A STAMP Analysis of the LEX Comair 5191 Accident

Thesis submitted in partial fulfilment of the requirements for the MSc in Human Factors and System Safety

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Abstract

A new view, a holistic systems view, that sees individuals in systems, is growing. It is a view which sees "human error is an effect of trouble deeper inside the system….[where] we must turn to the system in which people work: the design of equipment, the usefulness of procedures, the existence of goal conflicts and production pressure" (Dekker, 2007, p. 131) A new, holistic systems perspective, accident model is used for analysis of the Comair 5191 accident in Lexington, KY on August 27, 2006. The new model is called: Systems—Theoretic Accident Modeling and Processes (STAMP). It incorporates three basic components: constraints, hierarchical levels of control, and process loops. Accidents are understood "in terms of why the controls that were in place did not prevent or detect maladaptive changes, that is, by identifying the safety constraints that were violated and determining why the controls were inadequate in enforcing them" (Leveson, 2002, p. 55). This STAMP analysis of the 5191 accident illustrates the usefulness of the STAMP model to foster evaluation of the whole system and uncover useful levers for elimination of future loss potential thereby making progress on safety.

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Introduction

After a tragedy like the Comair 5191 accident an initial question is what caused this? The question is indicative of the predominant event model inherent in today's society, a linear chain of events. The dualistic deconstructionist notions of two giants of the scientific revolution, Rene Descartes and Isaac Newton, prepared the soil from which this model grew. Using a chain of events model, we start with the accident event and work backwards, taking the sequence apart (deconstructionism) to find what failed, either mechanical or human, (dualism) and the cause will unfold (Dekker, 2005). This assumes the deconstruction process can be done without so thoroughly contaminating the parts that reconstruction produces something entirely unlike what was originally taken apart to understand in the first place (Leveson, 2002).

A linear chain of events assumes a simplicity which is not present in the complex technological systems we build today. The events selected for inclusion are arbitrary, proximate, and can limit understanding of effective measures for preventing future loss (Leveson, 2002). Redundancy is often used as a failure prevention measure but this only interjects additional complexity into the system. In turn, complexity provides more possibilities for failures to develop with increasingly unexpected interactions. All the while, after each accident, the model used imposes nonexistent simplicity to the very system it is attempting to explain. To free ourselves from this "tangled hierarchy" (Lanir, 1986) we need a model which acknowledges the inherent complexity of the system, a model consistent with what it is attempting to explain. In short, we need a "systems model".

One such model has been developed by Nancy Leveson, Systems—Theoretic Accident Modeling and Processes (STAMP). STAMP is built upon systems theory. At its core are the ideas of emergence and hierarchy, and communication and control. Concentration is on the system as a whole as apposed to separating its parts. Accidents occur because of "inadequate control or enforcement of safety-related constraints" as apposed to simple component failures (Leveson, Daouk, Dulac & Marais, 2003, p. 3). Component interactions which break the system safety constraints generate events which are the result of inadequate control. However, mere identification of the inadequate control is not a stopping point. The systems control structure, itself, "must be examined to determine why the controls for each component at each hierarchical level were inadequate to maintain the constraints on safe behavior and why the events occurred" (Leveson et al., 2003, p. 3). Controllers act in harmony with their mental, or process models of the system[1]. These models are updated and kept consistent with information received through feedback in the process loop. Finally, the entire process occurs within a contextual environment.

[1] Mental models refer to a person, process models refer to groups of people at an organizational level.

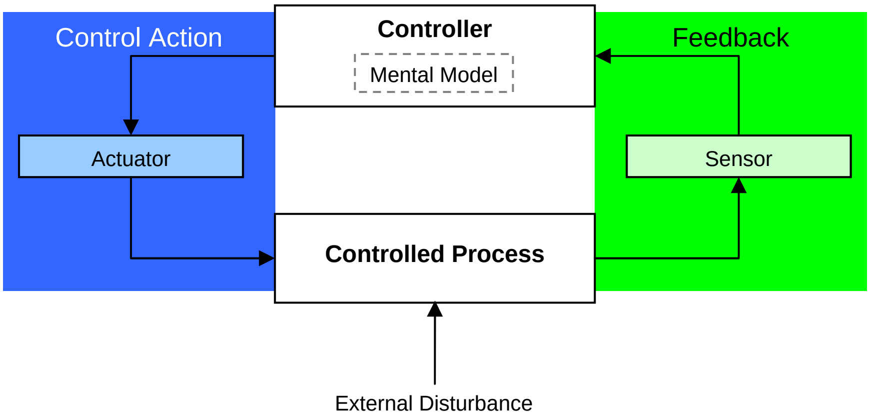

Figure 1 Basic Process Loop

A systems model view moves beyond the search for a "root cause" and its propensity for blame, and searches for the reasons why the system set the stage for an accident initially. It is important to remember the "local rationality principal": that each person in the system acts according to with what makes sense to them at the time (Dekker, 2006). A system view will also recognize that variability of human action is consequential in both success and failure (Hollnagel, 2008). Accidents occur amidst normal people performing normal work (Perrow, 1999).

The Basic Events of Flight 5191

Each of the flight crew members arrived at Lexington, Blue Grass Airport, (LEX) in different ways. The Captain, Jeff Clay, arrived as a deadhead crewmember in the aircraft cabin and released from duty at 1546 EDT[2] on August 26, 2006. First Officer Jim Polehinke arrived as an acting crewmember of flight 9471, an aircraft reposition flight, and was released from duty at 0200 EDT on August 26, 2006. Both crewmembers were scheduled to return to duty at 0500 and 0515 respectively, to operate flight 5191 from LEX to ATL (Atlanta Hartsfield International Airport).

On the morning of August 27, 2006 the crew met in the hotel lobby and took the 0500 hotel van to the airport. The crew checked in at the airport at 0515 and proceeded to the aircraft. Even though this was each crewmember's third flight day of their respective trips it was their first flight together of their trip pairings. The conversation captured, while at the gate, by the cockpit voice recorder (CVR) reveals a normal conversation of crewmembers becoming acquainted with each other while completing their respective preflight tasks.

Toward the last part of the gate flight preparation segment of approximately 20 minutes, the First Officer (FO) gave the takeoff briefing and mentioned that "lights were out all over the place" (National Transportation Safety Board, 2007, p. 140) when he had flown in two nights before. Varying from prescribed procedure, the FO also gave the taxi briefing, indicating they would take taxiway Alpha to runway 22 and that it would be a short taxi. This characterization was appropriate since the Air Terminal was at the north end of the airport close to the departure end of runway 22.

Unbeknownst to the crew, the airport signage was inconsistent with their airport diagram charts as a result of construction at the airport. The airport construction also resulted in various taxiway and runway lighting systems being out of operation at the time. Several of these inconsistencies were not part of the information given to the crew via the information channels available, i.e. the

[2] All times relating to the 5191 accident are in Eastern Daylight Time, unless otherwise specified.

airport Notices to Airmen (NOTAMs), company dispatch release information and the current Automatic Terminal Information Service (ATIS) (Air Line Pilots Association International, 2007).

When Comair flight 5191 pushed back from the gate at 0559, it was still an hour before sunrise, so conditions were dark. After pushback from the terminal gate and the ground crew's salute, flight 5191 called for taxi clearance with information Alpha. LEX ground control cleared "Comair one ninety one[3], taxi to runway two two", the FO confirmed with his read back, "…taxi two two" (National Transportation Safety Board, 2007, p. 150). As the captain began taxiing flight 5191 from the ramp area toward taxiway Alpha, he called for the flaps to be set at 20 degrees and for commencement of the taxi check flow. Having completed the taxi check list verbalization and establishing the aircraft on taxiway Alpha, Captain Clay then called for commencement of the before takeoff flow and check list. It was at this time that variation with procedure occurred in the form of conversation about other airline hiring practices. The conversation spanned forty seconds and completed a subject thread interrupted 15 minutes earlier. Because the conversation at the time was irrelevant to past, present or future flight operation industry regulations identify it as "nonessential conversation". Therefore it is considered incompliant with the commonly referred to "sterile cockpit rule". This conversation primarily consisted of the FO talking, while simultaneously accomplishing the forty-four actions/confirmations of the before takeoff flow (Air Line Pilots Association International, 2007).

The captain brought the aircraft to a stop short of runway 22, except, unbeknownst to him, they were actually short of runway 26. As the aircraft came to a stop the FO completed verbalizing the first part of the before takeoff check list, switched to the public address system and gave the passenger announcement. After receiving the flight attendant signal that the cabin was ready for departure, the final items of the before takeoff checklist were completed. First Officer Polehinke called LEX tower for takeoff clearance. The LEX tower controller scanned runway 22 to assure there was no conflicting traffic, then cleared Comair 191 to take off and fly runway heading. Three minutes and 30 seconds after commencing taxi from the gate area, Captain Clay transferred the flight controls to First Officer Polehinke and the takeoff sequence of Comair flight 5191 began.

A turbojet takeoff sequence is precisely scripted and trained to exceptionally tight parameters. It is the most consistently dynamic 30 seconds in aviation procedure, not only in terms of the aircraft's energy state, but also in terms of the crew's cognitive processing. The aircraft accelerates from zero knots to approximately 135-140 knots (150 mph plus or minus) and becomes airborne. Concurrently, the crew is making millisecond evaluations and decisions. They look for and are prepared to instantly categorize an abnormality as one requiring the abort reaction or continue action. There is no time to analyze. The pilot must know what is linked to each reaction and when, because often an anomaly is linked to the abort reaction for a few seconds and then becomes linked to the continuation action. Passing 100 knots the abort reaction becomes linked to only two categories, engine failure or fire and a perception the aircraft is unsafe or unable to fly. For those who have never had the privilege of performing a turbojet takeoff, it is impossible for words to convey the intensity with which the mind processes in this dynamic environment. Pilots' actions at this time, quite literally, result in life or death for all those aboard the aircraft.

The view down runway 26, when FO Polehinke took control, had the illusion of some runway lights. By the time they approached the intersection of the two runways, the illusion was gone

[3] Comair flight numbers are listed with Air Traffic Control using only the last three digits, thus radio transmissions refer to flight 5191 as flight 191.

and the only light illuminating the runway was from the aircraft lights. This prompted the FO to comment "dat [*sic*] is weird with no lights" and the captain responded "yeah" (National Transportation Safety Board, 2007, p. 157). During this exchange the aircraft was in full acceleration from 65 knots through 80 knots and was rapidly approaching the shift into the takeoff high speed abort regime. During the next 14 seconds, they traveled the last 2500 ft of remaining runway. In the last one hundred feet of runway, Captain Clay called "V1, Rotate, Whoa" (National Transportation Safety Board, 2007, p. 157). The flight became momentarily airborne and impacted a line of oak trees approximately 900 feet beyond the end of runway 26. From there, the aircraft erupted into flames and came to rest approximately 1900 feet off the west end of runway 26 (Burtch, 2006b).

Of the 50 people on board flight 5191, 49 were killed. The FO survived his serious injuries as a result of a dramatic rescue by City of Lexington Metro Police Officer Bryan Jared, and Blue Grass Airport Public Safety Officers Jon Sallee, and Pete Maupin who were able to deliver him to the hospital within 20 minutes of the accident.

A STAMP Analysis of the Comair 5191 Accident

The system hazard relevant to this accident is: *death or injury from runway incursions and operations on wrong runways or taxiways.*

The related system safety constraint is: *The safety control structure must prevent public exposure to death or injury during airport operations. Additionally, regulations must reduce exposure risks during periods of airport construction.*

Each component of the National Air Transportation System has a role in maintaining this general safety constraint. The individual components will, in turn, have their own safety constraints to enforce which are related to their unique component function in the overall system.

