

Naturalistic Decision Making in the Air Traffic Control Tower: Combining Approaches to Support Changes in Procedures

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ABSTRACT

Changes in air traffic control systems and procedures can result in a variety of changes in how controllers coordinate their activities, communicate, and perform their tasks. It is important to anticipate the effects of these changes before they are made, but no single method is adequate to assess all human performance issues. In this paper, we present a trio of complimentary methods to assess a variety of human performance issues and discuss the analytical merits of each. The methods include Cognitive Analysis and Modeling, Critical Incident Analysis, and Controller Coordination Analysis. For each method, we highlight its purpose and outline the product, with specific examples drawn from the domain of air traffic control in the tower environment.

KEYWORDS

Air Traffic Control, Cognitive Task Analysis, Cognitive Modeling, Coordination Analysis, Critical Incident Analysis, GOMS

INTRODUCTION

In an effort to alleviate congestion, many airports are seeking means to increase capacity. Such means typically include procedural revisions, the construction or reconfiguration of taxiways, and the construction or reconfiguration of runways. Reconfigurations that entail the construction of new runways and taxiways will almost always require procedural revisions, and they may also entail additional changes, such as the construction of satellite control towers or the reconfiguration of an existing control tower. While such improvements may increase capacity, they may also significantly change air traffic controller decision making and communication. So before such procedural changes are made, it is necessary to predict the effects they will have on air traffic controller performance.

Ideally, the new procedures would be evaluated in an interactive air traffic control tower simulator to predict how they will impact performance. However, such simulations are costly and time-consuming to construct and perform. Thus, our goal was to develop a Naturalistic Decision Making methodology that would identify key issues to guide the construction of scenarios for focused evaluation during simulation exercises. To gain a comprehensive understanding of controller decision-making and performance, we present a trio of complimentary approaches, including: the construction of controller cognitive models, an analysis of airport critical incidents, and an analysis of controller coordination.

Our selection of methods was guided by the fact that a comprehensive review of air traffic control procedures would require analysis of both routine and non-routine operations (e.g., occasions where errors occurred) and events. Since we identified workload and task completion time as important aspects of controller performance, we determined that cognitive modeling would be a suitable approach. But while cognitive modeling excels at predicting change for routine events, we determined that it would not adequately predict the effects of change in controller performance under non-routine operating conditions. This led us to select the critical incident analysis method to shed light on factors underlying non-routine events and errors, allowing us to determine which factors may persist or worsen with a new set of procedures. Yet another important aspect of performance is how controllers coordinate their activities and communicate. Again, we determined that cognitive modeling and critical incident analysis alone were inadequate to assess controller

coordination, so we developed a controller coordination analysis framework that leverages and combines previous research in that area. Our selection of methods demonstrates the modular and malleable nature of task analysis and suggests that the questions asked should drive the methods that are used. In this paper, we step through the development and application of the methods in the context of supporting change in the air traffic control tower environment. First, we provide a brief overview of air traffic control tower operations, and we then discuss the cognitive analysis and modeling, critical incident analysis, and coordination analysis in further detail.

OVERVIEW OF US AIR TRAFFIC CONTROL TOWER (ATCT) OPERATIONS

There are five common ATCT positions in the United States: flight data, clearance delivery (or a combined flight-data/clearance delivery position), ground control, local control, and tower supervision. The flight data controller's primary responsibility is to manage flight plan information for departures and coordinate this information with other controllers. The clearance delivery controller is primarily responsible for the pre-departure coordination of flight plan information with pilots. Ground controllers control and coordinate the movement of aircraft on the airport surface, whereas local controllers are responsible for controlling aircraft landings and departures. A tower supervisor is responsible for managing the overall control operations in the tower.

Control towers at larger airports may have additional controller positions, such as a ground metering controller whose main responsibility is to sequence departure aircraft on the ground. An air traffic manager may also be present to relay traffic constraints of the surrounding airspace to the other controllers. Communication between controllers and pilots occurs via radio, with different controller positions communicating over different radio frequencies.

The specific configuration of control towers varies widely, and is dependent on characteristics of the airport layout, traffic, geographic location, winds, and other factors such as noise restrictions. So operations at one tower may vastly differ from those at another.

Coordination and communication between different positions typically occurs either face-to-face or via flight strips. Flight strips are small pieces of paper that contain the most relevant information about a flight, including its departure and estimated arrival time, aircraft equipment and flight plan information. Depending on the tower's configuration, additional systems may be used for coordination and dissemination of air traffic management information.

