EVALUATING TRANSFORMATIONS OF THE AIR TRANSPORTATION SYSTEM THROUGH AGENT-BASED MODELING AND SIMULATION

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Abstract

To increase the capacity, safety, efficiency, quality, and affordability of air transportation systems require potentially revolutionary transformations. These transformations may involve system-wide changes and innovations as well as changes to individual components within the system. All of these changes require a robust modeling and simulation tool that can evaluate overall collective emergent system performance arising from individual components' behavior as proposed in innovative ATM concepts.

This paper proposes agent-based modeling and simulation (ABMS), including computational human performance models, as a conceptual framework and a simulation platform for a priori computational analysis method of predicting the impact of innovative ATM concepts. A specific test case of analyzing aircraft arrivals into LAX using a variety of spacing techniques was examined throughout as a demonstration, and as an opportunity to compare simulation predictions about current system behavior to available measures. The results indicate that ABMS has the capability to reveal unexpected emergent behaviors and can be used to investigate the causes of and potential solutions to them.

Introduction

Air traffic demand keeps increasing rapidly, leading to airport and airspace congestion, with corresponding flight delays. In order to address these issues, innovative air traffic management (ATM) concepts need to be provided and explored. Such innovations will remove many of the constraints in the current system and support a wider range of operations to accomplish the goal.

These innovations may be enacted through changes in technologies, processes, procedures, workers, and its organization. Typically, these changes can be made by transforming properties or aspects of individual components, or by transforming the interrelation between components within the system. Such advanced air transportation concepts will also dramatically change human's roles and tasks, for example in operations in which flight crews and air traffic controllers contribute to ensuring a more efficient traffic flow while maintaining safe aircraft separation. Modeling and simulation approaches are vital for evaluation of these concepts.

This paper proposes an agent-based modeling and simulation (ABMS) approach, incorporating computational human performance models, as a conceptual framework and a simulation platform to evaluate innovative ATM concepts. This agent-based simulation can integrate cognitive models of human performance, physical models of technology behavior, and models of their operating environment. Simulation of these individual models interacting together allows one to predict the impact of completely new transformations in the system's organizational structure, operating procedures and technologies. Thus, ABMS provides a valuable research and analysis tool for predicting individual behavior of each component of the system as well as system-wide behavior emerging from the interactions between individual components. Both micro-level (agent) and macro-level (system-wide) behaviors can be simulated simultaneously, highlighting system-wide issues arising from a change in airspace configuration, air traffic procedures, or air or ground technologies – as well as identifying unreasonable demands that system dynamics may place on individual agents, especially human air traffic controllers and pilots.

Background: Agent-Based Modeling and Simulation (ABMS)

Agent-based modeling and simulation (ABMS) is of increasing interest with respect to the modeling and simulation of complex socio-technical systems such as air transportation system [1,2]. The overall dynamic behavior of such a complex system typically emerges from the interactions among components. The collective and emergent behavior of individual system components including hardware, software, and human operators, therefore, can be modeled and simulated as an interaction among agent models [3,4,5,6].

Specifically, we view air transportation as a large-scale, complex socio-technical system composed of controllers, pilots, airline dispatchers, aircraft, airports, navigation aids, and technical devices. Thus, the individual behavior of these different entities and overall behavior of the NAS, can be modeled by a combination of agent models, environment models, and their interactions.

In simulating ATM systems by agent-based simulations, the overall behavior of the systems can be considered as emergent phenomena. 'Emergent' is formally defined here as a system property in which system behaviors at a higher level of abstraction are caused by behaviors at a lower level of abstraction which could not be predicted, or explained, at that lower level. In this case our levels of abstractions are the agents (typically humans) and the emergent system-wide behavior. Agent-based simulation provides interesting insights at both levels of abstraction. In addition to the system-wide behavior, the agents respond to their environment and each other in agent-based simulations. While we can model what the agents' responses would be to a variety of conditions, only simulation can predict what specific conditions they will need to respond to. As such, it is often just as interesting to use simulations to see what activities are demanded of an individual agent (e.g., a human air traffic controller or pilot) when put in the air transportation system as it is to see what the system-wide behavior will be in response to changes in agent behaviors, including new technologies, and changes in system structure such as new operating concepts for aircraft routing and separation, including distributed control structures.

More informally, our agent-based simulations are not based on any high-level models of air transportation; instead, we put agent models in a rich environment, simulate them in a realistic scenario, and see what system behavior comes out. Thus, agent-based simulations are uniquely suitable for evaluating innovative ATM concepts, such as dynamic airspace configurations and trajectory-based operations, as they are not necessarily built upon or parameterized by the structures used in current-day operations.