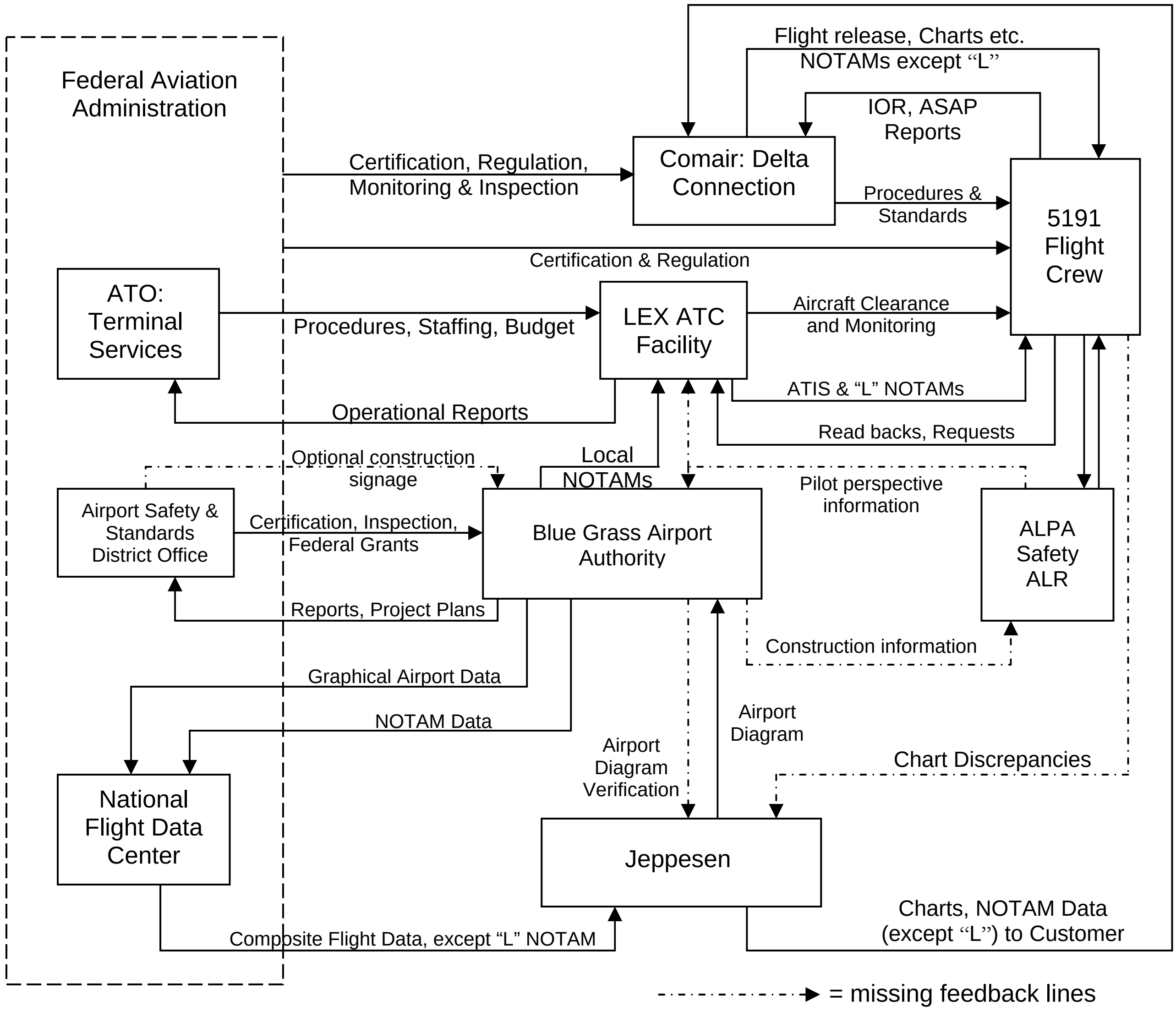

Figure 2 Basic Aviation Safety Control Structure. Lines going into the left of a box are control lines. Lines from or to the top or bottom of a box represent information, feedback, or physical flow.

The Physical Process View of the Accident

A common reality of “system accidents” is the lack of physical component failure. The Comair 5191 accident holds to this reality. The accident investigation revealed no aircraft failures. By defining the parameters of the physical system to include runway 26 and aircraft N431CA, then the “probable cause” of the accident at this level would be the inability of aircraft N431CA to become safely airborne in the distance provided by runway 26. The safety constraint enforced at this level would be that the aircraft must be able to attain a predetermined airspeed in order to safely become airborne.

The runway was not designed to provide adequate takeoff distance for aircraft with a weight greater than 12,000 pounds. In addition, the Canadair CL65-100 was not designed to be able to take off safely on runways of only 3501 feet. The limited distance of runway 26 is the contextual factor affecting the accident. The aircraft manufacture calculated, given the aircraft’s takeoff weight of 49,087 pounds, that a minimum ground roll of 3744 feet was necessary, i.e. 243 feet more than runway 26 provided (Burtch, 2006a).

The Flight Crew

This level of analysis involves those who are often referred to as "sharp end operators". They are those proximally closest to the accident events and can become the easy targets of blame in predominantly linear accident models. However, even at this lower hierarchical level, STAMP enables a decidedly non-liner view of the accident.

Evidence from the accident investigation confirms the crew of flight 5191 was well trained and qualified to safely conduct their responsibilities. All their proficiency evaluations were satisfactory and current. During interviews for the accident investigation the crew was described in such words and phrases as "professional", "by the book", "adhered to operations standards", and "followed the check list", by check airmen, instructors, and fellow pilots (Tew, 2006).

The company policies and operation procedures were designed to provide parameters in which to safely operate the aircraft. Additionally, Federal Aviation Regulations (FARs) and Air Traffic Control (ATC) clearances provide constraints to enable safe operation in the overall air traffic system. While a crew knows that there will always be some level of variation in day to day operational environments, they also trust the system to provide information about alterations known to, or brought about by, other segments of the system, i.e. re-designation, closing or moving of a taxi way. Crews recognize that correspondent regulations and standards are applied to other segments of the system in the same manner as expected within the crew's industry segment. In order for the system to operate, others are trusted to accomplish their responsibilities within the established guidelines.

In order to take off safely on the morning of August 27, 2006, the crew of flight 5191 had to safely taxi to runway 22. This is the primary constraint of the first level. All the other procedural, regulatory, and guidance parameters serve to facilitate the successful accomplishment of this task. Indeed, Captain Jeff Clay and First Officer Jim Polehinke believed they had safely taxied to runway 22. The fact that the aircraft was actually on runway 26 is not as interesting as how the system set up the pilots to believe they were on runway 22.

The human factors principle of "local rationality" says that people act in ways which make sense to them at the time (Dekker, 2006). Therefore, one's actions would provide indirect indications of one's mental model, because our "preconceptions" (mental models) dictate what action is understood to be correct (Weick, 1988). Thus, an examination of one's probable mental model makes it possible to come to an understanding of why one's actions are sensical. So, it is reasonable to conclude that the crew's actions were in harmony with each of their mental models.

Each crewmember's operational exposure to the north end of the LEX airport occurred prior to August 20, 2006, at which time the airport structure became inconsistent with the available charts. The crew received no information in their dispatch release paper work (which included available NOTAMs), the ATIS, or the Jeppesen airport diagram, which would indicate there was any difference from the crew's previous experience. In this case, the missing feedback information prevented the crew from being able to update their preconceptions. Therefore, their mental model remained inconsistent with physical reality. This characterization of the crew's mental model is supported by the FO's taxi brief. The brief not only implied a lack of anything unusual, it reinforced the normality of the taxi when the FO communicated that they would take "Alpha [to runway] two two, a short taxi" (National Transportation Safety Board, 2007, p. 141). The Chart for LEX did show taxiway Alpha as the route to runway 22 and it is, indeed, a short distance.

Normal taxi procedures allow the FO to complete various flows and checklists while the aircraft is in motion. Therefore the captain is the only crew member involved in surface navigation much of the time. High threat taxi procedures carry a control action that the aircraft is to be stopped while the FO is involved with checklists. This enforces a safety constraint that both crew members will be heads up and involved in surface navigation during abnormally complex and potentially confusing situations. According to the Comair Operations Manual in effect at the time of the accident, high threat taxi procedures are required if the visibility was less than 1200 feet, if there was no operational control tower, or if the captain believed exceptional vigilance was needed. On the morning of the accident, there were no restrictions to visibility and LEX had an operational control tower. Additionally, as there was no feedback indicating the taxi would require "exceptional vigilance", Captain Clay did not use high threat taxi procedures. Therefore, the associated control was not enacted, leaving the associated safety constraint unenforced.

The captain's probable preconception of the view from the runway 22 hold short line, prior to the airport changes of August 20, 2006, is important to consider. The angle and distance to the runway from both runway 22 and runway 26 hold short lines were within a few degrees of each other and perceptively similar. From the runway 22 hold short line, the view in the 10 o'clock position, across the runway, was dark. Slightly left of straight ahead, in the 11 o'clock position, on the far side of the runway, was a short line of red lights: the runway end identifier lights. A comparison of the view from the runway 26 hold short line, on the morning of the accident, revealed a strikingly similar picture. As already mentioned, the angles to the runway were within a few degrees of each other. The view ahead in the 10 o'clock position, across the runway was dark. Slightly left of straight ahead in the 1030 position, on the far side of the runway was a short line of red lights: the low barricade red lights, which could appear similar to runway end identifier lights.

An additional aspect of the hold short line preconceptions should be considered. Prior to the changes made on August 20, 2006, from the runway 26 hold short line there were no red lights anywhere. The view across the runway was not dark. Instead, blue taxiway lights marked the continuation of taxiway Alpha to the runway 22 hold short line. Therefore, when Captain Clay stopped at the runway 26 hold short line, the view closely matched his mental model from the runway 22 hold short point. The view also disagreed sharply with the preconception of the view from the runway 26 hold short line. Additionally, when a person is focused on one set of features, less prominent features are unlikely to be detected (De Keyser & Woods, 1990). The sign (located low and in the 930 position) indicating they were holding short of runway 26, was not detected in a manner to sufficiently alter the crew's preconceptions[4].

According to the NTSB interview (Tew, 2006) with the captain who was paired with FO Polehinke on his previous flight, it is reasonable to accept that the FO's mental model included details observed during that earlier flight. The captain indicated that all of the lights on the west side of runway 22 (the FO's side of the aircraft) were out except for the first 1500 feet between the approach end of runway 22 and the intersection of runway 26. When the FO arrived in LEX, there were, also, no center line lights on runway 22. These two items would have updated the FO's mental model of the runway and would become significant during the FO's takeoff of flight 5191. During the taxi north to the terminal, the Alpha taxiway lights, on the FO's side, were out the entire distance (Fedok, 2006). The encounter with these lighting outages are likely what updated the FO's mental model to the one of "lights are out all over the place" (National Transportation Safety Board, 2007, p. 140), expressed the morning of the accident.

[4] The descriptive views are based on the researcher's analysis of the LEX Signage and Marking plan chart (Fedok, 2006), as well as personal experience from operations in LEX prior to the Comair 5191 accident.

Captain Clay's mental model of the airport lighting would have been updated by the NOTAMs in the dispatch release, which indicated the following lighting systems to be out of service:

- Runway 4-22 center line lights
- Runway 4 touch down zone lights
- Runway 4 approach light system
- Runway 26 end identifier lights
- Runway 8-26 medium intensity runway lights.

His updated mental model was likely reinforced by the FO's comment, in the departure briefing, that "lights are out all over the place" (National Transportation Safety Board, 2007, p. 140).

A comparison of what the crew expected on the departure runway itself and the view on runway 26 gives a powerful understanding of the crew's "local rationality". Each runway has a crossing runway located approximately 1500 feet from threshold. They both have an increase in elevation at the crossing runway. The opposite end of each runway is not visible during the commencement of the takeoff roll. Each runway has a dark-hole appearance at the end. They both have 150 foot wide pavement (runway 26 was edge striped to 75 feet). Neither runway had lighting down the center line.

