation provides a potential hazard, a manual alternative must be provided: this requires adding a new procedure. For example, when a glass cockpit aircraft is on an instrument approach to a runway, there is a possibility of a “false capture”: a descent before alignment with the runway. The only feedback to the flight crews of this hazard (descending, but not toward the intended runway!), is a color change from white to green of a text symbol. To counter this, one airline’s SOP states: “to prevent a false capture, do not arm the approach mode until the localizer and glide slope pointers have appeared...” The above example shows how automation and procedures are inversely related. To “fix” a problem with automation, one must go one step down in the level of automation. Subsequently, this requires adding a new procedure.

Our observations suggest that high levels of cockpit automation makes it more difficult to mandate a large set of stringent procedures. Several factors lead to this:

- In advanced technology aircraft, the interface between human and machine is usually some form of computer input device. Tasks that must be conducted in real time require complex interaction with the computer, and hence are not amenable to simple procedurization.
- Many aircraft systems, such as the autoflight system, operate in a dynamic and sometimes unpredictable environment and therefore cannot be completely pre-

> programmed. In these cases, the autoflight system provides the pilot with several semi-automatic methods (or more accurately, “modes”) to choose from. For example, there are at least five different modes by which the autoflight system can fly the plane to another altitude. Attempts to completely procedurize such maneuvers by mandating one method may be too restrictive and possibly lead to non-compliance. One major U.S. airline, for example, attempted to procedurize the descent profile of its B-737 glass cockpit fleet—an activity that requires much interaction with the automatic flight system. Most flight crews simply ignored these procedures; non-conformity was at its extreme. Flight management had to quietly abandon the procedure.

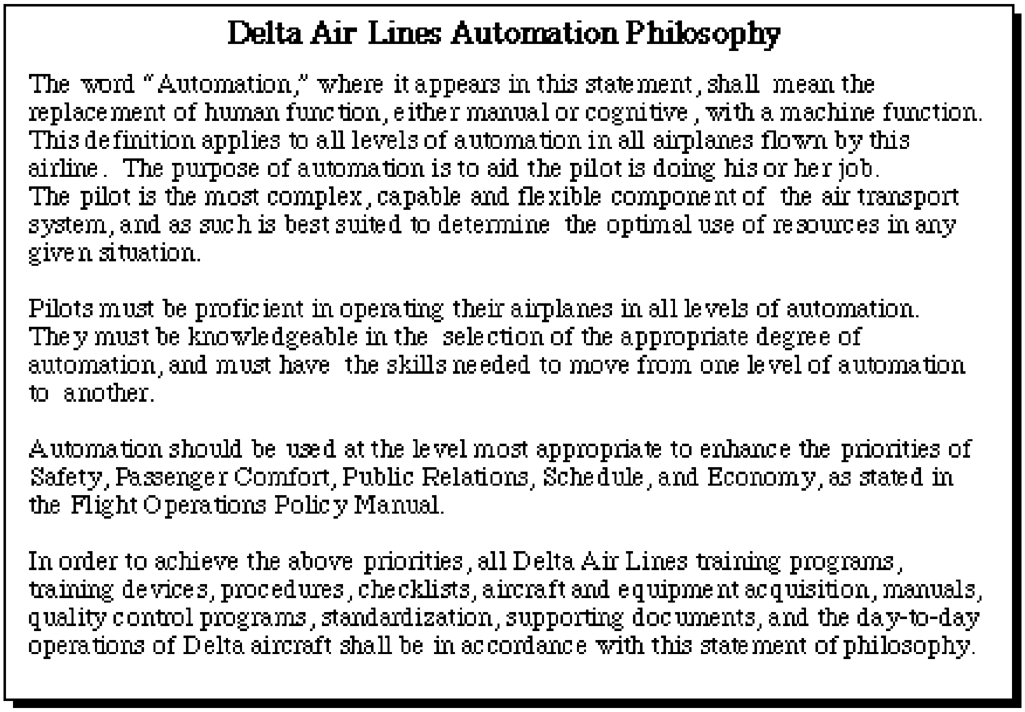
To conclude, a procedure that is ponderous and is perceived as increasing workload, and/or interrupting smooth flow of cockpit tasks, will probably be ignored. Even worse, there could be a spread of this effect, since a violated procedure may lead to a more general distrust of procedures, resulting in non-conformity in other areas.