Prior to departure, an aircraft will file a flight plan indicating its intended flight path, the location and time of departure, and the arrival airport. As a departing aircraft readies for pushback from the gate, the clearance delivery controller communicates the flight plan to the pilot (although this function is sometimes performed by an electronic datalink).

After a departing aircraft pushes back from the gate and reaches the active movement area outside the ramp area, a ground controller issues it taxi instructions. These instructions include the sequence of taxiways and runways to use to reach the departure runway, such as "American 123, runway 35L, taxi via Bravo, Alpha, hold-short of runway 29." Bravo and Alpha refer to taxiways, and the "hold-short" instruction indicates that the pilot is required to stop and ask for clearance prior to crossing runway 29 and continuing to taxi to runway 35L.

As the taxiing aircraft stops at runway 29 and waits for a crossing clearance, the ground controller will coordinate with a local controller who controls the traffic on runway 29 and ask if it is safe for the aircraft to cross the runway. Alternatively, the ground controller may instruct the pilot of the taxiing aircraft to switch to the local controller's radio frequency and receive a crossing clearance directly from the local controller. In this case the required coordination with the local controller is moved from the ground controller to the pilot.

After the aircraft crosses runway 29 and reaches the departure runway 35L, a local controller issues a departure clearance, such as "American 123, cleared for take-off on 35L". The aircraft then rolls onto the runway and initiates the take-off. After take-off, the pilot switches radio frequencies to initiate contact with the departure controller who issues clearances to the now airborne flight. The departure controller is located in the Terminal Area Approach Control Center (TRACON) that services the airport.

COGNITIVE ANALYSIS AND MODELING

Cognitive modeling is useful for making predictions about human performance across a wide range of routine tasks. This makes it ideal for assessing future concepts. In the case of air traffic control procedures, cognitive models can be useful both as a predictive tool and as a unique measurement instrument. Cognitive models enable objective, predictive measurement of mental workload and work time before a procedural revision is actually enacted. This allows the analyst to identify potential pitfalls with a set of procedures and determine the specific issues that should be evaluated in the simulation environment.

We utilized a method developed within MITRE for constructing cognitive models of air traffic control procedures. Below we discuss the method as well as the cognitive models themselves and the outputs they produce. The method begins with

the development of a basic understanding of the controller's or pilot's task and ultimately provides outputs that include objective measures of cognitive workload and work times. Figure 1 below shows the steps of the method.

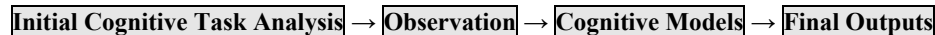


Figure 1. Steps in our Cognitive Modeling Method

INITIAL COGNITIVE TASK ANALYSIS (CTA)

The initial CTA provides the starting point on which the rest of our cognitive modeling method is based. The CTA acts as a decision inventory, enumerating all the decisions controllers must make over the course of each of their identified tasks. For each of the tasks, a control loop is developed. The decision is further annotated with environmental conditions, including when the decision is made, the tools used to support the decision (e.g., a radar system), and a high level classification of that decision (e.g. a planning decision). Since extensive work has been done on CTA in the aviation domain (e.g., Alexander et al., 1989), we adapted that work for use as a starting point in our analysis.

OBSERVATION

Upon completion of the initial CTA, the next phase is to perform structured observations in the existing air traffic control tower--before any procedural revisions are enacted. We use observation as a tool to capture metrics about key controller decision-making events highlighted in the initial CTA under a variety of airport operating conditions (e.g. day, night, high traffic load periods, low traffic load periods). Specifically, we are interested in determining when such events occur, how often they occur, how they occur in sequences with other events, how long they take, and what tools are used to facilitate them. We are also interested in assessing how contextual factors such as traffic load impact the metrics. As a secondary goal, we use observation to refine our initial CTA model. The ultimate use of our observational results is to inform our cognitive modeling development and to help validate baseline model predictions of controller performance.

To support observational data collection in the tower, we developed a PDA-based software application that allowed us to keep up with the rapidity with which controllers perform their tasks. The application allows the analyst to record each type of controller task identified in the initial CTA (e.g. using a tool such as the BRITE, issuing a command to an aircraft, or communicating with another controller) as the controller performs them. When a task is performed, the analyst clicks a button corresponding to the task, and the application records the task--along with the time it occurred--in an event log.

Figure 2 below shows the screen that appears when the software is first launched. It provides the analyst with several drop-down boxes to configure the software for the current data collection objective. The analyst is able to select the Application type (Timer to signify task events are to be accurately time stamped, or Linker to signify that it is only important to record task events in the order with which they occur). The analyst also selects the controller position that will be observed (e.g. Local, Ground, or Ground Metering), as well as the current configuration of the airport (e.g., Plan A).