Because cues indicating a problem are seldom obvious and situations may deteriorate in a piecemeal manner, one's understanding of the conditions can lag behind the rate of change (Orasanu & Martin, 1998). This concept is especially true during the dynamically intense takeoff sequence. In context of the takeoff procedure, edge striping, which narrowed the 150 foot wide pavement to the useable width of 75 feet, would appear subtle. Ambient light from the airport parking garage made the threshold of runway 26 appear bright and clear. In addition, lights from runway 22 gave the illusion of some runway edge lights on runway 26 (Air Line Pilots Association International, 2007). When the FO made the comment that it looked weird with all the lights out, they were passing over the intersecting runway. The visual impact of the unlit runway had just become evident, but the FO's mental model was one with runway lights out on his side. His ability to process the significance of no lights at all was lagging behind the pace of environmental change. The captain's reply of "yeah" only reinforced an expected runway condition consistent with the crew member's mental modals. The end of the runway was the only cue strong enough to make them realize their mental model was inconsistent with the reality confronting them through the windshield (Air Line Pilots Association International, 2007).

There are reasonable explanations as to why the crew did not notice that their heading during runway line up was not that of runway 22 (220 degrees). Comair had no specified procedures to confirm compass heading with the runway (Tew, 2006). Modern Directional Gyros (DG) automatically compensate for precession thus it is unnecessary to set the DG with the runway heading and compass indication as taught during primary flight training. For this reason many crews have abandoned the habit of checking the DG, runway heading and compass indication.

For the crew, a permeating factor was the effect of sleep loss fatigue. According to the Sleep, Activity, Fatigue, and Task Effectiveness Model / Fatigue Avoidance Scheduling Tool (SAFTE™/ FAST™) analysis, the 5191 Captain and FO were functioning in the questionable band of performance, at 87% and 89% effectiveness,[5] respectively (Air Line Pilots Association International, 2007).

[5] For comparison, a blood alcohol level of 0.08g/100ml equates to 70% effectiveness (Air Line Pilots Association International, 2007).

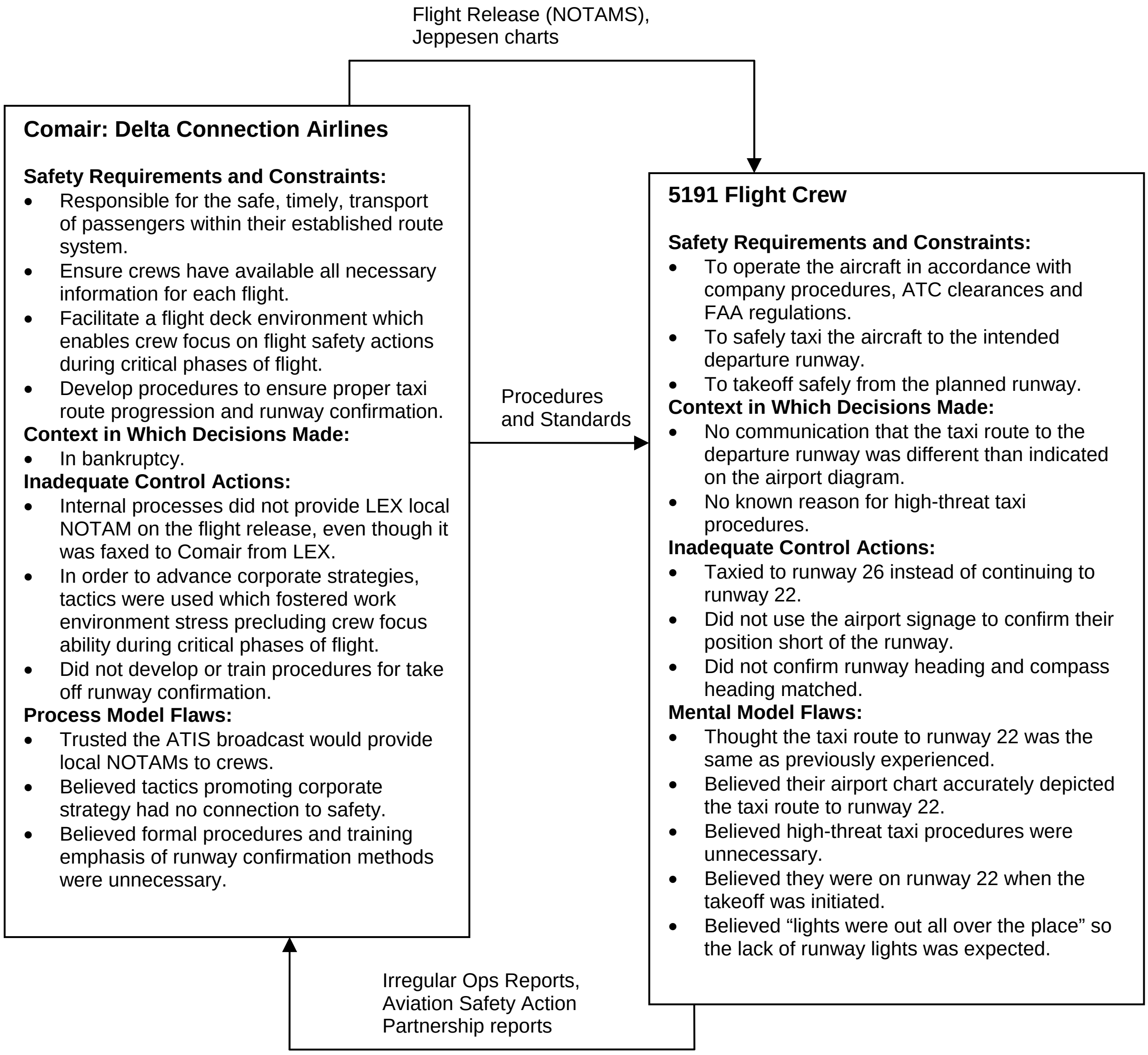

Figure 3 Comair Airlines Control Structure

Comair: Delta Connection Airlines

Comair had succeeded in operating almost 10 years accident free when the 5191 accident occurred. During those 10 years, Comair approximately doubled its size, was purchased by Delta Air Lines Inc., became an all jet operator and, at the time of the 5191 accident, was in the midst of its first bankruptcy reorganization. As is typical with all bankruptcies, anything management believed was unnecessary was eliminated, and everything else was pushed to maximum utilization. Although focusing on elimination of unnecessary factors is considered to be a reasonable strategic maneuver, it can, inadvertently, cause a crisis "through its effects on realities constructed by dishearteded [*sic*] workers" (Weick, 1988, p. 314).

During bankruptcy the federal laws allow an airline to force labor contract renegotiation and if necessary impose concessions on the labor group via a federal judge's ruling. "A campaign against a union is an assault on individuals and a war on the truth" (Levitt, 1993, p. 1). The conflict is waged on an emotional battlefield using weapons of disinformation and personal assaults to fire ammunition of threats, manipulations, lies and distortions.

In the weeks immediately preceding the 5191 accident, Comair had demanded large wage concessions from the pilots. Comair had also indicated the possibility of furloughs and threatened to reduce the number of aircraft, thereby reducing the available flight hours and implying reduction of work force. The economic pressure created by these threats was an intense stressor and a frequent subject of discussion among Comair pilots. In fact, during the 5191 preflight, the pilots engaged in a conversation regarding the financial stress factors caused and threatened by management. The conversational subject, while suspended for a time, did not conclude until after the taxi check procedure of 5191's taxi (National Transportation Safety Board, 2007). The impact of the impending cuts created an ongoing crisis situation which increased the pilots' propensity for distraction and, therefore, an elevated risk that critical information would be missed or unobserved.

The method corporate management chose to use in achieving cost reductions from the pilots involved using common tactics of job threats including intimidation and misinformation about the future. These tactics were a dysfunctional control input to the system which violated the safety constraint to facilitate a flight deck environment which enables crew focus on flight safety actions during critical phases of flight[6]. The unsafe control action elevated the risk that lower level operators (pilots) would be distracted from their primary task of safely navigating the airport. Safety concern is focused on the methods used to achieve the corporate cost reduction strategic goals not the goals themselves. Management believed that their corporate strategic actions had nothing to do with safety; that people would, somehow, leave their personal fears and emotions outside the workplace door and remain undistracted while doing their job, even when those distracting fears and emotions were propagated by management inside the workplace.

There were other methods available to Comair management which would have supported the safety constraint. In other less safety intense systems, such as the grocery store industry, when management uses such common tactics, they are unlikely to result in an elevated risk of death or injury to the public. However, when those same tactics are used in a safety intense system such as aviation, medicine, or nuclear power, etc., it is unreasonable to believe there will not be a negative effect on both individual and public safety. Nature does not recognize the barriers we set up compartmentally separating strategic and safety actions in an airline (Snook, 2000).

Confirmation of takeoff runway is a primary skill taught in primary instrument training. The present group of pilots was trained in aircraft that had Directional Gyros (DG) which required periodic manual synchronization with the compass to compensate for gyroscopic precession. While lined up on the takeoff runway threshold, the DG would be confirmed with the compass and set to the runway heading. This procedure served two purposes: to compensate for DG precession and to confirm proper takeoff runway.

Since modern transport category aircraft have automatic compensation for DG precession, there is no longer a need to manually set the DG to the compass during lineup on the takeoff runway. Comair's training did not, however, emphasize the need to continue to verify takeoff runway heading with the DG. There was, also, no active crewmember cross check procedure to use airport signage as confirmation of the runway being held short of while at the runway hold short line. These are two ways in which Comair did not maintain the safety constraint to provide procedures for takeoff runway confirmation.

[6] "Critical phase of flight includes all ground operations involving taxi, takeoff and landing, and all other flight operations conducted below 10,000 ft, except cruise flight. Taxi is defined as 'movement of an aircraft under its own power on the surface of the airport'" (Tew, 2006, p. 12)

Comair obtained NOTAMs from Jeppesen's electronic uplink. The dispatcher would then collect the necessary NOTAMs to be provided on each respective flight release. Jeppesen data did not contain local NOTAM information and Comair had no additional process to provide local NOTAMs on the flight release. Therefore, the LEX local NOTAM about the closure of taxiway Alpha North of runway 26, which had been faxed to Comair from LEX, did not become apart of the 5191 flight release (Fedok, 2006). Comair expected the airport ATIS broadcasts would provide all the local NOTAMs necessary for each flight (Tew, 2006). Comair also did not have a feedback method to verify that the ATIS broadcasts were reliable at consistently delivering all local NOTAMs. Comair's control action to provide all necessary information for the flight was therefore rendered inconsistent in maintaining the safety constraint. Appropriate control action was dependent on a system component which was autonomous and unmonitored by Comair.

Blue Grass Airport Authority (LEX)

At the time of the 5191 accident the LEX airport was in the final construction phases of a five year project. At the projects completion, the Runway Safety Area (RSA) would be lengthened from 100' to the 1000' required by FAA regulation current at the time. The LEX airport authority was, rightly, proud of its attention to detail, as each of the multiple FAA airport inspections conducted during construction revealed compliance in every respect (Air Line Pilots Association International, 2007).

A Safety Plans Construction Document (SPCD) is one of the first items to be completed for a multiyear project of this size. The SPCD is the measure by which the Airports District Office (ADO) verifies construction progress and allocates the next phase's grant money to the airport. The SPCD is the process model document used by the Airport Authority and ADO. According to the LEX SPCDs, the last phase of construction did not require a change in the route used to access runway 22. However, the day before the National Flight Data Center (NFDC) airport chart diagram publication changes submission deadline, the ADO program manager rejected the final phase SPCD because it would have resulted in runway 4/22 being longer than charted. In order to keep the runway published and actual length in agreement, the north runway threshold would have to be moved sooner than the previously approved SPCD outlined. This created a situation where LEX airport had to coordinate a construction stakeholder meeting to formulate a revised plan to the SPCD and to decide what airport diagram data would be submitted to the NFDC for publication on June 19, 2006, the day before the publication changes submission deadline (Fedok, 2006).