A. Automation Philosophy

Most airlines that fly glass cockpit aircraft have attempted to develop an operational doctrine for operating these aircraft. For those that have experienced difficulty, it is probably because they bypassed the conceptual (philosophy) stage and jumped immediately into policies, and in some cases straight into procedures. One of the problems with not developing and publishing a philosophy of operations is that policies, decisions, and ultimately procedures are put into place without an explanatory basis. The philosophy behind these decisions is neither articulated nor understood. What is more, philosophies change from time to time. Because these changes in philosophy are not made public, they can lead to confusion and to a compliance problem.

For example, one airline’s early automation doctrine was to fly an automated aircraft, to the extent possible, as if it were an older generation aircraft (e.g., Boeing B-727, Douglas DC-9), and thereby minimizing the use of advanced features. Then, following a change in management, it switched to a philosophy of “use the automation as much as possible” (in order to save fuel and engine wear). Recently, as indicated by the vice president of flight operations, the philosophy moved to a more “liberal” approach to automation, stating that “there are many ‘detents’ between ‘fully automated’ and ‘manual.’” Although this new doctrine has been conveyed to some crews, it was not done in a formal way.

Not surprisingly, many flight crews that we interviewed complained of inconsistencies in management's approach to automation. In contrast, the Delta Air Line automation philosophy statement leaves no doubt about where the company stands regarding use of levels of automation. The crews are expected to be proficient in employing the automation at every level, but the choice of automation versus manual modes remains in the cockpit.



Delta Air Lines Automation Philosophy

The word "Automation," where it appears in this statement, shall mean the replacement of human function, either manual or cognitive, with a machine function. This definition applies to all levels of automation in all airplanes flown by this airline. The purpose of automation is to aid the pilot is doing his or her job. The pilot is the most complex, capable and flexible component of the air transport system, and as such is best suited to determine the optimal use of resources in any given situation.

Pilots must be proficient in operating their airplanes in all levels of automation. They must be knowledgeable in the selection of the appropriate degree of automation, and must have the skills needed to move from one level of automation to another.

Automation should be used at the level most appropriate to enhance the priorities of Safety, Passenger Comfort, Public Relations, Schedule, and Economy, as stated in the Flight Operations Policy Manual.

In order to achieve the above priorities, all Delta Air Lines training programs, training devices, procedures, checklists, aircraft and equipment acquisition, manuals, quality control programs, standardization, supporting documents, and the day-to-day operations of Delta aircraft shall be in accordance with this statement of philosophy.

B. Technique

Cockpit automation resists stringent procedurization. To overcome this, pilots turn to technique. The term "technique" is defined here as a personal method (practice) for carrying out a task. The use of technique allows the pilot to express individualism and creativity without violating procedural constraints. If the technique is consistent with the procedure and the overlying policy, then the task is conducted with no violation of constraints. Techniques have been developed by pilots over years of experience. Every pilot carries with him a virtual catalog of techniques. These are often fine points which pilots have discovered for themselves, experimented with, or learned from other pilots. Why does the procedure writer not include the techniques as part of the procedure? Generally this is not advisable: the techniques are too fine-grained. If SOPs were replaced with the detailed descriptions necessary for one to carry them out, the flight operations manuals would be many times their present size.

C. Technique and automation

Cockpit automation has brought a plethora of techniques, largely consisting of ways in which the pilots choose to employ the automatic devices and modes to achieve a desired result. These techniques are the result of the great variety of ways that a task can be accomplished in a high-technology aircraft, due to its many modes and options. One example is the automatic level-off maneuver. Many pilots feel that left to its own, the auto-leveling commands flight maneuvers that are safe and satisfactory, but could be smoother and more comfortable for the passengers. Pilots also believe that in the auto-level-off maneuver the autothrottles are too aggressive. As a result of this, many have developed techniques to smooth these actions; most of these techniques involve switching autopilot modes during the level-off.