Agent Models of Human Performance

Of critical importance in the agent-based simulation of large-scale socio-technical systems is the inclusion of human components since their behavior also drives the system dynamics. The idea is to model the behavior of the humans in terms of agents. A computational agent model of human performance can be defined as a representation of human behavioral characteristics that can be implemented and executed in a simulation environment [8,9].

Even simple normative agent models of human performance provide valuable insight when used in the context of ABMS: they allow evaluation with respect to system performance resulting from well-known aspects of human behavior. For example, using simple agent models, agent-based simulation can observe whether the system will function as desired when all components act exactly as procedures, regulations and organizational structures mandate – and highlights areas where individuals' flexibility and creativity are still required to operate the system. Agent models are more descriptive of human performance than normative models and can therefore identify the impact of the accuracy, speed, and variability of human performance, which are critical to the emergent behavior of the larger system [7].

By representing the human as an agent in an agent-based simulation, it is possible to examine the interaction of human behavioral tendencies with system state over a wide range of circumstances. Recently, studies have examined using these human performance models as agents in large-scale agent-based simulations to evaluate air transportation safety and capacity issues [2, 6, 10, 11]. This approach adds fidelity both to the human performance models and to the larger simulation; correspondingly, agent-based simulation brings to these human performance models a dynamic representation of their environment, including detailed models of the physical and technical systems, and the opportunity to dynamically interact with other humans. Ultimately, it is hoped that these simulations will have sufficient fidelity in their agents' ability to reason and react to unexpected situations to examine a wide range of potential precipitators of hazardous situations.

Established methods of agent-based simulations have focused more on the agents than on their environment. Following an ecological viewpoint of human behavior, we propose that many aspects of human performance are driven by the environment and should be represented as such. Consequently, we have developed specifications of the constraints and affordances implicit within the environment that can establish both a modular software mechanism for codifying environment structures relevant to many types of agents and a more-accurate conceptual representation of agent behavior [5,6,12]. Within this representation, components of the environment include not only physical components such as radar and aircraft, but also the process components such as operating procedures, with their availability to the agents described via representations of operating context.

The model is a discrete-event simulation in which events are defined as temporal increments (called "ticks") of a clock that sends a message to all agents to proceed with their functions at each event. The events/time base is a variable that can be set by the analyst using the model. The resolution of this event-base was varied in the Big Airspace simulation so that the model could concentrate its data collection in epochs of high intensity operation, and reduce its collection in times of reduced activity.

An activity is triggered in the model in two ways. Either by decomposition of goals to be performed, or by occurrence of a specific value in the environment for which there is a daemon to respond and identify that value as significant and requiring action. When an activity is triggered in service of the mission goal or in response to environmental stimuli, the activity, prior to its having an effect in the simulation, is managed by the scheduler.

Activities are characterized by several defining parameters that include the conditions under which the activity can be performed, its relative priority with respect to other activities, an estimate of its duration for scheduling, its interruption specifications, and the resource required to perform that activity. The scheduler is a blackboard process that evaluates these parameters and develops a time for the activities performance in the ongoing simulation. Following a multiple resource assumption, activity load is defined for Visual, Auditory, Cognitive, and Psychomotor dimensions. Activities also require information for their performance. The information requirement is identified as knowledge either held in the operator's memory or available from the environment. If the information necessary for activity performance is available, and its priority is sufficient to warrant performance, then the scheduler operates according to heuristics that can be selected by the analyst. In most cases, the heuristic is to perform activities concurrently when that is possible, based on knowledge and resource constraints.

Demonstration: ABMS of LAX Arrivals

The agent-based Reconfigurable Flight Simulator (RFS) architecture [12,13] was used to examine the impact of innovations in the air transportation system. The RFS agent-based modeling and simulation framework encapsulates complex, dynamic internal behaviors as computational objects representing the internal dynamics of environment components and the agents. This simulation platform was constructed using the object-oriented design approach in C++ and provides a fairly general and extensible architecture that has since been built on to incorporate novel conceptual constructs suitable for complex-agent based simulations. Specifically, the RFS conceptual framework builds on the principles of cognitive engineering to describe the components of the work environment, i.e., technology, processes and information, and the humans and automated agents, in task-relevant ways and using a structure-preserving form using the same attributes and structure as used by system designers and human operators. The framework includes both declarative models of system components and their interrelations, and computational models of those complex, dynamic behaviors that cannot be adequately described declaratively [12].