The decisions made during the June meeting resulted in the LEX airport operational configuration the morning of the 5191 accident. In attendance at the meeting were officials from LEX airport, FAA ADO, FAA LEX ATCT, and construction subcontractors. But there was no pilot representative. It was decided to re-designate taxiway Alpha 5 (A5) as Alpha because that would be familiar to pilots using the airport (Fedok, 2006). While this action makes sense to those who live with the airport continuously, it violates the safety constraint requiring taxiway *changes* to be clearly identified. The inappropriate control action of renaming taxiway A5 to Alpha hides the physical taxi route change across runway 26 in order to reach runway 22. The June meeting group's process model of lower level operations did not identify the hazard being created because there was no information feedback from pilots (lower level operators). A pilot perspective could have pointed out that the significant physical change (a 70 degree left turn across runway 26, as opposed to the familiar slight left turn across runway 26) in taxiway Alpha could be more hazardous than realized. Creating a new physical taxi route that still carries the old familiar name, taxiway Alpha to runway 22, sets up a situation where neuro-linguistic programming implies lack of change. This, then, lead to confusion when the realities encountered were not as expected. Confusion is often a by-product of system asynchronous evolution as created here between the airport chart, clearance phraseology, and the physical airport structure.

Several crews acknowledged difficulty dealing with the confusing aspects of the north end taxi operations to runway 22, following the changes which affected a seven day period prior to the 5191 accident. One veteran captain, who flew in and out of LEX numerous times a month, stated that after the changes "there was not any clarification about the split between old alpha taxiway and the new alpha taxiway and it was confusing" (Tew, attachment 1, 2006, p. 25). A First Officer, who also regularly flew in and out of LEX, expressed that on their first taxi after the above changes, he and his captain "were totally surprised that taxiway Alpha was closed between runway 26 and runway 22. The week before, [he] used taxiway Alpha (old Alpha) to taxi all the way to runway 22. [I]t was an extremely tight area around runway 26 and runway 22 and the chart did not do it justice" (Tew, attachment 1, 2006, p. 29). The crews of both Sky West and Eagle flights, which departed minutes ahead of accident flight 5191, also noted moments of positional confusion taxiing to runway 22 (Tew, 2006).

Even though these and, undoubtedly, other instances of crew confusion resulted during the seven day period of August 20-27, 2006, there were no effective communication channels to provide this information to LEX, or anyone else in the system. After the 5191 accident, a small group of aircraft maintenance workers approached an NTSB ALPA safety group member and expressed concern that they, also, had experienced confusion when taxiing to conduct engine run-up's. They were worried that an accident could happen, but did not know how to effectively notify people who could make a difference. Then, the 5191 accident happened, as they had feared (P.S. Nelson, personal communication, August 30, 2006).

LEX airport authority, as of the time of the 5191 accident, had received no reports of confusion from pilots, either directly or through Air Traffic Control Tower (ATCT) communication. In the seven days between the airport reconfiguration and the 5191 accident, there had been eight daily successful departures during periods of darkness (Fedok, 2006). The LEX airport authority believed, even in the face of existing charting inconsistencies, that no "unsafe situation" (Fedok, attachment 7, 2006, p. 6) existed. This is an example of the "fallacy of centrality"; if incidences were occurring, one would have reports about it. The inverse would also be true: the absence of reports means there were no occurrences (Westrum, 1982). Because of missing feedback, the LEX airport authority's process model did not recognize the existing airport hazard and therefore was inconsistent.

The 5191 accident provided feedback which identified the runway/taxiway identification hazard and updated the LEX airport authority's process model. The airport authority then implemented a control action consistent with their updated model. They placed a large lighted metal "X" on runway 26, several hundred feet down from the threshold and prior to where runway 22 intersects runway 26. This effectively blocked an aircraft from turning down runway 26 and thereby enforced the safety constraint and ensured runway 22 selection. The "X" was left in place until construction of taxiway Alpha 7 was completed, ending the period of asynchronous evolution between the airport diagram and the airport physical structure (National Transportation Safety Board, 2007). However, the feedback section of the process loop remains unchanged. Therefore, until the process loop feedback is provided, LEX's process model will again become inconsistent during future periods of asynchronous system evolution. Hazards will again be unrecognized and inadequately controlled leaving safety constraints unenforced.

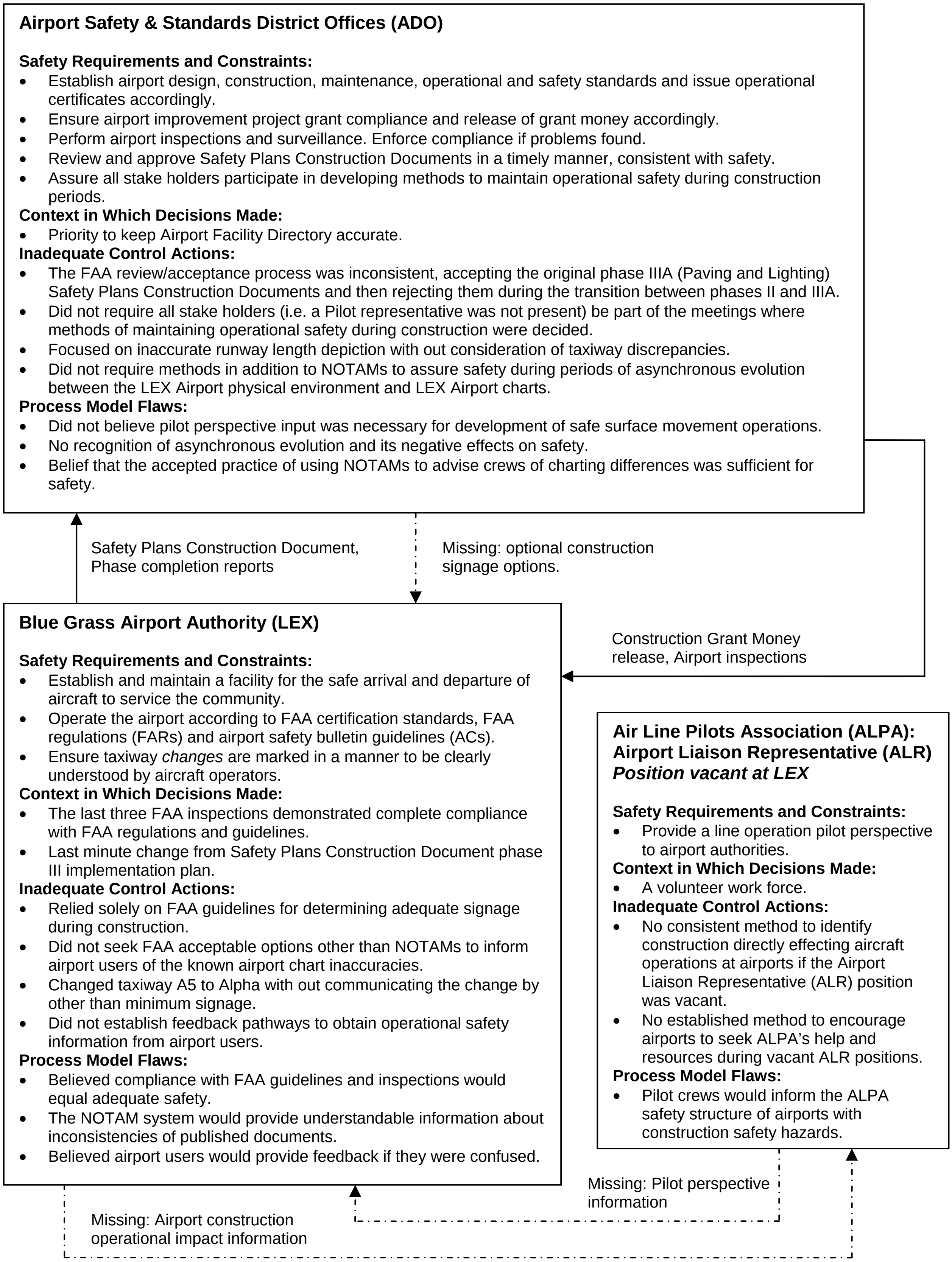

Figure 4 Airport Facilities Control Structure

FAA Airport Safety & Standards District Office (ADO)

The Airports District Office (ADO) is responsible for review, approval and oversight of airport construction projects, administration of Airport Improvement Project grant funds and coordination of Airport Facility Directory (AFD) publication changes. The ADO is the hierarchical level above the local airport authority, in this case LEX. This level conducts airport inspections as a method of evaluating compliance with guidance and regulation (Fedok, 2006).

The day before the AFD publication submission deadline, the ADO informed the LEX airport that the final phase Safety Plans Construction Document (SPCD) was unacceptable. The entire document had been approved prior to the commencement of the construction project and now the ADO changed its position. This change of position was a late control action and therefore outside the constraint necessitating timely review of the SPCDs. The SPCD, as originally approved, would result in runway 4/22 length inaccuracies with the AFD. For a short period of time, the runway would actually be longer than published, which was not acceptable to the ADO. The ADO appears to have exhibited a "this and nothing else" fixation (De Keyser & Woods, 1990) by focusing exclusively on how the runway length would cause an inaccurate AFD and dismissing resulting inaccuracies of taxiway depictions by moving the runway 22 threshold earlier than originally proposed. An additional unanticipated hazard of moving the runway 22 threshold was the negative effect it would have on a controller's ability to determine an aircraft's position from the control tower cab. This will be explored in greater detail in the LEX Air Traffic Control Facility section.

The ADO did not accept LEX's SPCD outline of publishing interim airport charts in the AFD for two reasons. One, the ADO believed changing the chart over multiple revision cycles would create a high propensity for inaccuracies to occur. Two, because of the multiple chart changes, it was believed, the possibilities for pilot confusion would be magnified. The June 2006 meeting of construction stakeholders concluded with an agreement to publish the AFD chart depicting the final configuration: post construction. This control action initiated a period of asynchronous evolution which began when the airport embarked on phase III of the construction project. The resultant hazards during the period of asynchronous evolution were to be dealt with by following the normal practice of using Notices to Airmen (NOTAMs) to advise pilots of chart inconsistencies (Fedok, 2006).

Inspections at LEX did confirm the airport was following regulatory guidelines but there appeared to be no indication that signage and marking options were presented other than the specified regulatory minimums (Fedok, 2006). While it is normal practice for NOTAMs to do the "heavy lifting" of communicating chart inconsistencies (asynchronous evolution hazards) to pilots, more effective means were available.

An incident, in 1989, where two air carrier flights departed a closed runway and struck construction barricades a few thousand feet from the runway threshold resulted in the FAA using signage and markings, in addition to those required, to help prevent departures from the closed runway. The runway layout was similar to LEX; both runways intersected each other near their respective thresholds. Taxi to the departure runway required crossing the closed runway threshold. In the 1989 incident, a sign was added at the taxiway entrance to the closed runway stating "Runway 17 Closed to Air Carrier Aircraft". Additionally, a red line marking was painted leading across the closed runway threshold and indicating the way to the departure runway (Air Line Pilots Association International, 2007). While these signage and marking enhancements are not required by regulation, neither do the regulations prevent them. For some unknown reason, the positive outcome of the incident did not result in organizational learning, which would have incorporated the information in the ADO process model. Perhaps this did not occur because knowledge of these construction signage and marking enhancements remained hidden in the NTSB Safety Recommendations database, making them difficult to find and incorporate into the corporate knowledge.

Another marking enhancement, not provided as an available possibility for reducing confusion at LEX, was outlined in FAA Advisory Circular (AC) 150/5340-1J-Standards for Airport Markings. The AC provided instruction for the application of "Enhanced Hold Short Marking with Surface Painted Holding Position Signs". Because of LEX airport's size, implementation of this helpful marking was optional. Implementation of this marking was a focus of the ALPA ALR safety emphasis and would have been encouraged if the safety constraint had been maintained by soliciting pilot input at the SPCD meetings.