Other techniques have been developed to “trick the computer.” For example, the pilot of a glass cockpit aircraft, wishing to start a descent from cruise earlier than directed by the computer, can either enter a fictitious tail wind into the flight guidance computer, or can enter an altitude for turning on thermal anti-ice protection (which he or she has no intention of actually doing). Both methods will result in an earlier descent point. Why would the pilots do this? Because experience has taught them that the correctly computed path often results in speeds that require the use of spoilers, which creating vibrations that discomfort the passengers [21]. We emphasize that these are techniques and not procedures: they represent the superimposition of the pilot’s own way of doing things upon a standard procedure.

D. Techniques and procedures

Techniques are developed in relation to procedures. The procedure specifies tasks, while the technique is the pilot’s way of adding his or her own methods for doing the task. Techniques are usually found in tasks that are more loosely procedurized (e.g., level-off task). Techniques are rarely found in tasks that are tightly procedurized (in which every action is detailed in the procedure, e.g., aborted takeoff, engine shut down). Consider the following as an example for a technique which is added to an existing procedure: One airline’s altitude setup procedure states that the “pilot not flying sets the altitude alerter altitude and points to the altitude alerter. The pilot flying points at the new altitude and verbally acknowledges it.” One captain stated that in addition to the above procedure, he (as pilot not flying) first sets the altitude in the altitude alerter, and only then reads back to ATC whatever he has entered into the altitude alerter. While the task takes somewhat longer when performed this way, it attempts to eliminate the possible transformation error between what is held in the pilot’s short-term memory and what is actually entered to the machine. This technique does not violate the procedure, but rather uses a unique method to reduce the likelihood of error. A graphical description of the relationship between this technique and the overlaying procedure can be seen in Figure 3.

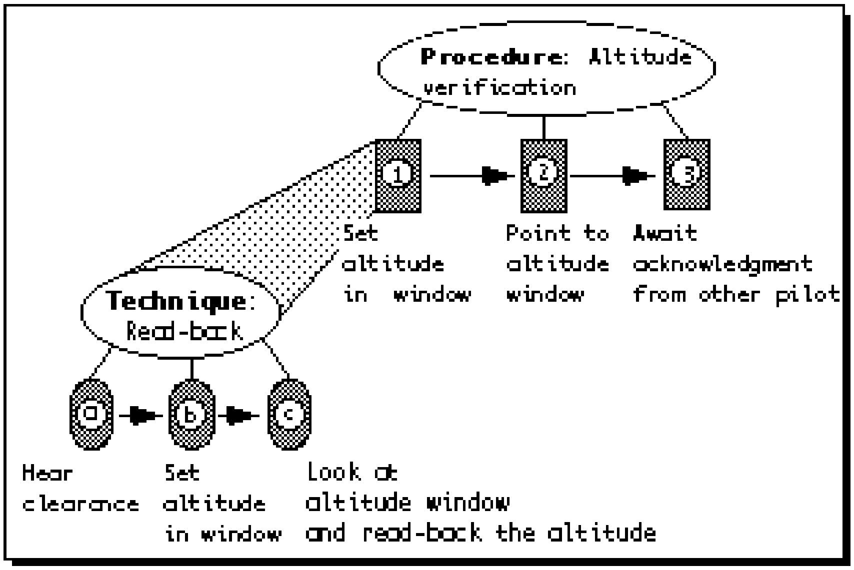


Figure 3. Framework of a technique and procedure

E. Technique and policies

Any given technique may indeed conform to the written procedure but could still entail an unnecessary risk or inefficiency. For example, federal regulations require that when flying above 25,000 feet, if one pilot leaves the cockpit, the other must don an oxygen mask. Pilots find this burdensome, and we have observed low conformity with the mandated federal regulation. We observed an interesting technique to legally overcome the regulation. In a two-pilot aircraft, the captain left the cockpit briefly while the aircraft was climbing to 33,000 feet. At about 20,000 feet the first officer called Air Traffic Control and requested level-off at 25,000, which he maintained until the captain returned, and then requested a continuation of the climb. In this case the pilot conformed to the regulation, but at some cost to the company (increased fuel usage resulting from sub-optimal climb profile) and possibly some inconvenience to the ATC system.

The technique is in full conformity with the regulation and company procedures. Yet, if the company policy/philosophy includes a statement about efficiency of operations, then it may not be consistent with such a statement. It is therefore not enough for the technique to conform to the procedure; it must also be consistent with the policies. There are cases there is no procedure for a given task and related procedures do not help in solving the problem. At this point policies are the only guidance to the crew on how they may use a technique. (Examples can be found in reference [5]).