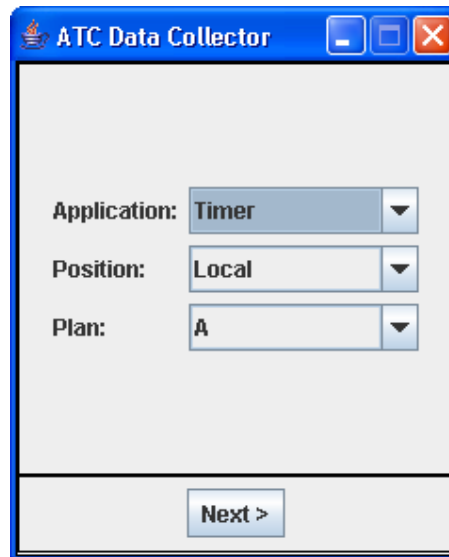


Figure 2. The Main Configuration Screen

Once initial configuration options have been selected, the analyst next selects the controller's location in the tower (Figure 3). If the controller moves at any time during data collection, the analyst may return to this screen to select the new location.

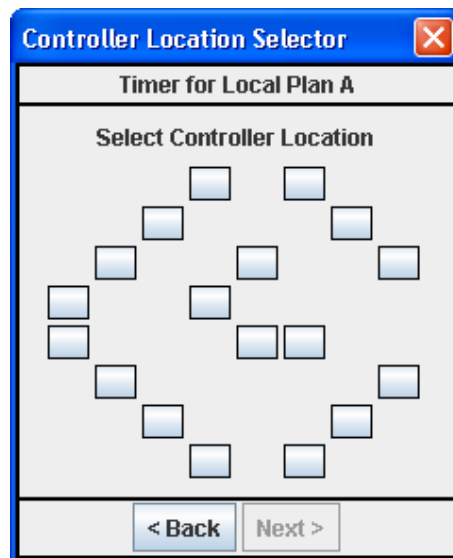


Figure 3. The Controller Location Selection Screen

Having indicated the controller's location in the tower, the analyst may then begin recording data. Figure 4 below shows a sample of the Task Event Recorder screen configured to record data for a local controller. Buttons corresponding to types of tasks the local controller may perform are on the left. In this case, controller tasks are broken down into three groups: commands the controller may issue to an aircraft, tools the controller may interact with, and other positions in the tower the controller may communicate with. When the analyst clicks a button corresponding to a task (such as "Pos & Hold"), the task and the time it occurred are added to the end of the event log (shown as a scrollable box on the right). The analyst may annotate a task that has already been added to the event log by clicking it to launch the event log editor.

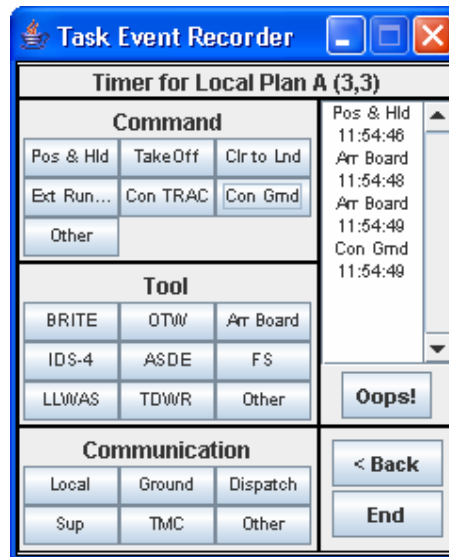


Figure 4. The Task Event Recorder Screen

Figure 5 shows the event log editor after clicking the “Arr Board” task that occurred at 11:54:59. The event log editor allows the analyst to change the type of task, or to append any additional notes to be saved along with the task in the event log. When the analyst is finished recording data for the current controller position, they click the “End” button to return to the main configuration screen. Upon clicking “End”, the contents of the event log, along with the controller position, location in the tower, current airport configuration, and any additional notes associated with tasks, are stored for future analysis.

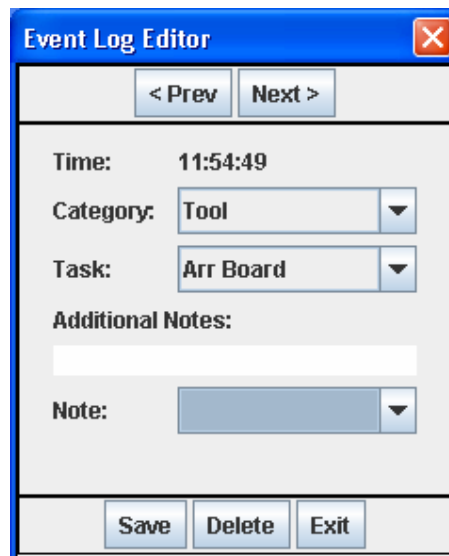


Figure 5. The Event Log Editor

All aspects of the software’s logging capabilities may be modified by altering a configuration file. Any number of controller positions (along with any number of tasks that a particular controller performs) may be configured. In addition, the grid of controller locations in the tower and the various configurations the airport uses may also be altered. Thus, analysts may alter the software if the observations uncover additional tasks that were not identified in the initial CTA.