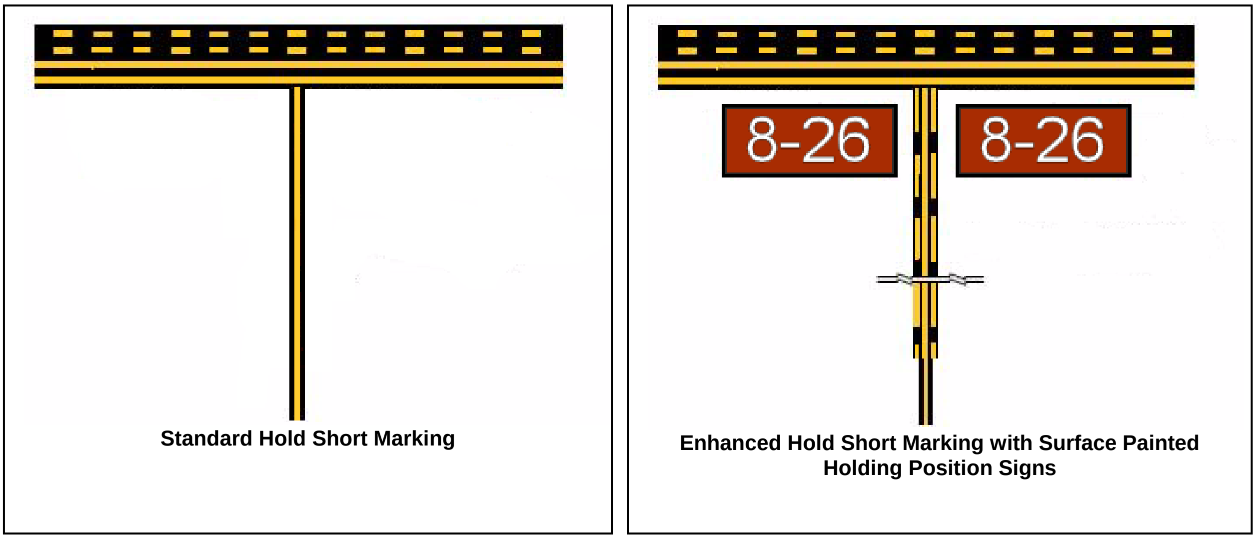

Figure 5 Standard and Enhanced Hold Short Markings

Air Line Pilots Association (ALPA): Airport Liaison Representative (ALR)

One part of the ALPA safety structure is the network of Airport Liaison Representatives. These pilot volunteers work with an air carrier airport authority contributing a pilot perspective to activities and planning. An advantage for the airport authority is the fact that the ALR represents a collective airline pilot point of view rather than only a specific air carrier's agenda. Through the ALR, the airport authority obtains access to ALPA's safety resource of engineers and network of professionals around the world, both in and out of the piloting profession (Air Line Pilots Association, 1999). A strength of the ALR program is its all volunteer nature; volunteers often are highly motivated and dedicated to their work. Yet the program's volunteer nature is also a weakness. Not all air carrier airports have an ALR assigned to them. LEX was one of the airports which did not have an ALR assigned to it during the construction period prior to the 5191 accident. As a result, LEX did not have this information resource available to them.

ALPA has yet to develop a method presenting ALPA's resources and encouraging information exchange with airport authorities who don't have ALR's. Some type of fallback mechanism, in cases where ALR's are unavailable, is necessary to maintain the safety constraint of providing line pilot perspective feedback to the airport control structure. The absence of an ALR deprived the ALPA safety structure and the airport authority of timely feedback about how airport construction impacted safe operations. The ALR is a necessary feedback sensor in the process loops of both the ALPA safety and airport safety control processes.

LEX Air Traffic Control Facility

On the morning of the 5191 accident, one controller occupied the tower at LEX. He had been working all night and was nearing the end of his shift. The controller was working both tower and radar functions. This meant he was responsible for Clearance Delivery, Ground Control, Local Control ("LEX tower" over the radio), Departure Control, Approach Control, hourly weather observations and recording of the automatic terminal information service (ATIS). The LEX controller, Christopher Damron, characterized his work load as "busy during that 10-min period" (Hall, 2006, p. 17) surrounding the 5191 accident.

US controllers are not required to specify each runway crossing on the taxi route to the departure runway. If the clearance does not include instructions to specifically hold short of a runway, then crossing clearance is inherent (Aeronautical Information Manual (AIM) 4-3-18 effective at the time of the accident). The control action of monitoring flight 5191's taxi to runway 22 necessitated insuring that runway 26 was crossed on the way to holding short of runway 22. The physical route of taxi to runway 22 changed seven days prior to the 5191 accident. After the change, taxiway Alpha incorporated a 70 degree turn across runway 26 instead of proceeding directly across, as the Jeppesen chart depicted (ALPA, 2007). (See figure 9). Despite the physical changes at LEX, a controller could still use the identical clearance phrase, "taxi via Alpha to runway 22" and it would be an accurate acceptable clearance.

According to the NTSB interview, Mr. Damron was not aware of any airline pilot confusion as a result of the August 20, 2006, changes at LEX. He also thought the taxi route to runway 22 was still similar to pre-August 20: a pilot would continue to take taxiway Alpha to runway 22. Additionally, Mr. Damron did not characterize the taxiways north of runway 26 as hazardous (Hall, 2006). It is reasonable to conclude, therefore, that Mr. Damron's mental model lacked awareness of operational hazards in the area between runway 26 and runway 22. From Mr. Damron's point of view, there was no reason to provide taxi clearances specifically directing the use of taxiway Alpha and crossing of runway 26 in order to reach runway 22. He gave the clearance he'd always used, "taxi to runway 22" (National Transportation Safety Board, 2007, p. 150).

At the time of flight 5191's accident, Mr. Damron was two hours from finishing the last shift of five for the week. His eight hour shifts had been arranged in a series of two evening shifts, two day shifts and one midnight shift, known as a 2-2-1 rotation. The 2-2-1 rotation ends with the last day shift and the midnight shift occurring within a single 25 hour period. According to the fatigue study by Belenky (2007) for ALPAs NTSB submission[7], the 2-2-1 rotation resulted in Mr. Damron clearly working under significant fatigue. The fatigue study used the Sleep, Activity, Fatigue, and Task Effectiveness Model / Fatigue Avoidance Scheduling Tool (SAFTE™/ FAST™) analysis, which indicated Mr. Damron was functioning at 72% effectiveness. This level of effectiveness is equivalent to a blood alcohol level of just under 0.08 g/100ml (Air Line Pilots Association International, 2007).

Fatigue adversely affects one's ability to remember. New tasks are adversely affected to a greater extent than tasks which are routine (Horne, 1988). The controller's actions on the accident morning appear to agree with this finding. The controller remembered to record the ATIS (a routine task), but a relatively new item, the taxiway Alpha NOTAM (a new task), was omitted. Fatigue was likely the major factor behind the lack of control action necessary for maintaining the safety constraint to include all local NOTAMs in the ATIS broadcast. Even though Mr. Damron

[7] The Belenky (2007) fatigue study is part of the appendix to the ALPA NTSB submission (see Air Line Pilots Association International, 2007).

was significantly fatigued, he reported he "felt fine" and was "alert" (Hall, 2006, p. 20). According to sleep loss fatigue studies it is not uncharacteristic for subjects to demonstrate an impaired ability to self evaluate their state of fatigue (Van Dongen, Maislin, Mullington & Dinges, 2003).

Mr. Damron expressed, repeatedly during his NTSB interview, that flight 5191 turned in the direction of or onto runway 22 following acknowledgement of the takeoff clearance. His mental model reinforced interpreting flight 5191 as taking off from runway 22. That was what he'd always experienced after issuing a runway 22 takeoff clearance. Both NTSB observers and Mr. Damron expressed the difficulty of determining an airplane's position around runways 22 and 26 thresholds. It was movement of the runway 22 threshold as part of the construction which created this difficulty. From the control tower cab, the thresholds of runway 22 and runway 26 appear to overlap. This made it difficult to ascertain which runway the aircraft was on. It was also difficult to determine whether the aircraft was on a taxiway or a runway. Only when the aircraft moved down the runway could it be determined where the aircraft was located (Hall, 2006).

Analysis of the Air Traffic Control (ATC) transcripts included in the NTSB *ATC Group Chairman's factual report* (Hall, 2006) reveals that from the time flight 5191 joined taxiway Alpha until after stopping short of runway 26, Mr. Damron was constantly involved with Radar function[8] control tasks. He switched focus to Tower function control for a 30 second period during which he cleared flight 5191 for takeoff. Then he returned focus to Radar function control tasks. By the time he could have switched back again to Tower function control tasks, flight 5191 was approaching the runway 26/22 intersection. Mr. Damron had only seconds to ascertain flight 5191's position short of the runway. To make matters worse, the airplane was in the most difficult place it could be and in the worst energy state for position confirmation: sitting stationary.

There is a direct correlation between one's capacity to take action and one's perception of events. Limiting one's capacity for action correspondingly limits one's perceptions (Weick, 1988). Mr. Damron said he would tell the flight crew they were on "runway 26, it's closed" (Hall, 2006, p. 10) if he saw the airplane on runway 26. The reality is that Mr. Damron did not see (perceive) flight 5191 on runway 26. His capacity to act, and therefore maintain the safety constraint of continuously monitoring all aircraft in the air and on the surface, had been diminished in two ways. First, the operational demands of working tower functions and radar functions, as illustrated, reduced capacity, significantly[9], over what it would have been if he had responsibility for tower function tasks alone. Second, the effects of sleep loss fatigue would have further reduced his capacity. This is because fatigued subjects require significantly longer time than non-fatigued subjects to detect and assimilate information. Fatigue slows reactions to stimulus and fosters a reduced ability to recognize dynamic change (Dekker, 2006). Sleep loss fatigue also increases predisposition to "plan continuation"; in other words staying with the plan in progress even though the changing situation indicates opting for a new one might be better (Orasanu, Martin & Davison, 2002).

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[8] Radar function control tasks involve airborne aircraft and consist primarily of monitoring a two dimensional diamond shape representing the aircraft on a CRT screen and issuing directional clearances to the aircraft via radio. Tower function control tasks involve ground taxi, takeoff, and initial airborne climb movement of aircraft and consist primarily of visually monitoring the aircraft from the control tower cab and issuing directional clearances to the aircraft via radio.

[9] ATC transcript analysis revealed: During the four minute period between 5191's call for taxi and the takeoff roll the controller's time was divided 50/50 between Tower function (TF) and Radar function (RF). Role changes between TF and RF occurred six times. There were eight TF communication exchanges and 28 RF communication exchanges. During the three minute period between 5191 joining taxiway Alpha and the takeoff roll the controller's time was divided 40/60 between TF and RF. Role changes between TF and RF occurred three times. There were three TF communication exchanges and 24 RF communication exchanges.

The LEX Air Traffic Control (ATC) facility was operated 24 hours daily, incorporating Tower and Radar approach/departure services, manned with a staff of 19 controllers. In a 2004 staffing study (Hall, 2006), Mr. Ortman, the facility manager, clearly stated that 19 controllers were insufficient to operate a 24 hour facility. At the time of the 5191 accident, Mr. Ortman had been working for over two years to obtain an adequate staffing solution. During that two year period, Mr. Ortman provided official staffing studies as well as written communications proposing: reclassification of LEX airspace at night, (which would allow closing the facility at night), increasing the staff allotment to 20 controllers, or an increase of overtime budget (in order to adequately staff the tower at night). In the fall of 2005, when verbal guidance was given that Tower and Radar functions must be split between a minimum of two controllers, LEX was still only allotted a staff of 19 controllers.

A proposal was offered, during the fall of 2005, to have Indianapolis Air Traffic Control Center (ZID) work LEX approach/departure at night (Hall, 2006). Allowing ZID to handle the Radar function at night would leave LEX responsible only for Tower function. Thus, compliance with staffing guidance could be maintained using one controller at night. But, no word regarding the proposals status was received. The only direction Mr. Ortman received regarding the various budget/staffing options, proposed during the previous two years, admonished him to remain within his allotted budget. A February memorandum emphasized his overtime budget amount of $17,000 (equivalent to 35 days of midnight shift staffing for the year) and that it was "essential to the overall fiscal success of the hub[10] that every manager does their part and manages responsibly and ensures that the Hub Manager is informed immediately when issues arise that may adversely impact the budget" (Hall, attachment 3, 2006).