To construct an agent-based simulation within our framework, three components must be developed. First, models of the individual agents must be developed that are capable of emulating the relevant behaviors within the system. Second, a model of the environment must be developed which furnishes the agent models with the information they need about the physical and process aspects of their context. Third, mechanisms must be provided for the agents to act and interact, including mechanisms for timing and data passing.

LAX Airspace Modeling

In an effort to improve the safety and efficiency of air traffic management at Los Angeles International Airport (LAX), the Federal Aviation Administration (FAA) has modified certain jet arrival routes, air traffic control sectors, and air traffic control (ATC) coordination procedures. This study employs real world scenarios, which include differences in traffic flow control methods such as Time-Based Metering (TBM) and Miles-in-Trail (MIT) from the LAX.

LAX has two final approach courses, one heading for the north airport complex (Runways 24L/R) and one heading for the south airport complex (Runways 25L/R). The current westbound arrival configuration to LAX consists of three main flows of aircraft that are funneled into one stream by Los Angeles Center (ZLA). The traffic is then worked primarily by one TRACON controller who provides sequencing to the southern approach course. Another TRACON controller handles inbound arrivals from the north and west, sequencing them to the northern final approach course. These approaches are then managed by a feeder sector controller for proper spacing.

Aircraft arrivals from the east typically create a much greater volume of traffic on the southern arrival course than the northern course with the current routes and procedures. This traffic configuration results in an imbalance in controller workload, and, at times, significant aircraft delays and thus increased user costs. By simulating three terminal sectors and the higher two en route sectors concurrently, computational agent models of controller could realistically control aircraft from the boundaries of the high-altitude sectors to the Los Angeles International Airport.

Figure 1 illustrates the air traffic control system examined here. It shows the eastern part of the airspace for Los Angeles International airport (LAX). The system modeled in this demonstration consisted of five air traffic controllers, each controlling the airspace in one of the five contiguous sectors on the eastern approach to LAX. A number of flights fly through these sectors: some of them are arrivals into LAX; others are considered 'over-flights'.

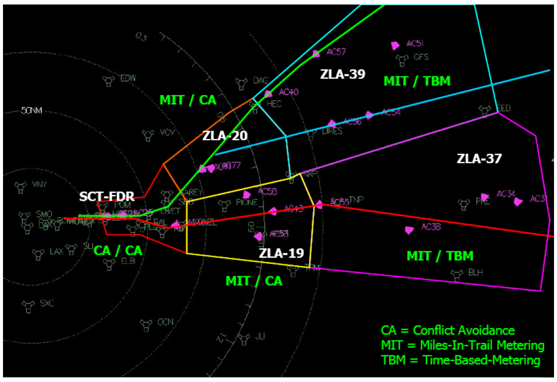

Figure 1. Eastern Airspace of the Los Angeles International Airport (LAX)

The airspace is spatially divided into multiple contiguous sectors (ZLA-39, ZLA-37, ZLA-20, ZLA-19, SCT-FDR), where the boundaries of these sectors are predefined as abstract polygons in the airspace. The air traffic, i.e., all aircraft, in each of these sectors is monitored for conflict-free and procedure-compliant operation by air traffic controllers, each working on their respective sectors. Each sector controller is equipped with a radar screen that displays the traffic in their sector, a voice radio to transmit traffic control commands to the aircraft and receive requests from aircraft, and a specific set of control procedures. These elements constitute the workspace of the controller, with which the controller interacts to achieve his or her goals, i.e., maintain safer operations and ensure compliance with assigned procedures. In this demonstration, this system is transformed through changing the procedures and by changing which procedures are in the workspace of each air traffic controller.

Of interest here, TBM is one initiative that operationally changes from distance-based control of spacing in air traffic flows to time-based control [14,15,16]. TBM, accomplished through the use of Traffic Management Advisor (TMA), is a traffic management technique used to provide an efficient and orderly flow of traffic by assigning crossing times for arrival aircraft at points along its route of flight. The dynamic planner (DP) of TMA schedules all aircraft landing at an airport, providing a "scheduled times of arrival" (STA) for each aircraft at a meter fix and at the runway to delay aircraft. Scheduling is redone according to a modified first-come-first-served order. Aircraft are sequenced according to their estimated time of arrival (ETA) at the meter fix. The schedule conforms to acceptance rate constraints and to FAA aircraft spacing requirements. Since TBM utilizes the automation tool, TMA, to generate conflict-free scheduling of aircraft, it was expected that the TBM will be effective at increasing capacity and reducing workload of air traffic controllers.