In summary, we see that there is room for flexibility and of individualism even within rigid procedurization and standardization. Yet this requires a coherent structure of procedures and policies. If a given technique is not consistent with published procedure and stated policy, calling it a "technique" accomplishes little—it is a deviation from SOP, nothing more and nothing less.

V. PROCEDURE DESIGN CONSIDERATIONS

Philosophies, policies, and procedures cannot be developed and designed without consideration of the operational environment in which they will be employed. Commercial aviation procedures are complex because of the ever-changing environment (e.g., weather, scheduling demands, airport limitations). In order to successfully manage the flight, cockpit procedures must be compatible with the device itself (e.g., electrical panel, flight management computer) as well as with external demands (e.g., maintenance, ATC, dispatch). When this compatibility is achieved, the process of conducting the task is more efficient and the likelihood of error is reduced. The following discussion will present the design considerations associated with extra- and intra-cockpit tasks and their related procedures. For a detailed discussion see reference [5].

A. Extra-Cockpit Activities

Many cockpit procedures are dependent on the activities of exterior agents such as air traffic controllers, dispatchers, maintenance crews, gate agents, cabin crew, and more. The design of such procedures must compatible with (1) the structure of these external demands and (2) the methods that can be used by the cockpit crew to respond. For example, one company's SOP requires a check of log books for open maintenance items prior to activating any controls or switches in the aircraft. The logic behind the procedure is that this check will prevent a flight crew member from activating a system that may be inoperative, thereby causing more damage (e.g., attempting to start an inoperative power unit). At most stations, the aircraft log books are in the cockpit when the flight crews come on board. However, at some remote stations, due to unique maintenance procedures, the log book is brought to the aircraft five minutes before push-back. Therefore the procedure cannot be accomplished in those stations. A change in the procedure, so that this information can be obtained from another source, or a change in maintenance procedure is required to defeat this incompatibility.

This is an example of what we call "system procedures." The system in this case involves not only the cockpit crew and the aircraft, but also agents and activities external to the cockpit. Such system procedures must be developed by using a common definition of the task and involving all the components of the system in the design of the procedures and policies. If system procedures are designed piecemeal, then the product may be an inefficient procedure, unbalanced set of responsibilities, and complicated dependencies. All are the foundations of a potential system breakdown.

Compatibility between components in the system is not restricted to matching cockpit procedures to the operating environment; it can also be the other way around. For example, we once observed a flight in which the ground controller cleared a medium size aircraft (an Airbus A-320) toward a runway intersection. The tower controller tried to schedule the taxi such that jumbo jets (e.g., Boeing B-747) will line up for takeoff at the beginning of the runway, and small and medium size jets will line up for takeoff at an intersection several hundred feet down the runway. After the aircraft taxied to the intersection, the controller communicated to the flight to prepare for takeoff from that point. The crew, however, insisted that they use full runway. The reason? The company's policy prohibited the flight crews from making intersection takeoffs. The controller, unaware of the company policy, felt that the crew was unwilling to cooperate with him. The result was frustration on both sides, inefficient scheduling of aircraft, and a long delay.

Scheduling of Procedures. Two factors affect the flow of procedures in the cockpit: first is the sequencing of tasks and procedures, which is specified by the designer of the SOPs and checklists; second is the actual scheduling of tasks and procedures, which is conducted by the cockpit crew. The goal is to optimize the sequencing in the design process and to promote efficient scheduling by the crews. Tasks require time, attention, and cognitive resources, and therefore they contribute to workload. The designer's goal is not merely to minimize workload, but also to distribute it throughout the phase(s) of flight in order to avoid periods of very high or very low workload. While this is important for any routine operation, it appears to be extremely important in today's automated two-person cockpit [22].

Window of Opportunity. For every task on the flight deck, there is a "window of opportunity" defined by two physical boundaries. For example, the window of opportunity for conducting the "DESCENT" checklist can be defined as the flight segment between the start of the descent and 10,000 feet. These physical boundaries (descent point – 10,000 feet) can be translated into a time period during which the procedure must be executed. This time period is not a constant, but varies as a function of the altitude at the start of descent, rate of descent, and wind direction and velocity.