> When cost cutting is focused on less important units, it is not just decreased maintenance which raises susceptibility to crisis. Instead, it is all of the indirect effects on workers of the perception that their unit doesn't matter. This perception results in increased inattention, indifference, turnover, low cost improvisation, and working-to-rule, all of which remove slack, lower the threshold at which a crisis will escalate, and increase the number of separate places at which a crisis could start (Weick, 1988, p. 313)

Mr. Ortman was left in a double bind. He could follow the written direction to remain within budget or follow the staffing verbal guidance. Both could not be achieved. Mr. Ortman understood the direction given to him as weighted in favor of budget so he "manag[ed] the limited staffing" (Hall, 2006, p. 22) with one controller on the midnight shift. The control directives communicated from upper hierarchy were dysfunctional because at this level they conflicted with each other; both could not be complied with and maintain the safety constraint.

After the 5191 accident the necessary financial relief was granted to separately staff tower and radar functions according to the staffing guidance and expedited controller hiring was initiated.

[10] LEX was one of nine Air Traffic Control facilities and four contract towers in KY and TN which make up the Cincinnati (CVG) Hub.

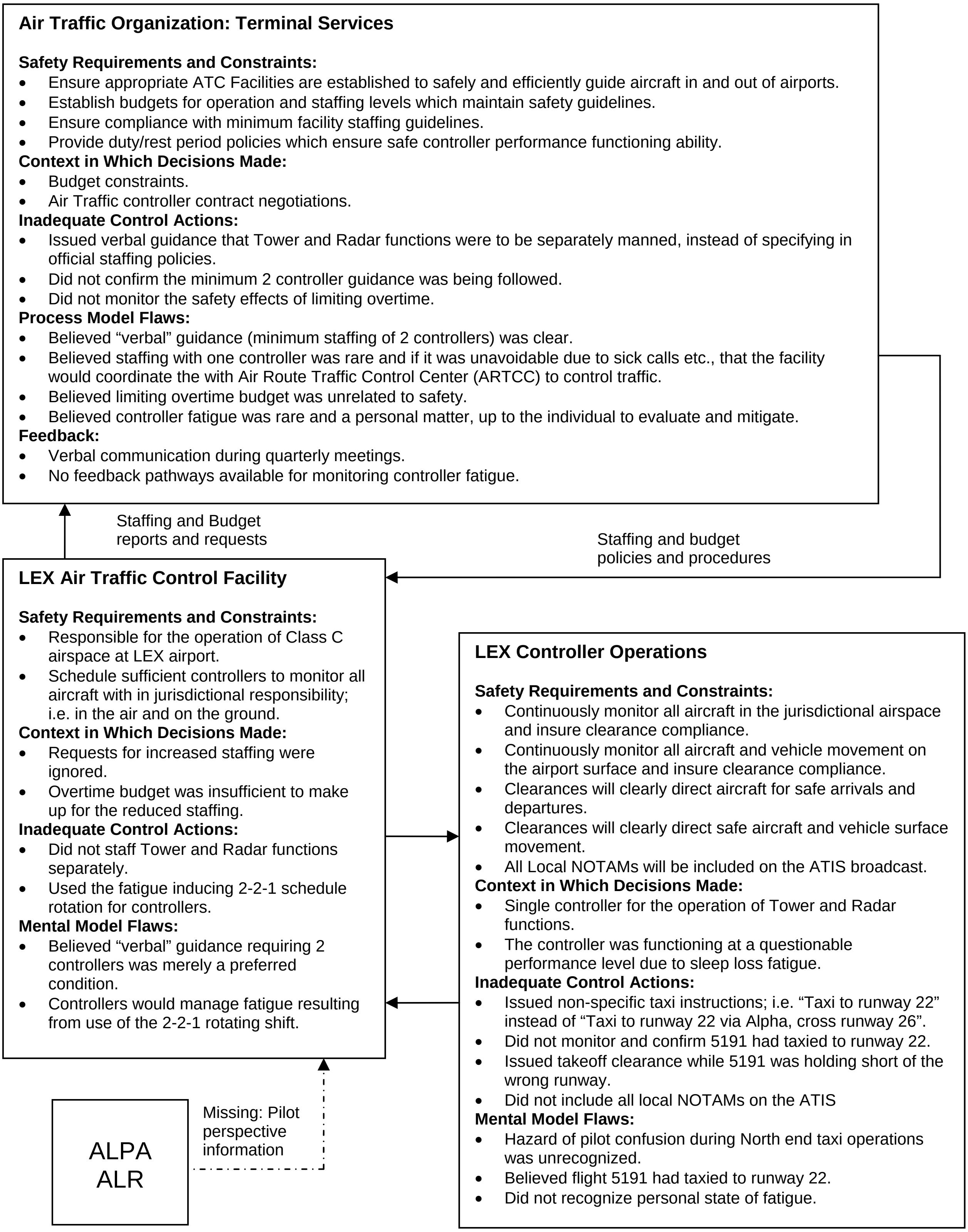

Figure 6 Air Traffic Control Structure

FAA Air Traffic Organization: Terminal Services

The control directive responsibilities in the areas of budget/staffing and fatigue are the focus of this level STAMP analysis. FAA funding battles are a regular occurrence on Capital Hill and result in constant budget pressures. In August 2005, the FAA Vice President of Terminal Services clarified that Tower and Radar functions were to be separately manned. This was done in the form of verbal guidance personally briefed to section managers and expected to be carried on down the chain to each facility manager. Terminal Services management's primary means of monitoring compliance with the verbal staffing guidance was verbal communication received during quarterly meetings with subordinate management. Terminal Services believed the guidance was clear and was consistently being followed. Indeed, surprise was expressed upon discovering LEX had been routinely combining Tower and Radar functions with one controller (Hall, 2006).

On two separate occasions, January 2006 and April 2006, the LEX facility manager sent email communication requesting additional overtime budget or staff increase. It was clearly expressed that either additional staff or more budget to pay the available staff overtime was required in order to staff separate Tower and Radar functions during the midnight shift. The LEX facility manager stated that he "continue[d] to staff only 1 [certified professional controller] CPC on the midnight shift so as to have a fighting chance of staying within my OT [over time] budget" (Hall, attachment 2, 2006, p. 1).

There appears to be a disconnect between the Terminal Services understanding of the situation at LEX facility and what was actually occurring. The process model of lower level operations was inconsistent with reality. Reliance on face-to-face verbal reports during group meetings is a common method of assessing lower level operations (Shockley-Zalabak, 2002). However, this method has liabilities when relied upon as a primary means of gathering information about lower level operations. A common element of verbal communication within groups is that individuals will rarely elaborate on uncomfortable situations that differ from the group. Especially when subordinates are communicating with superiors, this leads to a tendency for adverse situations to be underemphasized by the group members (Bernstein & Nash, 2005). It is likely these communication dynamics played a major role in why an inconsistent perception of LEX operations persisted despite direct email communication from LEX about the direct relational effects between budget and the verbal staffing guidance compliance.

The actions and communications of Terminal Services management were consistent with their process model of lower level normal operations. However, for some reason, information feedback channels were unmonitored, or limited to the extent they were impotent in ability to maintain consistent operational process models. The lack of feedback and or incorporation of information left an unusual situation unrecognized at the Terminal Services management level. Therefore, their control actions were dysfunctional. The overlapping control actions of fiscal efficiency and separate manning of Tower and Radar functions interacted such that the safety constraints were violated. As illustrated at the lower level, it was impossible to comply with both control directives. Because the feedback part of the process loop was ineffective, Terminal Services management did not know what the actual effect of their control actions was.

When it came to fatigue, controllers were left on their own. Terminal Services management expected that if controllers felt sleepy or tired, the controllers would evaluate and change what they were doing prior to the shift. Management had no knowledge of controllers calling in fatigued. Since calling in sick implied the individual was incapacitated, fatigue was not considered a legitimate reason to use a sick call (Hall, 2006). Fatigue was believed to be practically nonexistent. Terminal Services management acknowledged having no established method of gathering information on controller fatigue and, even if there had been a method, there was no way of incorporating that information so as to become part of the corporate knowledge. The 2-2-1 shift rotation was a favorite of controllers because it would yield the equivalent of an extra day off work. Yet this rotation, as demonstrated by scientific study, results in significant sleep loss fatigue impairment (Air Line Pilots Association International, 2007). The fatigue hazard was unrecognized. Effectively, this resulted in the absence of an entire process loop necessary to enforce the safety constraint that duty/rest periods assure safe controller performance functioning ability.

It becomes clear that communication methods and feedback channels at the Terminal services organizational level need to be reexamined. People act according to what they believe is happening around them and when that model is inconsistent actions can and often do push a perceived normal situation, critical (Dekker, 2005). Keeping process models consistent with lower level reality is necessary so that communication and directives (control actions) do not put lower levels of the organization in impossible and dangerous goal conflicts. The only way to preclude inconsistent process models is to keep them synchronized with a complete information feedback network.

Following the 5191 accident the guidance to separately staff tower and radar functions was formally documented and LEX was given the necessary finances to consistently staff the facility accordingly. The 5191 accident served to update the process model so that the Terminal Services management provided safe (functional) control actions. But, nothing was done to repair the process loop feedback channel which is necessary to preclude their process model becoming inconsistent again in the future.

National Flight Data Center (NFDC)

The National Flight Data Center is just what its name implies; it is the central data collection, repository for all information defining the National Air Space (NAS). The NFDC also distributes charting data to outside vendors who format it for various consumers. Additionally, the NFDC operates the Notice to Airman (NOTAM) system. Information, other than NOTAM, is prepared according to 56 day dissemination/publication cycles. NOTAMs are used to communicate changes occurring between publishing cycles. The NOTAM system is the feedback channel to system users about inconsistencies in other primary NAS information formats, i.e. charts, electronic databases, temporary procedures etc.

> A BRF HIST OF THE AVATN NOTAM BGNS WI THE MARITIME INDSTRY. MARINERS NEEDED TO BE ADZD OF ANY RTE CHG/HAZ. A KNOWN HAZ/CHG IN RTE WAS PBLSHD IN WKLY NOTICES TO MARINERS FROM THE US NAVY. NOTICES TO MARINERS WERE EFF, USBL, /EASY TO READ BECAUSE THE RPRT WAS PBLSHD IN PLN LANGUAGE. AVATN ADPTD THE NOTICE TO MARINER INST WHICH BCM THE NOTAM. NOTAMS WERE FORMTD TO BE COMPTBL WITH TLTYPS FRM THE 1920'S. TLTYPS TRANSMITTED INFO SLWLY AND RQRD THE VOL OF TRANSMITTED CHRCTRS BE KEPT TO A MIN. THIS RSLTD IN CDD CNTRCTNS BCMNG PART OF THE NOTAM FORMT. AS TECHNOLOGY IMPRVD NEW DSTRBTN MTHDS WERE ADPTD BUT THE NOTAM FORMT RMND AS DVLPD FOR THE TLTYP.

The above paragraph is written that way for a purpose. It is the manner which weather and NOTAM information is presented to flight crews. The next paragraph is the plain language translation.

> A brief history of the aviation NOTAM begins within the maritime industry. Mariners needed to be advised of any route change and hazard. A known hazard and change in route was published in weekly notices to mariners from the U.S. Navy. Notices to mariners were effective, usable, and easy to read because the report was published in plain language. Aviation adapted the notice to mariner instrument which became the NOTAM. NOTAMs were formatted to be compatible with teletypes from the 1920's. Teletypes transmitted information slowly and required the volume of transmitted characters be kept to a minimum. This resulted in coded contractions becoming part of the NOTAM format. As technology improved new distribution methods were adopted but the NOTAM format remained as developed for the teletype.

The above exercise illustrates one problem with the NOTAM system: it is difficult to understand and gather critical relevant information, even when that information is present. The other problem is that the NOTAM simply is unavailable to the pilot, for some reason.