This change is enacted through component and network level changes in the work-processes in the work environment of air traffic controllers. The success of such a work processes based transformation is highly dependent on the successful integration of humans, technology, work-processes and information in the system. Thus, the first task identified the important task descriptions and work processes to include in the simulation models. This demonstration included three work-processes used by the air traffic controller:

1. Miles-in-trail (MIT): These traditional work-processes help the air traffic controllers space aircraft on the same route by a given distance. The MIT procedures are meant to space arriving aircraft by a specific in-trail spacing that is expressed in terms of nautical miles and is provided to the air traffic controllers by the air traffic management units or is agreed upon by controllers of adjoining sectors. These procedures are meant to achieve a specific arrival rate while also spacing aircraft to allow for additional aircraft to merge into the stream.

2. Time-Based-Metering (TBM): In time based metering of arrival flows the Traffic Management Advisor (TMA), a technological aid, provides the controllers with 'delay times' that specify when each aircraft should arrive over a specific fix. The time-based-metering work-processes are meant to achieve high arrival rates and to help the controller slow and space the aircraft to 'absorb' their delay times in order to conform to scheduled times of arrival and to ensure the desired arrival rate.

3. Conflict Avoidance (CA): These work-processes are meant to help the air traffic controller avoid conflicts between aircraft. A conflict is a situation when two aircraft come closer than five nautical miles horizontally and one thousand feet vertically above an altitude of 18,000 feet, and three nautical miles horizontally and one thousand feet vertically below 18,000 feet. Such an occurrence of the loss of separation, also called an 'operational error' in real operations, is referred to as a 'violation' in this study.

The assignment of work-processes to each controller was one way of specifying the system's network level structure. For example, when exercising MIT control, the controllers of the higher sectors, i.e., ZLA-37, ZLA-39, ZLA-20 and ZLA-19, were given the MIT work-processes, while the SCT-FDR controller was given the Conflict Avoidance work-processes. On the other hand, when exercising TBM control, controllers of sectors ZLA-37 and ZLA-39 were given TBM work-processes while the other three were given conflict avoidance work-processes.

Agent Models

Several agent models and environmental aspects are modeled to simulate the five eastern approach sectors as shown in Figure 2. The agent model of human operators such as air traffic controllers and pilots was based on Air-MIDAS, developed by NASA Ames Research Center (ARC) and San Jose State University (SJSU) primarily for aviation-related applications. This model contains several functions within its model of human performance. Domain knowledge serves as pre-established knowledge about the task, often represented as procedures and a rule-base of goals and processes for core tasks. An upgradeable world representation also acquires and maintains knowledge about the current state of the environment. Within this framework, a symbolic operator model maintains queues of tasks waiting to occur, and switches tasks between them according to knowledge and goals [8].

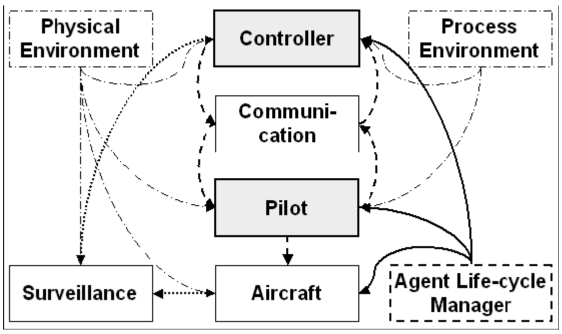

Figure 2. Agents and Environmental Aspects in Simulation of LAX Arrivals

These core behaviors of the Air-MIDAS were implemented within the RFS for computational efficiency and to facilitate agent interaction with the work environment. Agent model of air traffic controller is modeled as a collection of skills, capabilities, and internal processors which build on each other through the use of internal agent architecture in the RFS as shown in Figure 3. These internal processors run autonomously and employ these skills, capabilities, and the worker's knowledge of the work environment to accomplish its goals. The activity processor starts and performs activities to achieve its goals. Each of the activities is associated with the skills and capabilities, and each activity requires a certain number of internal cognitive resources that are provided by the 'resource provider'. The controller agents are continuously updated by a dynamic environment model about the airspace and aircraft flight paths.