COGNITIVE MODELS

We have exclusively used modified Goal, Operators, Methods, & Selection Rules (GOMS) models in the course of our work on air traffic control cognitive modeling. More specifically, we used a GOMS variant known as Natural GOMS Language (NGOMSL) with a modification (as discussed in Estes and Masalonis, 2003; Estes, 2001) that provides a measure of working memory load. Figure 6 shows an example model for a pilot performing a separation task under Instrument Meteorological Conditions (IMC) flight rules.

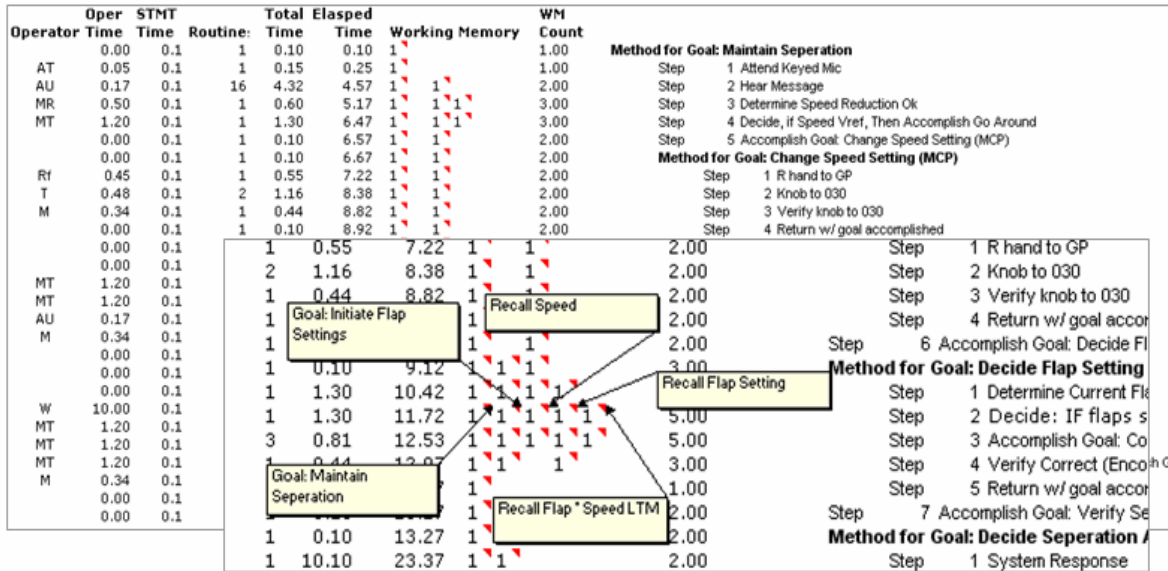


Figure 6. Cognitive Model of a Pilot Completing a Separation Task Under IMC Flight Rules

In order to provide some insight into the contents of these models, it is helpful to review a specific task for which a model has been constructed. Consider the relatively simple task of a controller transferring a pilot to a new frequency (known as Transfer of Communications (TOC)). A basic sequence for the task is shown in Figure 7.

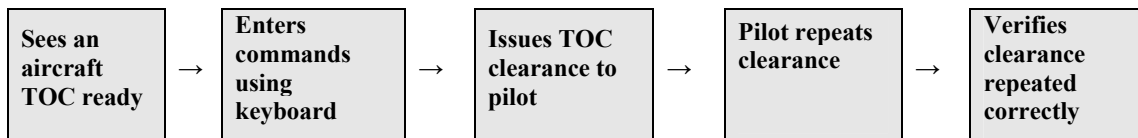


Figure 7. Transfer of Communication (TOC) Task

The initial CTA would have identified both the basic task sequence (as shown in Figure 11) and the more detailed portions of the task. For example, it would have identified the reference point on the radar display for determining when the TOC task should begin, as well as any actions with the flight strip that might occur during the TOC task. Given this information, a cognitive model can be constructed that represents the cognitive activity that would happen during the course of performing the TOC task.