The difficulty in understanding written NOTAMs comes from the fact that they were not designed according to human factors interface principles, but rather according to the functional restrictions of the 1920's teletype. This resulted in NOTAMs which used contractions, unfamiliar or ambiguous coded words, and all uppercase letters. While the technology used for NOTAM distribution has advanced with the times, the NOTAM formatting has not (Hoeft, Kochan & Jentsch, 2004). The effective date information is coded and often missing altogether. There is no provision for sorting NOTAMs according to a useful priority. Rather, the pages of NOTAMs often require a "needle in a haystack" type search for the next relevant critical piece of information. The end result is a NOTAM system which has been characterized as cumbersome, making it hard to follow and, therefore, easy to misinterpret, misunderstand and pass over critical information. This, in turn, has created a sense of overwhelm and overload followed by an atmosphere of system distrust (Hoeft et al., 2004). A crewmember during an NTSB 5191 interview expressed it this way,

> There were a lot of items that were listed out on the NOTAMS during the previous month including the instrument landing system (ILS), lighting systems, taxiways, etc. You would hear the ATIS and not want to listen to it because it was long and you were busy during the approach phase but you would have to force yourself to listen to it to make sure you got all the new information (Tew, attachment 1, 2006, p. 28).

Ten years before the 5191 accident, the Human Factors Research and Engineering Group of the FAA published a *Human Factors Design Guide* (Wagner, et al., 1996) (Ahlstrom & Longo, 2001). Six principals from this guide address the primary issues of NOTAM format. One: The text of a document shall be written in clear, simple language, free of vague, ambiguous, unfamiliar and unnecessary words (HFDG paragraph 10.2.3.1.1). Two: Information shall be presented to a user in a directly usable form; a user shall not have to decode or interpret data (HFDG paragraph 8.1.1.4). Three: The use of abbreviations shall be minimized (HFDG paragraph 8.2.5.4.4). Four: Text should be presented in a combination of uppercase and lowercase letters, following standard capitalization rules (HFDG paragraph 8.2.5.8.1). Five: When task performance requires or implies the need to assess the timeliness of information, the display should include time and date information associated with the data (HFDG paragraph 8.1.1.8). Six: Designers should base the order of items on natural rationale such as frequency of use, related functionality or the normal sequence of user actions (HFDG paragraph 8.2.9.5).

Incorporating these principles, developed by another branch of the FAA's own organization, into a modern NOTAM format would maintain the safety constraint to provide critical information in an understandable format. The NOTAMs presented to flight 5191 are an exhibit of how the existing NOTAM format made it difficult to understand and extract necessary information. The existing NOTAM format was inadequate to maintain the understandability safety constraint.

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KLEX APT 2006080BB09V01 08/024 06 20AUG2200/ UFN
LEX 4/22 ASDA 7003 TORA 7003 TODA 7003 LDA 6603
KLEX APT 20040304BDFV01 4/1897 04 09MAR1944/ UFN
BLUE GRASS, LEXINGTON, KY.
VOR OR GPS-A AMDT 8A ....
CIRCLING MINIMUMS: MDA 1580/HAA 601 ALL CATS. VIS CAT C 1 3/4.
ALTITUDE AT HYK 5.00 DME 1580.
TEMPORARY FAS CONTROLLING OBSTACLE 1240 MSL/205 AGL TOWER AT
380007.65N-0843132.58W.
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Sample NOTAMs from the 5191 dispatch release

Blue Grass Airport, Lexington, KY (KLEX)

Airport NOTAM 08/24 effective: 08-20-2006 2200 UTC until further notice

Runway 4/22
Accelerate-stop distance available 7003'
Takeoff runway available 7003'
Takeoff distance available 7003'
Landing distance available 6603'

FDC NOTAM 4/1897 effective: 03-09-2004 1944 UTC until further notice
Due to a tower 205' above ground level and 1240' MSL, located 4.6 DME from the Lexington VOR (HYK) just north of the final approach course, the **approach minimums** are **increased** as follows:

VOR-A or GPS-A approach

Cross CUGIG intersection (HYK 5.0 DME) at 1580' MSL
Circling minimums: All categories, MDA 1580/HAA 601'
Category C, visibility 1 ¾

Sample NOTAMs formatted according to the FAA HFDG principles

Figure 7 LEX NOTAM samples

NOTAM information was available to the crew from two primary sources. The dispatch release on which the dispatcher had placed NOTAMs available to him from company vendors, and the local ATIS broadcast which was the only flight crew source of local NOTAMs (NOTAM–L)[11]. On the morning of the accident, the 5191 crew had to decode through two and one-half pages of LEX NOTAMs. Only a few were relevant to the taxi and takeoff procedures. At the top of the second page of LEX NOTAMs was the first NOTAM with relevant information. The NOTAM gave the declared distances for runway 4-22, indicating an (ASDA 7003) accelerate stop distance available of 7003 feet. This would have been used to cross check information in the runway analysis manual. The next NOTAM (LEX 22) indicated the runway 22 ILS Glide Path was out of service. This was of secondary importance for the 5191 departure, as it would only be relevant in

[11] At the time of the 5191 accident, information about taxiway closures, airport rotating beacon outages and other information which had little effect outside local operations, was disseminated as local NOTAMs.

the event of a departure emergency return to Lexington Airport. The next three NOTAMs indicated various lighting outages and all had headers beginning "LEX 4", the opposite runway of that expected for departure. However, the first NOTAM in this group, 4/22 RCLL OTS (runway 4/22 runway centerline lights out of service), contained critical information about how the departure runway 22 would appear[12].

At the bottom of the next page were two more critical NOTAMs. They gave lighting information about runway 26, REIL OTS INDEFINITELY (Runway End Identifier Lights are Out Of Service Indefinitely), and the MIRL OTS INDEFINITELY (Medium Intensity Runway Lights are Out Of Service Indefinitely). This was critical information needed by the 5191 crew in order to build an accurate mental model of runway 26's appearance. This runway had to be crossed in order to reach the hold short point of runway 22. These lighting NOTAMs should have built a mental model of how the two runways appeared to be lit. First runway 22, lighted except for the center line stripe, second, runway 26, no lights at all. This information is critical, yet difficult to decipher from the presented context. According to a recent study, only 69% of professionals who dealt with NOTAM deciphering every day were able to extract critical information (Hoeft et al., 2004).

NOTAMs often contain large amounts of information which must be gathered from several different sources. The information is then processed through multiple agencies, each with their own operating standards and formatting practices. Eventually, the NOTAMs are gathered in the NFDC database and distributed back to users in the system. Ironically, the longer a NOTAM existed, the harder it became to ensure it had been obtained. This was because it moved from the short term electronic database to diverse containment vehicles such as the NFDC bi-weekly paper publication, *Notices to Airmen*. One could not go to a single NOTAM source and be assured that every NOTAM had been obtained (Hoeft et al., 2004). Therefore, the existing NOTAM dissemination network was inadequate to maintain the safety constraint assuring operators receive all necessary information.

It is not surprising that the NOTAM system played its part in the 5191 accident. A NOTAM-L indicating that taxiway Alpha north of runway 26 was closed until further notice should have been included on the ATIS broadcast. In addition, two other NOTAMs were not available to the 5191 crew. One indicated the runway 4/22 distance remaining signs were out of service, the other designated runway 26 as a daytime use only runway. A search of the NTSB database revealed several incidents and accidents in which misunderstood and or missing NOTAMs were contributors (P. S. Nelson, personal communication, August 30, 2006).

Just over a year after the 5191 accident, the NOTAM system was modified and the Local NOTAM category was incorporated into the Distant NOTAM (NOTAM-D) and is disseminated throughout the system. The NOTAM system has also incorporated a single web accessible database where all NOTAMs can be accessed. These improvements help to maintain the availability safety constraint. But the understandability constraint is unenforced because the inadequate control actions have yet to be updated. Therefore, the conversion of NOTAM-Ls to NOTAM-Ds aggravates understandability by greatly increasing the volume of coded NOTAMs necessary to decode prior to each flight. The control actions enforcing one constraint without control actions enforcing the other has destabilized the system in a new way. Both constraints must be enforced in order to restabilize the system.

[12] LEX runway 4/22 was equipped with High Intensity Runway Lights and Centerline Lights.

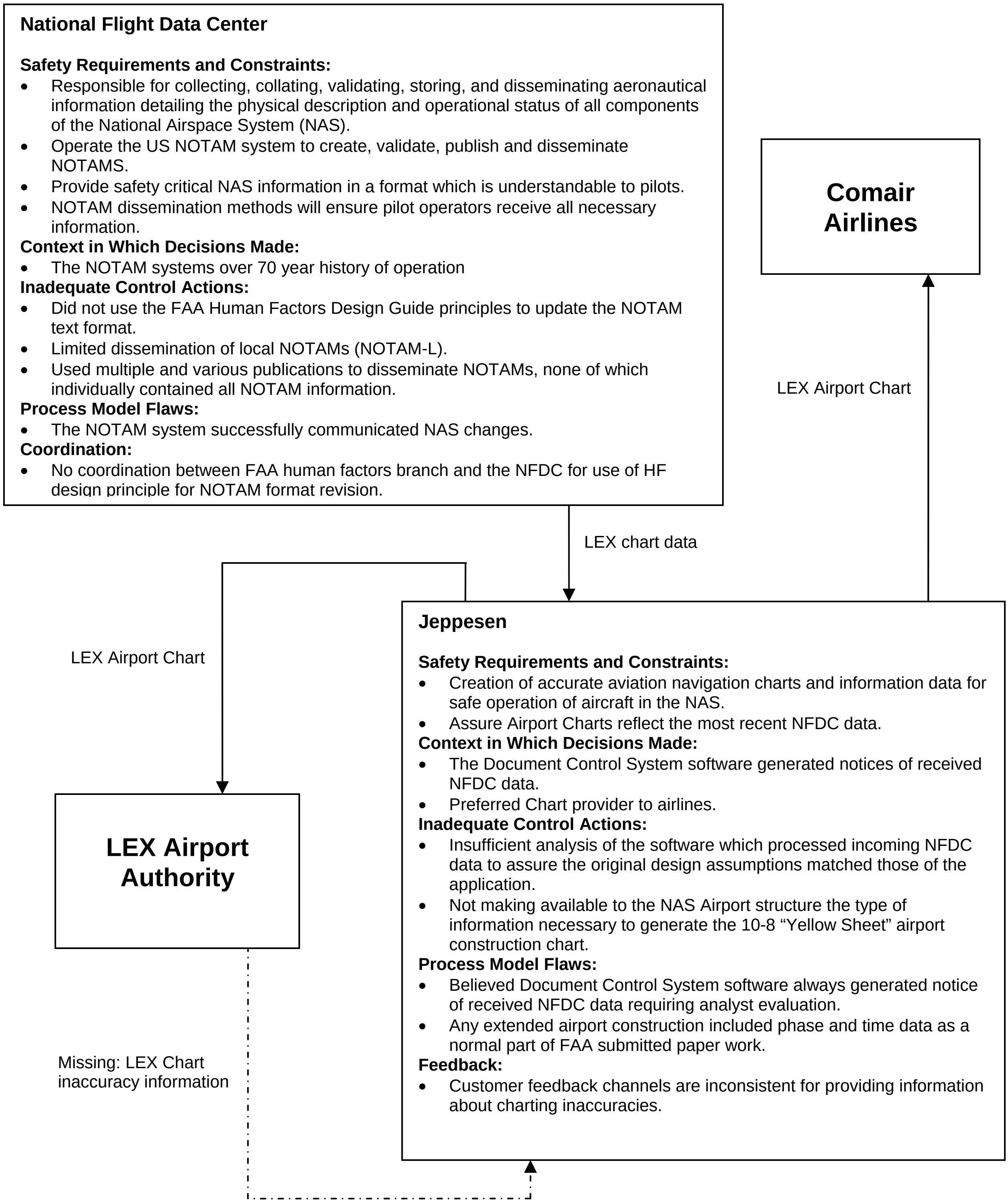

Figure 8 NFDC Charting Data Structure

Jeppesen-Charting Division

On the day of the 5191 accident, the Jeppesen airport diagram for LEX did not reflect the most recent National Flight Data Center (NFDC) information. Even though the NFDC information was also inconsistent with the physical layout of North end taxiways, it most closely matched reality (Air Line Pilots Association International, 2007).