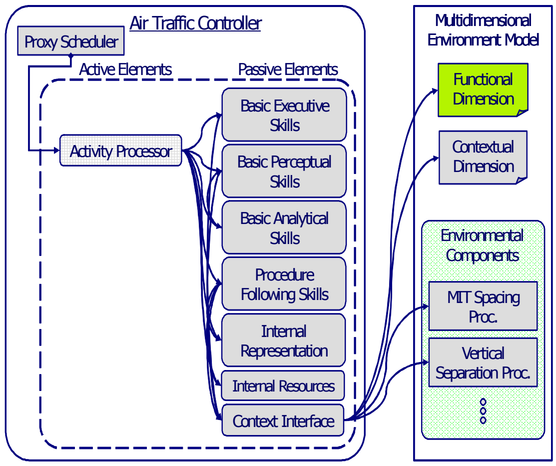

Figure 3. Agent Model of Air Traffic Controller

As described earlier, the work environment imposes a requirement on human's skills and capabilities that must be modeled to appropriately represent a human operator situated in it from the ecological modeling point of view.

Model of the Work Environment

The components in the work environment of the air traffic controllers include the aircraft, the surveillance and voice radio equipment and the work-processes. It should be noted that not all these components have the same lifespan as the controller: aircraft appear in the work environment according to their schedule and then exit the airspace. Thus, this is a dynamic work environment.

Viewed from top-down, the contextual dimension is constructed by assembling contextual nodes for each component of the work-environment and then associating them through contextual-compositions. In this case, the contextual dimension includes one contextual node for each control sector, which further subsumes the contextual nodes for the surveillance equipment, the control equipment, the wind measurement equipment, the work-process information system and the flight strips management system as shown in Figure 4. These further subsume contextual nodes containing those parts of each component available to the controller.

Viewed from the bottom-up, the model of each component of the work environment includes a set of properties and usage mechanisms. These attributes are grouped into aspects that map them onto the contextual dimension of the work environment. For example, let us consider the aircraft component. For the purpose of air traffic control, the work-relevant properties of the aircraft may be summarized as; Latitude, Longitude, Altitude, Ground speed, Vertical speed, Heading, Flight Path Angle, and Flight Plan.

The aircraft dynamics are modeled to three degree of freedom and account for the performance of limitations of commercial aircraft. Their dynamic models interact in continuous time with the wind conditions represented in the environment model. A range of wind conditions were tested representing tail wind and head wind situations for the arriving aircraft. Aircraft agents are injected into the simulation at specific times based on real flight data of actual days at LAX. Other physical entities and processes such as the radar, the navigational aids, the winds and the communication channels have been modeled in the RFS simulation framework [12].

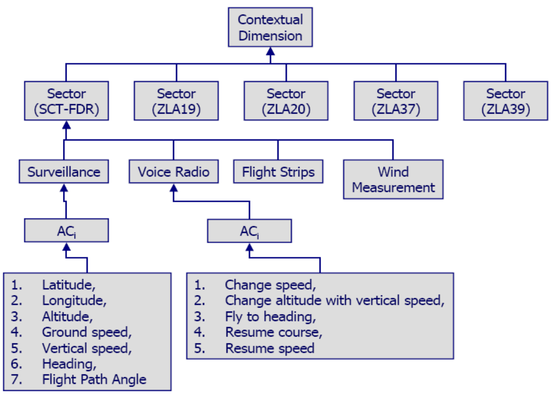

Figure 4. Part of the Contextual Dimension in the Case Study

Each aircraft model also has a set of contextual aspects that map these attributes onto the contextual nodes comprising the contextual dimension. The surveillance equipment includes a set of contextual aspects of each aircraft within its monitored airspace through a contextual-composition relationship. The internal dynamics of the surveillance equipment ensure that at any given point of time in the simulation the contextual nodes of all aircraft in the sector are included in the contextual node of the surveillance object. Similarly, contextual nodes are created for flight strips available in the context of a controller as shown in Figure 4. The usage mechanisms of an aircraft include:

1. Change speed,
2. Change altitude with vertical speed,
3. Fly to heading,
4. Resume course, and
5. Resume speed.

In the real world, these usage mechanisms are available to the pilot through controls in the cockpit or through flight management systems. In this study, these pilot-controller communication mechanisms were assumed not to be important for the analysis and these usage mechanisms were directly made available in the context of a controller by mapping them over to their contextual dimension through their voice radio equipment.

The functional dimension relates the environmental components to the goals through means-ends-constraints relationships; in other words, it identifies them as affordances and constraints towards one or more goals. The construction of the functional dimensions starts with identification of the goals shown in Figure 5.

Once the goals have been identified, the environmental components are tagged as means and constraints. In this case we have two kinds of environmental components: technological artifacts and work-processes. For the sake of brevity of this discussion, Figure 5 shows a partial model including only the goals and the work-processes. In the figure, the associations with arrowheads identify that the component at the tail of the arrow is a means to the work-objective at the head of the arrow. If the arrowhead is a dot, it identifies the component at the tail of the arrow as a constraint. Changing a controller's available work processes (e.g., from MIT to TBM) requires them to re-evaluate their functional dimension to identify components available to them in their context that will enable them to meet their goals.