Although a given task can be effectively accomplished at any time within the window, it appears that there is an advantage in conducting the task early in the window of opportunity [7], [17].

The above discussion is applicable to a recent airline accident in which a MarkAir Boeing B-737 crashed short of the runway at Unalakleet, Alaska [13]. The captain, who was flying the aircraft, misread his chart and descended five miles early then depicted on the chart, striking terrain some eight miles short of the runway. The National Transportation Safety Board (NTSB) in its accident report stated that the first officer (copilot) did not notice or did not inform the captain of his error. The NTSB believed that this is because the first officer was preoccupied with his other cockpit duties. The first officer had two tasks to perform: (1) reconfiguring the engine bleeds to prevent foreign object damage; and (2) starting the auxiliary power unit. The Safety Board found that the copilot was overloaded with configuration tasks that could have been done earlier. He therefore could not keep up with monitoring the progress of the approach and back up the captain's actions. The window of opportunity for reconfiguring the bleeds began during the descent phase and should have ended before the approach phase. The NTSB recommended that MarkAir change its checklist and procedures accordingly.

Decoupling of Tasks. Tight coupling is a mechanical term which is used here to denote a phase, or a task, that is made up of several actions that are interrelated, performed simultaneously, and time dependent [15], [16]. The problem with tight coupling is that when unexpected events occur, the time dependency and the interrelation between components make it difficult for pilots to intervene quickly and efficiently in order to contain the unexpected situation. A takeoff is an example of a tightly coupled task because of the time dependency and the relation to other aircraft on the ground and in the air.

We use the term *decoupling* to denote the process in which the designer is trying to "break away" some of the interactions inherent in a phase or a task. In decoupling an activity, the level of criticality is an important factor. Not all cockpit tasks conducted during the same phase of flight are equivalent in terms of criticality. Some may be more critical (e.g., monitoring the final approach), some may be less (e.g., cabin announcements). In most cases, the primary tasks are continuous (taxiing the aircraft, looking for taxiway, etc.), while the secondary tasks are discrete tasks (entry of manifest changes into the computer, configuring bleeds). Critical primary objectives should be well "guarded." This can be done by decoupling secondary or tertiary tasks that may interfere with performing the primary task. See reference [5] for a discussion on task priority and methods for achieving decoupling.

B. Intra-Cockpit Activities

Procedures are an integral part of the pilot-machine interface, specifying and dictating the actions by which the pilot is expected to interact with the machine. Procedures, therefore, must be compatible with the device. For example, the procedure which dictates the sequence of items in programming a flight guidance computer, must be compatible with the structure of this interface in terms of page structure, hierarchy, and the text to be entered.

The flow of procedural steps. In the cockpit of an airplane, the instruments, units and system panels are arranged in a certain “geographical” locations according to frequency of use, criticality, and other human factors considerations. In designing efficient and error-resistant setup procedures, the steps must follow some logical and efficient flow of motor and eye movement along the cockpit panels. Checklist procedures that serve to verify the accomplishment of these setup procedures can also be conducted in the same sequence. For example, one can conduct the “BEFORE ENGINE START” checklist from the aft (upper) portion of the overhead panel, moving with the checks toward the lower part of this panel. By using a top-to-bottom order of checking panels and items, the design can accommodate population stereotype of sequence as well as biomechanical considerations [4].

Aircraft systems and procedures. A procedure that details how to operate a particular sub-system must be accurate and compatible in terms of its procedural steps, actions, and flow. The following examples will show how much the procedural designer must be attuned to the engineering aspect of the device (or sub-system). One company’s emergency procedure for coping with asymmetrical flap extension (which can have significant effect on lateral control of the aircraft) had to be rewritten when it was found to be inaccurate. The problem? The power supply for activating the flaps, following asymmetrical flap extension, was different from the standard configuration for this model aircraft. The airline, which originally specified the non-standard power supply configuration, failed to modify the procedure accordingly. (The inaccurate procedure was in effect for some five years before it was detected). Such problems are not unique to airlines. During Space Shuttle Mission 49, the crew of the orbiter Endeavor tried to deploy a rescued satellite (Intelsat). The primary and backup deployment circuits would not send power to the cradle holding the satellite. “Investigation showed that the checklists used in Mission Control and on Endeavor were identical to those on the other three NASA orbiters. But the problem occurred when circuitry for Endeavor’s wiring was engineered differently and the checklists were not changed to conform with the new orbiter's design.” The problem was finally overcome with the help of engineers in Ground Control [1].