In the cognitive model, the TOC task would begin with the firing of a “Scan DSR” goal. This is followed by the identification of an aircraft ready for TOC. Several pieces of information are then placed in working memory, including the aircraft’s current location, acid, flight plan, and the radio frequency for the next sector. We use working memory load as a means with which to assess mental workload. Perceptual and motor responses are also modeled, such as the controller opening the channel or writing a note on the flight strip - including even saccades across the display. Total work time for the task is derived by summing the time for each of these steps to occur.

In the case of modeling new procedures, we construct cognitive models for both the current procedure (for use as a baseline) and the future procedure. For example, in a data link environment, the controller would uplink the TOC

clearance rather than speak it. Armed with our models, it would be possible to determine changes in work time (how long it takes to complete the TOC task) and mental workload both with and without a data link. Our observational data provides a means with which to validate the baseline model predictions.

FINAL OUTPUTS

As previously mentioned, final outputs include mental workload and work time using a new set of procedures. As an illustration, a typical result from an analysis for a busy U.S. airport is shown in Figure 8. These results are from cognitive models of tower air traffic controllers responsible for issuing takeoff and landing clearances for a variety of different runway configurations. Note that the red line in the workload profiles indicates a level of seven working memory chunks. This is shown simply as a reference and is not meant to imply that anything above that line is “too high.”

Using the output from the models, comparisons of workload and work time utilizing different sets of procedures and systems can be made quickly. With further analysis, models may also provide insight into questions of staffing. For example, the models may be used to answer questions about the number of controllers that would be needed if intersecting runways are used instead of mixed-use runways.

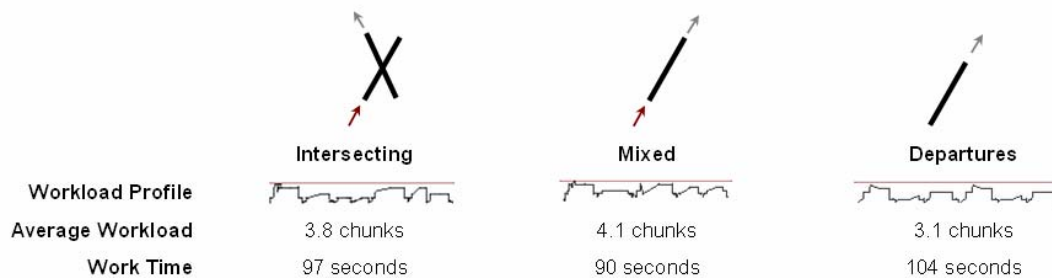


Figure 8. Cognitive Model Outputs for Tower Controller

CRITICAL INCIDENT ANALYSIS

The cognitive analysis and cognitive modeling provide us with a thorough understanding of how controllers perform their jobs under routine operating conditions. To extend this analysis, we aim to gain a greater understanding of the non-routine conditions that have given rise to incidents such as runway incursions. Such events may arise from situational factors such as weather, runway configurations, and frequency congestion, as well as from human performance related factors such as fatigue and degraded situation awareness. Armed with an understanding of the factors that lead to such events with a current set of procedures, we aim to then identify similar factors that may persist using the new set of procedures and cause unsafe operating conditions.

The approach we adopt is a three-pronged one. First, we review incident reports for airport surface movement events that have occurred at the current airport using the existing set of procedures. Incident reports may be culled from the Aviation Safety Reporting System database, the National Transportation Safety Board Aviation Accident and Incident database, as well as from any incident report files the airport maintains. In the course of our incident analysis, we develop an incident categorization scheme and assess how frequently certain types of incidents occur. Table 1 below shows a sample incident categorization scheme.

Environmental Factors	Pilot-Controller Communication Factors	Controller Related Factors
Intersecting runways in use	Non-standard or non-specific phraseology used	Issued clearance with obstruction present
Parallel runways in use	Instructions issued rapidly	Issued clearance to wrong aircraft
Aircraft landing and departing from the same runway	Responded to instructions issued to a different aircraft	Controller-controller miscoordination
Poor weather Conditions	Misinterpreted instructions	Workload excessive
Wind conditions	Misheard instructions	Failed to visually scan runway
	Read-back not given or not corrected	Anticipated Separation Error
	Frequency Congestion	

Table 1. Sample Incident Categorization Scheme

If possible, we next perform a similar incident analysis on an airport that has procedures in common with the proposed set of procedures, or is at least configured in some way that is similar to the proposed airport configuration. The results of these initial incident analyses enable us to gain an understanding of the factors (or combination of factors) that typically underlie such incidents.