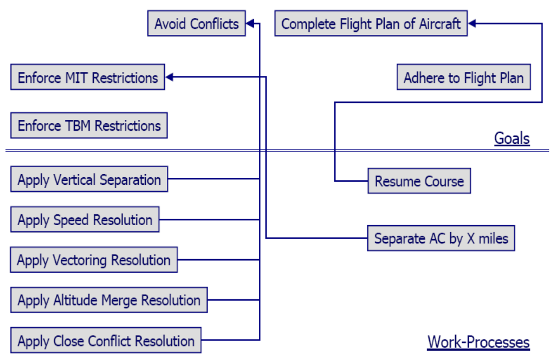

Figure 5. Relating Goals and Work-Processes via the Functional Dimension

Since innovations in the air traffic systems being modeled are implemented in the environment by changing the environmental components, and their placement in the controller's contextual dimension within the work environment, models of the air traffic controllers are automatically generated from the work environment model. Five controllers are modeled, one for each of the control sectors. They are each allotted to a specific sector in the contextual dimension as shown in Figure 4, thus making the appropriate contextual node (and any it subsumes) available to each controller. They are each allotted a subset of goals from the set shown in Figure 5. For instance, when the system design represents an MIT configuration, the air traffic controller for sector ZLA19 (one of the four higher sectors that enforce MIT restrictions between arrivals) is allotted the following objectives: Enforce MIT Restrictions and Complete Flight Plan of Aircraft. For an environment-centered design, making these allotments is the only activity required when designing the system.

However, an agent also needs to be constructed as a configuration of skills, capabilities and processors inherent to human performance. The RFS simulation platform is capable of building the agent based on the system-level design. Specifically, using the model composition architecture, the model construction engine first identifies all environmental components associated with the allotted goals on the functional dimension and with all components in the contextual dimension that are associated with the allotted context of the worker. The usage mechanisms of these components are identified and the skills and capabilities associated with them are picked out from the computational model registry and added onto either an empty agent model or to a template agent model which may be hand-picked by the designer.

When a template model is picked by the designer, the model construction engine identifies those skill and capability implementations from the computational model registry that correspond to the template. These skills and capabilities are then aggregated into the agent. At this point the agent model is ready to be used in the simulation for operational analysis; in addition, the assembled list of skills and capabilities can be examined during network analysis to examine the feasibility of the set for the intended worker and to identify training and information requirements for the worker.

Analyzing Configurations of and Changes to Air Traffic Systems

This section describes analyses of innovations to this air traffic control system. In the MIT configuration, the controllers of the four higher-altitude sectors (ZLA-39, ZLA-37, ZLA-20 and ZLA-19) are given, within their contextual dimension, procedures for distance-based separation between aircraft (MIT procedures); in TBM operations they are given TBM procedures. We also examined whether either MIT or TBM alone were sufficient to prevent violations, or whether the controllers also needed to explicitly do pair-wise comparisons of aircraft separation for conflict avoidance. Once these changes were made in the contextual dimension, the system and agent construction architecture automatically constructed the computational models needed for the simulation. The agent models did not have to change because they were already capable of processing whatever set of work-processes is assigned to them.

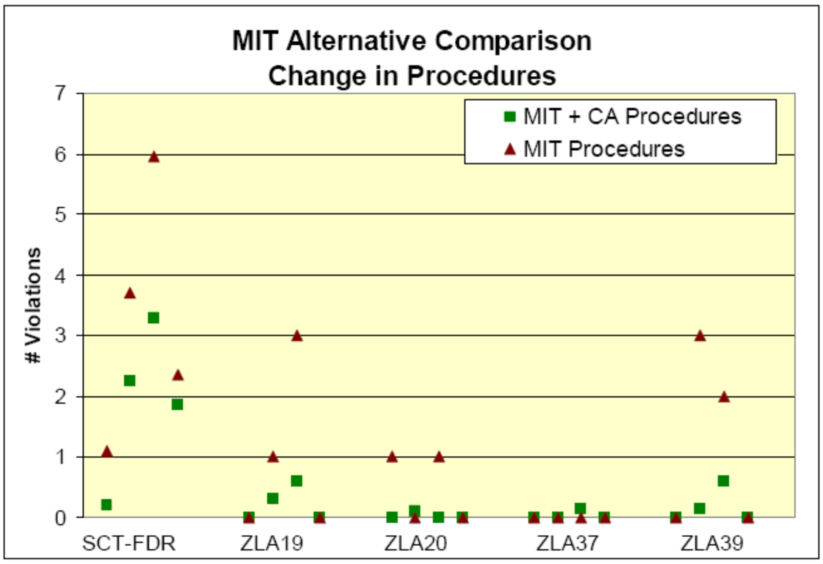

Figure 6. Comparison of Average Number of Separation Violations per Sector per Scenario for Changes in Air Traffic Procedures