Cockpit layout and procedures. During our field study we have observed instances of incompatibility of procedures with the ergonomic layout of the flight deck. Consider the flap/slat and gear levers, for example. Traditionally, gear and flap/slat levers were mounted in the first officer's area (right side of the cockpit). They are not within easy reach for the captain in the cockpit of a widebody airplane. In most U.S. airlines the captain and the first officer rotate the duties of pilot flying and pilot not flying each flight. If the first officer is the pilot flying, the SOP usually dictates that the captain raise the gear and flaps/slats after takeoff. To do this, the captain must lean to the right of the throttle quadrant to grasp the gear or flap/slat lever(s). In several widebody aircraft cockpits the captain cannot see the flap/slat detents very well and he or she can accidentally push the throttles rearward (an action that will lead to thrust reduction during takeoff). Similar problems in reaching for a lever may occur when the first officer, as the pilot flying, wants to use the speed-brakes which are located close to the captain’s seat and across the throttle quadrant.

There are two approaches for solving this incompatibility: (1) procedural change, and (2) hardware change.

1. Some have argued that since the existing cockpit layout cannot be changed (within reasonable boundaries of cost efficiency), the procedure should be changed so that when the first officer is the pilot-flying, he or she will retract/extend the gear.
2. In contrast, the designers of new generation aircraft such as the Airbus A-320 and McDonnell Douglas MD-11, have located these levers on a pedestal between the two pilots. It is within equal reach distance for both the captain and the first officer. These aircraft were designed during a different social era than their predecessors. Social culture has affected the airlines' philosophies of operation (a flatter cross-cockpit authority gradient) and the airlines' policies (rotation of pilot-flying duties), and has thereby affected associated procedures. To accommodate these philosophy, policy, and procedural changes, the cockpits were designed accordingly.

Paperwork and procedures. Documents, manuals, checklists, and many other paper forms are used in the cockpit. The compatibility between the procedures and their associated devices (manuals, checklist cards, etc.) affects procedural execution. Ruffell Smith [18] reported that excluding aircraft flight manuals, the amount of paperwork needed for a flight from Washington D.C. via New York to London, had a single side area of 200 square feet. Interestingly, the 15 years since Ruffell Smith's study have not yielded any reduction in cockpit paperwork. On the contrary, the problem has only intensified [3]. During one cockpit observation we encountered a situation that exemplifies this problem:

While the aircraft was taking off, the "Hydraulic RAT Failure" warning appeared on the aircraft's electronic monitoring display. The concern was whether the ram air turbine (RAT) was unlocked and hanging down from the belly of the aircraft. The captain decided to abort the takeoff and work on the problem. However, he could not find the written procedure that specified how to verify whether this indication was true or false (RAT sensor failures have occurred in the past). There were five places where this procedure could be listed: (1) the Flight Operational Manual, (2) the Supplemental section in the flight manual, (3) Operations Bulletin, (4) the aircraft newsletter, and (5) on the dispatch paperwork. The procedure could not be found in any of these. An attempt to find it using an index failed—there was no index in the manual. The captain called the local maintenance station and asked them to read it to him on the radio. They could not find it either. After waiting for several minutes, he decided to conduct the procedure from memory—a clear violation of a company policy that requires that procedures must be conducted from the book and not by memory. (These deficiencies have since been corrected by the airline.) We argue that the entire documentation supplied to the cockpit (and elsewhere) should be regarded as a system, and designed accordingly as a system, not a collection of independent documents. A clear and logical (from the user's view) structure for this system and a criterion for the location of different procedures is important.

Computerwork and procedures. Procedures dictate tasks, and often these tasks involve some form of transformation (e.g., converting altitude reported in meters to setting the altimeter in feet). A complex transformation between input and output may increase workload, create possible confusion, require procedural aiding, and worst of all, invite error. The following example illustrates this problem in the context of data entry to the flight management computer of a high technology aircraft.