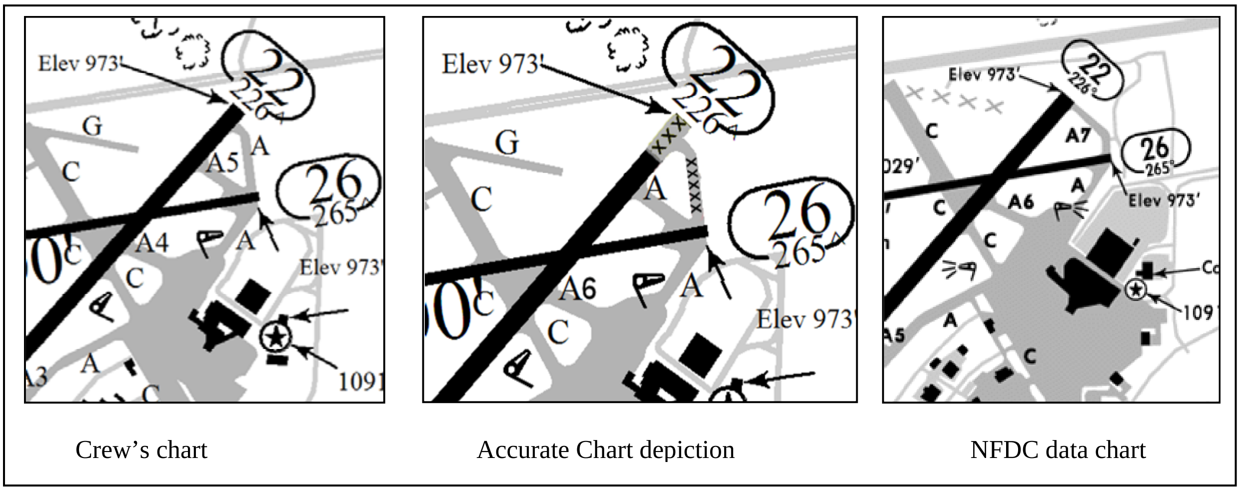

Figure 9 North end of LEX airport

Jeppesen used a document control system (DCS) to process National Airspace System (NAS) information received from the National Flight Data Center (NFDC). The DCS software reports received information for an analyst to review and incorporate in the necessary charts. The DCS software was designed to only make reports of information received during business hours Monday through Friday. However, the knowledge of this software design protocol was not discovered until the 5191 accident prompted an internal Jeppesen analysis of the DCS software (Fedok, 2006).

There was no software "error" or "failure". The software performed exactly as it had been programmed. The DCS software's report generator (control action) put Jeppesen's revision process in a state where it was unable to maintain the NFDC data consistency safety constraint. This type of situation often occurs when process models either lack sufficient specificity or are unclearly communicated between the designer and programmer during software development. "Basically the problems stem from the software doing what the software engineer thought it should do when that is not what the original design engineer wanted" (Leveson, 2002, p. 38). Additionally, the situation could result from software reuse which did not incorporate a thorough evaluation of the "original design decisions and design rationale" (Leveson, 2002, p. 141) with that of the new use parameters. In either case, the software process model, as Jeppesen understood it, was inconsistent with the actual DCS software process.

The fact that the LEX chart inaccuracy was only discovered by a special internal Jeppesen review points to the inadequacy of customer feedback channels to provide information of charting inaccuracies. LEX was not the only airport chart uncorrected. Six other airports were also left inaccurate from the DCS software process and discovered from the Jeppesen review as apposed to customer feedback (Fedok, 2006). The feedback delays in this part of the process loop made it impossible to enact appropriate control actions which would maintain the chart accuracy constraint.

The Jeppesen "yellow sheets" provide valuable safety information, in graphical form, to pilots about the nature and location of airport construction activities. They are one of the tools Jeppesen uses to provide information facilitating safe operation of aircraft in the National Airspace System (NAS). The yellow sheets are proprietary to Jeppesen and result from Jeppesen's own internal development criteria. If data received from the NFDC does not contain specific information about construction stages and effective dates, a yellow sheet is unlikely to be produced (Fedok, 2006). Because the NFDC LEX data transmitted did not contain the necessary information, a LEX yellow sheet was not produced. The safety constraint could be consistently maintained if Jeppesen were to provide the FAA Airports division with the information criteria necessary to generate a yellow sheet. The FAA could then make sure airports provide this data as part of submissions to the NFDC during airport construction.

Federal Aviation Administration

Safety Requirements and Constraints:
- Establish and administer the National Aviation Transportation System.
- Coordinate the internal branches of the FAA, to monitor and enforce compliance with safety guidelines and regulations.
- Provide budgets which assure the ability of each branch to operate according to safe policies and procedures.
- Provide regulations to ensure safety critical operators can function unimpaired.
- Provide and require components to prevent runway incursions.

Context in Which Decisions Made:
- FAA funding battles with the US congress.
- Industry pressure to leave duty/rest regulations alone.

Inadequate Control Actions:
- Controller and Crew duty/rest regulations were not updated to be consistent with modern scientific knowledge about fatigue and its causes.
- Required enhanced taxiway markings at only 15% of air carrier airports: those with greater than 1.5 million passenger enplanements per year.

Mental Model Flaws:
- Enhanced taxiway markings unnecessary except for the largest US airports.
- Crew/controller duty/rest regulations are safe.

Figure 10 FAA Control

Federal Aviation Administration

Budget battles with Congress are a regular occurrence whenever the FAA's budget is up for renewal, and 2006, in that way, was not unusual. Nevertheless, knowing about an unpleasant process does not necessarily make it less stressful, it can, however, reduce susceptibility for surprise and its compounding effect on stress. As has been shown, budget controls, likely initiated as a result of pressure at this level, reverberated down to the lowest system level. This is not to say that policies at the top level were unnecessary. On the contrary, they probably were necessary. However, without a clear, accurate model of lower level operations, the manifestations of those policies were difficult to predict and unexpected. Then, if the feedback in the process loop is inadequate or missing, it is impossible to enact the appropriate control actions to maintain the safety constraint.

The FAA regulatory rest and duty regulations date back to the 1930's. Fatigue resulting from the application of these antiquated regulations, has been identified by the NTSB as a contributing factor in several accidents over the past 15 years. Fatigue has been on the NTSB's most wanted list since its inception in 1990. The process loop is providing feedback which indicates an unstable, hazardous system state. However, for some unknown reason, there are no corresponding control actions enforcing the safety constraint requiring pilots and controllers to be able to function unimpaired. Control actions that enforce the safety constraint are necessary to stabilize the system in a safe state.

The FAA Advisory Circular (AC) 150/5340-1J Standards for Airport Markings, issued in April 2005, underspecified the airports which were required to comply with its guidance. During the final development phase testing, the enhanced markings were demonstrated to be an effective control action for maintaining the safety constraint to prevent aircraft from entering a wrong runway. However, the FAA required implementation at only the Air Carrier airports with 1.5 million or more passenger enplanements per year. This amounted to only 73 of the Air Carrier airports; the other 426 Air Carrier airports were allowed the *option* of implementing the enhanced markings. The feedback part of the process loop was active, but the concomitant control action was inadequate to enforce the constraint in over 85% of the system.

At a cost of less than $500 per intersection, making it one of the least expensive airport safety components[13], it is unlikely that expense was the prime consideration for such a limited implementation requirement (Air Line Pilots Association International, 2007). LEX was among the 426 airports at which the safety constraint was unenforced because of inadequate FAA control action, which gave most airports the option of enacting a proven safety enhancement. It took the 5191 accident and the 49 lives lost to recognize the necessity of implementing the enhanced markings and enforce the safety constraint at all air carrier airports. Since the 5191 accident, the FAA has revised the AC. It now requires all air carrier airports to implement the enhanced markings.

Conclusion

The model used in accident or incident analysis determines what we what look for, how we go about looking for "facts", and what facts we see as relevant. A linear chain of events promotes looking for something that broke or went wrong in the proximal sequence of events prior to the accident. A stopping point, often, is arbitrarily determined at the point when something physically broke or and error occurred (Leveson, 2002). In accidents where nothing physically broke, then, in perfect dualist fashion, we look for human error (Dekker, 2005). Once human error is targeted as a likely source, then the investigation searches until a "human error" is found. That is guaranteed to be a sure thing, because humans are involved in all systems (Hollnagel, 2007). It is also especially easy to find "human error" because "there is almost no human action or decision that cannot be made to look more flawed and less sensible in the misleading light of hindsight." (Hidden, 1989, p. 147).

The 5191 accident is just such an accident; no physical part broke. An investigation using a linear chain of events model found, in fact, "human error" to be the cause. Such a conclusion is not necessarily inaccurate when the focus is narrow and captures only a core sample of the system whole. However, this conclusion does little to answer why the people acted as they did. It does not see the "accident [as a] puzzling whole" (Dekker, 2005, p. 3). The 5191 accident is a classic example of "multiple contributors—each necessary but only jointly sufficient—combin[ing]" (Woods & Hollnagel, 2006, p. 3). The STAMP model propels the analyst to keep digging to find why each system actor played their part as they did and how the system set the stage for them to play it that way. It is important to remember that accidents arise out of usual performance in unusual circumstances, not unusual performance in usual circumstances (Hollnagel, 2008)

Timely, accurate, understandable, and sufficient information is vital so that each level controller has a consistent process or mental model of the system. When the process loop is incomplete, because of an unreliable or missing feedback component of the loop, the absent information results in an inconsistent mental model. The controller becomes, if you will, a blind driver. There is no way to be sure the control actions are enforcing the safety constraint. The usual performance may no longer be safe. An inconsistent, or out of sync, process/mental model of the system results in inadequate and or unsafe (dysfunctional) control actions which destabilize the system. If there is no feedback to the controller of the compromised system state then there will not be any corrective control actions to restabilize the system.

[13] Other airport safety components, such as runway centerline lights and in pavement hold short lights cost thousands of dollars per light for purchase and installation (P. S. Nelson, personal communication, March 30, 2007).

The point of view after the accident has much more information than anyone had prior to the accident. The 5191 accident forced information flow throughout the Air Traffic System, thereby updating process models at all levels. This is evidenced by the actions of those involved at various levels of the system: closing of runway 26 with a large lighted "X" placed so that use of the runway from taxiway Alpha was impossible, immediate implementation of controller staff increase and overtime budget at LEX by Terminal Services, modification of Jeppesen software eliminating unreported NFDC information receipt, and reclassification of L-NOTAMs to D-NOTAMs, thereby disseminating local information system wide. However, the anagnorisis[14] triggered by the 5191 accident prompted narrowly targeted safety solutions. The enacted solutions only targeted situations exposed directly by the accident. No solutions were put forth to correct the underlying structure which fostered process model inconsistencies, inadequate and dysfunctional control actions and unenforced safety constraints. There was no recognition that it was the system whole which actively set the accident stage for action. Yet, this makes sense, in a way, too. Remember the world view presented at the beginning? It took a decidedly non-linear, non-chain of events analysis to uncover the workings of the system whole. This type of thinking is not part of the fabric of people's thinking, Cartesian-Newtonian logic is.

New thinking is, however, slowly taking place. Haddon (1967) argued 40 years ago, that the most successful accident mitigation point is not necessarily closest to the event. He believed that accident prevention measures targeting proximal causes are not as successful, nor as important, as prevention which would eliminate future loss potential all together. A new view, a holistic systems view, that sees individuals in systems, is growing. It is a view which

> …sees human error as a symptom, not a cause. Human error is an effect of trouble deeper inside the system.…[where] we must turn to the system in which people work: the design of equipment, the usefulness of procedures, the existence of goal conflicts and production pressure (Dekker, 2007, p. 131)

As illustrated here, STAMP is a useful model to foster evaluation of a complex system holistically and uncover useful levers for elimination of future loss potential. STAMP is an accident analysis model which recognizes the complexity of the National Airspace System, and remains analytically consistent with that reality. It incorporates principles of system design and operation which promote adequate control actions that enforce safety constraints. Thus, energy and resources can be appropriately focused so that the resulting system is one where safety is its emergent property. Then will we have made progress on safety.

[14] Anagnorisis: the startling discovery that produces a change from ignorance to knowledge (Britannica online, 2008).

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