Figure 6 compares the performance of MIT procedures alone to MIT and CA procedures in terms of the number of separation violations found in each sector over multiple runs in several scenarios. Though performance is improved for the new design alternative, the overall rates were still higher than those identified from radar data of the same traffic situations.

Agent Type	Unlimited resources	Limited resources (Max Resources = 7)		
Source of Variability	Accuracy	Accuracy	# Resources	
Distribution	Uniform	Uniform	Normal	
Activity	Probability	Probability	Mean	Stdev
Monitor Traffic for Conflicts	1	0.8	3	1
Monitor Traffic for MIT Spacing	1	0.8	3	1
Monitor Traffic for TBM Compliance	N/A	N/A	2	1
Change Speed	N/A	N/A	4	1
Change Heading	N/A	N/A	4	1
Change Altitude	N/A	N/A	4	1
Resume Course	N/A	N/A	4	1
Resume Speed	N/A	N/A	4	1
Monitor Sector Boundary Conformance	N/A	N/A	2	1
Wait	N/A	N/A	1	1
Follow Procedures	N/A	N/A	2	1

Figure 7. Summary of Worker-Level Transformation in Air Traffic Controller Model

To further examine the causes of violations, the human performance model was replaced with a worker model with resource limits and without any stochastically induced inaccuracies in its activities in terms of the probability of detecting a conflict or a spacing problem in every scan of the radar display as shown in Figure 7. This transformation was enacted using the same declarative model of the worker by simply (1) replacing the reference in declarative model to the facet for the original resource provider with a modified version that did not limit resources and (2) replacing the reference in the declarative model to the facets for the activities involving inaccuracies to slightly modified facets which did not have inaccuracies. Rerunning the model constructor on the new declarative model of the system created the computational model of the transformed worker and the system. Simulations for the same scenarios as before yielded the results shown in Figure 7. The improvement in performance (i.e., reduction in violations) was expected due to increased accuracy and improved response time of the worker. These results cannot be validated since the real air traffic system is always operated by resource constrained controllers, but this exercise does demonstrate the ease with which the impact of various human performance parameters can be examined in innovative ATM operating concepts.

Figures 6 and 8 illustrate the 'macro' or 'system-level' measures that ABMS can provide. In addition, ABMS allows measurement of the internal resources required of each air traffic controller in any particular traffic situation and using any particular procedure. This provided a raw estimate of controller workload; while such an estimate can not be reliably used to predict the exact point where a human will saturate (i.e., their performance break down due to over-work), it does allow for good insight into the relative effects of different ATM innovations on taskload and its implications relative to known human resource limitations.

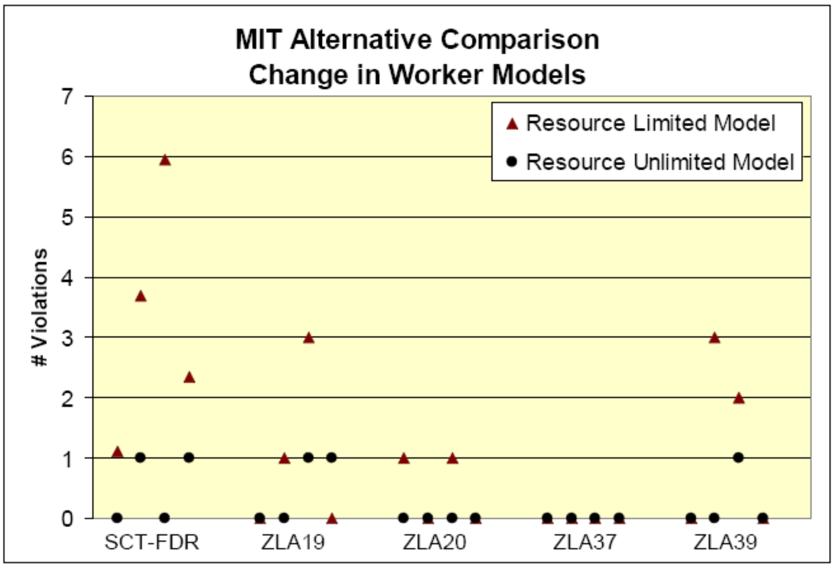

Figure 8. Comparison of Average Number of Separation Violations per Sector per Scenario for Changes in Air Traffic Controller Models