Based on the results of our initial incident analysis, we next conduct interviews with controllers that allow us to gain a greater understanding of the underlying contextual and human performance related factors behind operational errors. This analysis goes beyond the understanding that can be gained from analysis of incident reports alone. If possible, we conduct critical incident interviews with controllers at each airport using the Critical Decision Method (CDM) (Klein, Calderwood, & Macgregor, 1989). The construction of incident probe questions and selection of appropriate incidents for analysis is informed by both the important factors identified in the initial incident analyses as well as by the potential pitfalls identified in the cognitive modeling analysis (see above).

For example, one controller-related factor that we determined to be important was anticipated separation errors. Anticipated separation errors occur when controllers fail to anticipate the required separation or miscalculate the impending separation between aircraft (Cardosi & Yost, 2001). Anticipated separation is a traffic flow management strategy that controllers use where they issue clearances with some type of obstruction present, but, based on their judgment, they predict that the obstruction will be clear by the time the clearance is actually executed (e.g., aircraft x will be off the runway and out of the way by the time aircraft y lands). This increases controllers' workload, as they must not only maintain awareness of the current situation, but they must also use that awareness to make predictions about future situations. We determined that this strategy is likely to be relied upon when traffic loads are high, when the same runway is being used to both land and depart aircraft, or when two intersecting runways are both in use. Thus, in our incident interviews, we would be sure to elicit scenarios from controllers where anticipated separation was a factor, and we would also address situations that may arise utilizing a new set of procedures where controllers would be likely to make anticipated separation errors.

CONTROLLER COORDINATION ANALYSIS

One of the important areas identified for analysis and not adequately addressed by either cognitive modeling or critical incident analysis is controller coordination. To perform this analysis, a method that leverages and combines previous work in this area was developed. Our method, summarized in Figure 9 and described in detail below, was developed in cooperation with air traffic control subject matter experts and postulates a procedure based on best practices in the field.

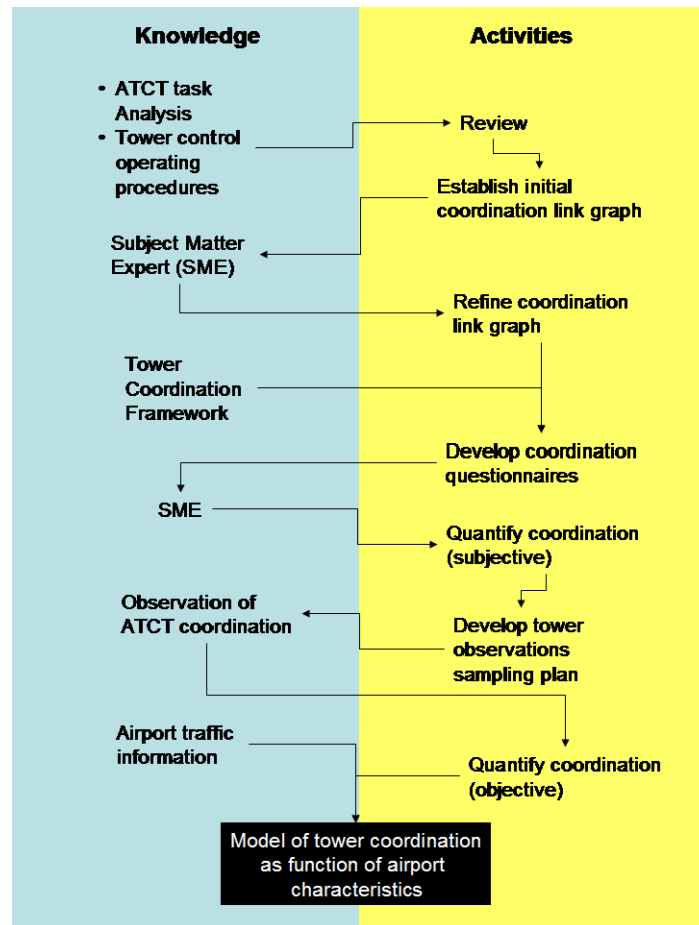


Figure 9. Methodology for the Assessment of Air Traffic Control Tower Coordination

Coordination has been defined as management of dependencies between activities (Mallon and Crowston, 1993). In the aviation domain, Peterson, Bailey, and Willems (2002) developed a descriptive framework for en-route controller coordination. This framework categorizes coordination into three dimensions: coordination topics (e.g. coordination concerning traffic), grammatical form (e.g. questions, commands), and communication expression (e.g. verbal, non-verbal).