The crew of a Boeing B-757, preparing to fly from Miami to Washington National, was dispatched with a computer-generated flight plan that required crossing the Carolina Beach aeronautical beacon. The identifier for Carolina Beach beacon was listed as "CLB." When the crew attempted to enter the flight plan into the computer, it resulted in an error message of "not in database." What was the problem? The Carolina Beach beacon is a non-directional beacon, of which very few are still used for navigation by jetliners. The flight plan, to be correct and compatible with the "expectations" of the computer, should have read "CLBNB." It was not until the crew took out their paper charts and traced the route that the data entry error was apparent [21]. If the same computer-generated flight plan had been issued to a older technology aircraft, there would be no such incompatibility. But that is exactly the point—documents must be compatible with the equipment they support.

VI. IMPLEMENTING PROCEDURES

One should not assume that management's duties are over once a procedure is designed and implemented. The practices of the users and the outcome of the procedure are also within the responsibility of management. A common complaint of many flight crews is that procedures are being changed at a rate far greater than would seem required by such external factors such as new federal regulations or air traffic control procedures, new equipment, etc. Many believe that flight managers sometimes change procedures for the sake of making a political statement or to justify a project that they are responsible for. The situation can be alleviated by management seeking to minimize non-essential procedural changes, and by, wherever possible, explaining the reasons for the changes. Some of the counter-measures that management can take in attempting to avoid minimize non-essential procedural changes are listed below.

A. Experimentation

We recommend that important flight-deck procedures should be validated experimentally by testing them against the behavior of regular pilots, and not the judgment of others. The experimentation should take place in the appropriate flight simulator using a true sample of the target population, i.e., regular pilots, as opposed to management pilots. A simulator test will uncover possible problems that would not be apparent to persons writing procedures "around the table." This may also reduce the likelihood of modifications to the procedure down the road.

B. Documenting Procedures

It is extremely important that the operational logic that leads to the construct of a procedure be documented and maintained. Documentation is essential in order to provide for the efficient and cost effective development, modifications, and maintenance, as well as for understanding the concepts behind a complicated set of procedures [19]. While observing several procedure-design sessions, we noted that flight management personnel who were responsible for designing procedures could not recall the operational logic and the constraints that prompted an existing procedural sequence. This is understandable, especially in light of constant change in personal in flight management departments. However, the result is inefficiency—much time is spent in trying to recall or understand the logic and constraints that led to the construct of the procedure. Critical constraints may be forgotten, and what is even worse, constraints that may no longer exist, are being "carried along."

C. Communicating Procedures

Once the decision to change a procedure is approved by flight management and the Federal Aviation Agency (FAA), the change must be communicated to the line pilots. This may seem the most trivial part of procedure modification, but it is not. Pilots will usually, in some form or another, resist changes in procedures, particularly the ones that appear to be "change for the sake of change." Management must be able to persuade itself and the line pilots that the procedure change is truly necessary and beneficial. Flight crews, therefore, have to know the why behind a procedure change and not just what and how. The "Four-P" model could be used in this regard, as the logical progression from philosophies, policies, to procedures can be described.

VII. CONCLUSIONS

Flight deck procedures are the backbone of cockpit operations. They are the structure by which pilots operate aircraft and interact with other agents in the system. Procedures are one of the most important factors in maintaining flight safety during both normal and abnormal conditions.

It was traditionally believed that procedures are only hardware/software dependent—that they are inherent in the device. We have tried to show throughout this paper to that this is not the case. We argue that they are also dependent on the operational environment, the type of people who operate them and the culture of the company they work for, and the nature of the company's operations. Procedures are not inherent in, or predicable from any single entity.

We have attempted to demonstrate that even in this highly procedurized system there is room for individualism, and that individualism can and should be allowed in these human-machine systems. We have also tried to show that there is no set of procedures that can substitute for the intelligent human operator. And therefore both the capabilities and limitations of the human operator and the unique environment in which he or she is to operate must be thoroughly considered in the process of designing procedures.

There is no "royal road" to procedure development. There is no such thing as an optimal set of procedures. No manager will ever be able to "open up the box," install the device, and install "good" procedures along with it. Nor do we anticipate that any computer technology can make this easier. Pilots are trained to fly by procedures. Aircraft are built to operate by procedures. Government regulations are based on procedures. It is a long, tedious, costly, exhausting process. We do not know of any shortcuts.

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