Finally, to illustrate the predictive power of these simulations, an interesting emergent behavior observed in this study was that more conflicts were found with TBM, in which aircraft are metered at a fix (CIVET in this specific study) in our simulation than in the real data. Figure 9 shows the simulated trajectory and real radar track of AC13. In our simulation, aircraft flew directly to the fix, CIVET, and then turned into the LAX. Based on the TBM procedure, arrival aircraft 13 need to be delivered to the metering fix at the STA with conflict-free scheduling. However, in our simulation we found that there are a number of conflict violations around the meter fix, contradicting this assumption within the TBM process.

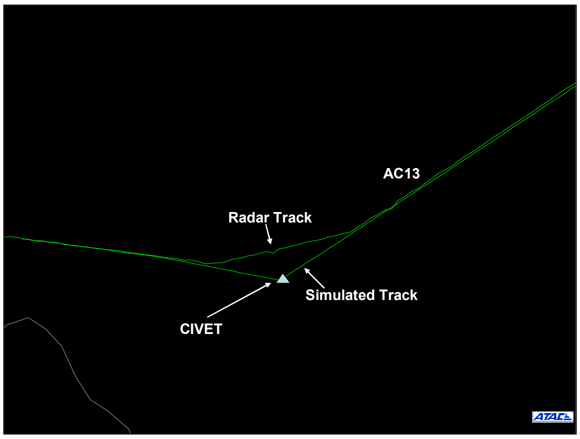

Figure 9. Observed Trajectories of AC13: Real Radar Data and Simulation with Air-MIDAS. Figure courtesy of ATAC Corp.

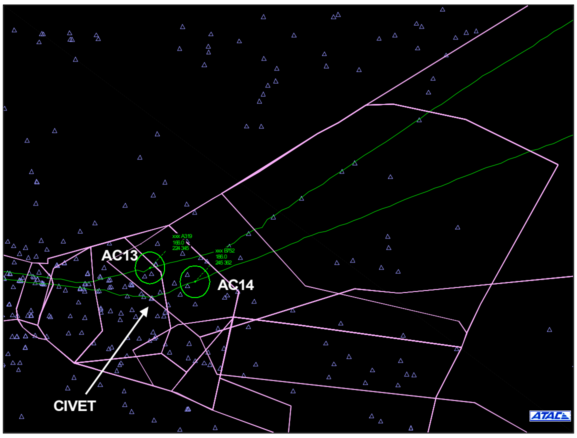

Figure 10. Observed Trajectories of AC13 and AC14 from Real Radar Data. Note lateral deviation of AC13 away from CIVET. Figure courtesy of ATAC Corp.

To validate our model, our simulation results were compared with the real radar data. The real world data revealed that the aircraft were commanded to deviate from the original flight path and bypass the meter fix to avoid the conflict. While our simulation followed the TBM procedure, the controllers in 'real-life' were still also applying the conflict avoidance procedure, often requiring lateral deviations from the arrival profile to keep a conflict-free sector while meeting the TMA required delay times. The controllers in the sector didn't know that TBM provides a conflict-free scheduling, so they issued a conflict resolution command to the AC13 when they detected a potential conflict with another aircraft that gets very close at the merge point, as shown in Figure 10. To our knowledge, the extent to which controllers are required to command lateral deviations from aircraft while conforming with TMA-required delay times was not expected during implementation of TBM procedures.

In terms of efficiency, once the basic system components were developed and verified, it took one researcher about two days to enact the comparison based on human performance inclusion, configure and run 40 simulations for each scenario on each of eight different machines, post process the data, and analyze it. It took about three days to do the same for the variants of procedures. This level of effort is sufficiently low as to motivate such analyses as a regular, integral part of assessment of innovative air traffic systems

Conclusions

This study highlighted the ability to use ABMS to model innovative air traffic management operating concepts in a structure-preserving manner, explain and predict their emergent behavior, and compare performance of different system design alternatives. These developments provide detailed representations of system behavior and human performance suitable for the impact of transformations of the air transportation system. This study employed a case study in modeling and simulating the air traffic control system at the Los Angeles International Airport (LAX). Using this conceptual framework and simulation platform it is possible to transform the system in a number of ways and to evaluate the impact of the innovations on the emergent system-wide behavior. In doing so, ABMS is also capable of providing detailed insight into the demand placed on the human controller, and to identify causes of and explore potential solutions to identified problems.

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