The Peterson et al. (2002) framework was used as starting point for the development of our ATCT coordination framework. Coordination topics were extracted from Alley et al. (1987), who had performed a task analysis of ATCT operations, and from the Standard Operating Procedures (SOP) document of an ATCT. SOPs outline the responsibilities and duties of tower controllers. A subject matter expert from an ATCT also reviewed the initial list and added additional topics. We established a list of approximately fifty five coordination topics for the local control, ground control, ground metering, and clearance delivery positions. Coordination topics include such things as “respond to requests for transfer of control” and “plan and issue ground movement instructions.”

A subset of these coordination topics (e.g. forward flight plans, establish departure sequence) is represented using link charts in Figure 10.10 and 11 that show tower coordination as defined in an example SOP. Numbers on these charts refer to the SOP defined responsibilities but were renumbered for illustrative purposes.

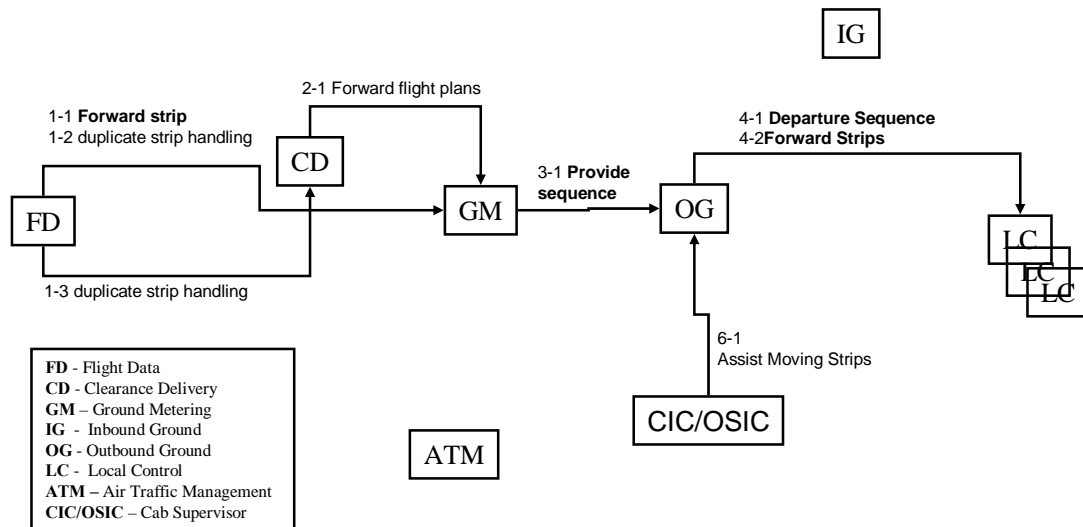


Figure 10. Example of Flight Strip Coordination in an Air Traffic Control Tower

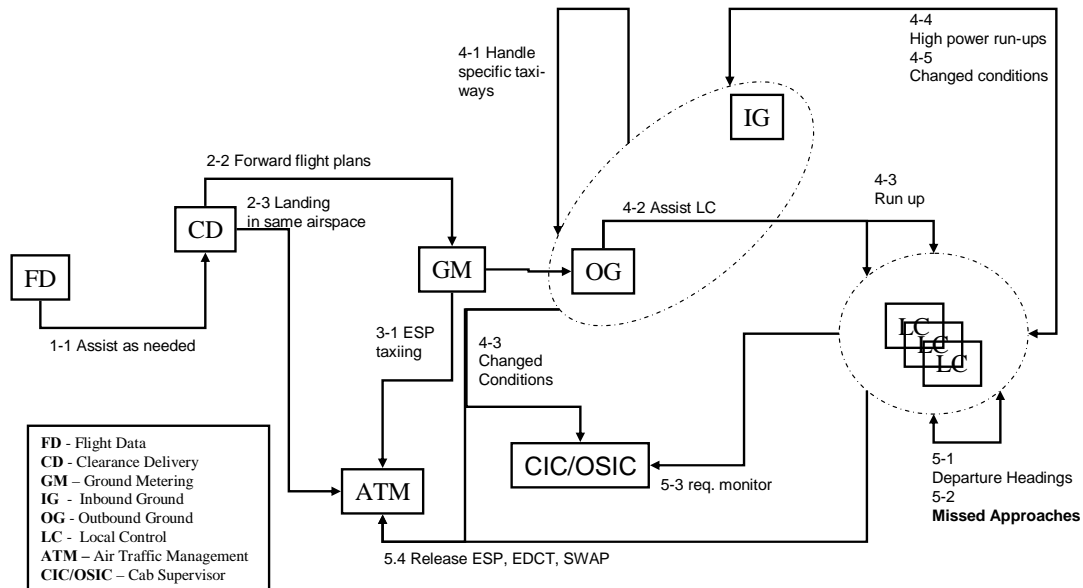


Figure 11. Example of Face-to-Face Coordination between Controller Positions in an Air Traffic Control Tower

The initial list of coordination topics was then used to elicit operational knowledge about control tower coordination from former air traffic controllers who served as subject matter experts (SMEs). The purpose was to derive an understanding of the aspects of coordination in the context of changing tower procedures. First, narratives about the initially identified coordination topics were collected from the SMEs. The discussion was structured around a card sorting technique (e.g. Cooke 1999). SMEs first sorted coordination topics into two piles of either high or low subjective importance. After the sorting, SMEs articulated the rationale for their importance ratings and described the coordination topics. These narratives initially reflected a wide variety of experiences that controllers have had at their specific control towers. Over time, however, the SMEs began to think along similar dimensions when describing the coordination topics.

The SMEs focused mainly on the seven dimensions that are summarized in Table 2 and described below.

	<i>Coordination Dimensions</i>	<i>Example</i>
1.	Topic	Active runway crossings
2.	Controller Positions	Ground and local controller
3.	Estimated Frequency of coordination	Very frequent
4.	Estimated Time Criticality of coordination	Immediate
5.	Coordination dependencies	Visibility Conditions
6.	Estimated workload of coordination	Low, no follow-up activity required
7.	Medium of coordination	Face-to-face

Table 2. Initial Coordination Framework

The first dimension is the coordination topic, and the second dimension is the controller position.

The third dimension indicates the coordination frequency, quantified a five point scale, with values of very rarely, rarely, occasionally, frequently, and very frequently.

The fourth dimension describes coordination time criticality, reflecting the time frame in which SME's determined a coordination request should be responded to. Values on the time criticality scale were immediate (less than 5 seconds), high (five to ten seconds), medium (ten to thirty seconds), and low (thirty seconds or more).

The fifth dimension describes events and conditions that influence coordination. These include environmental conditions such as visibility, weather, winds, traffic loads, and other airport characteristics such as runway or taxiway closures.

The sixth dimension describes the level of coordination workload. Coordination workload was indicated as the amount of follow-up activity required for a specific coordination topic. It was rated on a scale with values of easy, medium, and hard. Easy workload required no or very little additional coordination with other controllers after the initial coordination, medium workload required some follow-up coordination, and high workload required substantial follow-up. Workload was also judged as high when more than two controller positions were involved.

The seventh dimension describes the coordination medium. SMEs reported using face-to-face communication, radio communication, telephone communication, and communication using flight progress strips.

The three SMEs then ranked the coordination topics along the listed dimensions. The top three coordination topics that require especially high coordination are:

1. Resolution of conflicts for taxiing aircraft (e.g. pilot fails to hold-short of intersection).
2. Active runway crossings.
3. Runway crossing under Land-and-Hold-Short Operations.
4. Response to requests for runway condition data
5. Response to air traffic flow restrictions

BENEFITS

Our coordination framework is intended to guide the identification of coordination activities that may be impacted by changes in airport systems and procedures. For example, new communication media (e.g. from face-to-face to radio or to system automation) can significantly impact tower coordination. "Active runway crossings", for example, were rated by the SMEs as frequent and highly time-critical but with little requirement for follow-on coordination. This coordination topic poses different requirements on the communication medium than, for example, "responses to flow restrictions", a coordination topic the SME's deemed to occur less frequently and with less time-criticality but with potentially significant amounts of follow-on coordination. In this example, the coordination framework can help guide the design of communication media to best support controller coordination. It can also identify coordination topics that will be most impacted by proposed communication media changes and should be examined in a simulation.

Our framework can also help determine the frequency of various coordination activities in a specific tower. Such knowledge can be important in determining which coordination activities are most important and should be evaluated in simulation. To perform this quantification, coordination activity frequency is first estimated by tower controllers. These estimates are then used to derive a tower observation sampling plan by identifying which activities should be sampled to obtain empirical coordination frequencies. Once coordination frequency data have been collected, these data can be correlated with actual airport surface traffic characteristics, allowing us to build computational models that predict how coordination frequency changes with changes in airport traffic characteristics.

CONCLUSION

We presented a combination of complimentary approaches to address important aspects of controller performance. The combination of analytic techniques provides a comprehensive assessment of air traffic control operations in the tower environment. It allows us to make predictions about the effects of procedural changes on air traffic controller performance, and it provides results that may be used to guide the construction of a series of representative scenarios for use in interactive tower simulations. Our development of a suitable set of methods demonstrates two fundamental lessons that we've learned in the course of our analysis: methods typically require customization to meet the analysis demands of the domain, and a combination of methods is typically needed. We continue to adapt and refine our methods as we apply them in our analysis work at MITRE.

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