Simulation Modeling in Support of a European Airspace Study

JOHN MORRIS, JOHN JAMES, JAMES DeARMON,
KELLY CONNOLLY, PAULA MAHONEY
The MITRE Corporation
202 Burlington Road Rte. 62
Bedford, MA 01730-1420
USA
jemorris@mitre.org http://www.mitre.org

Abstract: To address some questions of usage of European airspace by United States Air Force aircraft, two simulation models are employed. The first model offers a wide array of functions to represent aircraft movement and management of aggregates or "flows" of aircraft. The second model uses a Petri net approach to represent the complexity of a flight planning/replanning operation, in order to estimate staffing requirements.

Key-words: Simulation model, Petri net, air traffic management, airspace congestion.

1 Introduction

A recent study by The MITRE Corporation used two corporate owned and developed simulation models, which we describe hereunder. The MITRE Corporation is a not-for-profit research and systems engineering firm, chartered to perform work only in the public interest, i.e., working for government, either domestic or foreign. Two major sponsors are the United States Air Force (USAF) and the Federal Aviation Administration (FAA), who supported the development of the simulation models.

Our team was tasked with answering questions regarding airspace usage by USAF military flights over Europe. The USAF must make investment decisions regarding avionic capabilities (i.e., electronic equipment on aircraft—radios, altimeters, navigation equipment, etc.), and our research looked into the advantages of full avionic equipage of the fleet (about a dozen types of aircraft). With full avionic equipage, civilian Air Traffic Control (ATC) provides the best, expedited service. The problem was made more complex via the requirement that differing types of aircraft, departing from different airfields, rendezvous at a given time and place.

The two simulation models to be described in this paper are the Collaborative Routing and Coordination Tools (CRCT, pronounced "circuit") and MSim. CRCT was used to model civilian air traffic and airspace, as well as USAF military flights' intersections with airspace sectors. MSim was used to model arrival times of aircraft, as well as the staffing requirements for the flight planning/replanning function.

2 Background on Airspace Study

The success of the USAF in the international arena hinges on the ability to access civilian airspace in a wide array of sovereign policies. Onboard aircraft equipage determines the level of ATC services and access to airspace—in general, the better the equipage, the better the service and access. The term *Communication Navigation Surveillance / Air Traffic Management (CNS/ATM)* is used to refer to these avionic capabilities. It is not cost effective for the USAF simply to equip every aircraft with the best-available avionics. Rather, a trade-off analysis emerges: what level of spending for upgrades coincides with a given level of performance? Lacking access to the best routes and altitudes, military aircraft are subject to increased mixing with the civil fleet, and may suffer congestion delay. We modeled this phenomenon for two future years by using two different simulation models.

Several hypothetical scenarios were considered. For each scenario, cases where military aircraft were "CNS capable" (enabled to meet CNS requirements to the extent possible) and "CNS not-capable" (lacking on one or more CNS capabilities) were examined. A hypothetical flight sortie was considered, whereby various aircraft are to rendezvous at a given time and location. Full results have been presented in other papers [1, 2], and are not repeated here. Rather, this paper discusses the underlying simulation models.

In general terms, CRCT was used to model civilian air traffic over Europe, and using some published equations for sector loading, the times and locations of congestion were computed. Next, the subject USAF military flights were likewise "flown" in the simulation model, and the times of sector-by-sector intersection were recorded. This data on congestion and military flight paths was next presented to the MSim simulation for processing. MSim modeled the dynamic interactions—military flights being delayed via reroute around congested sectors, or queuing for tankers to periodically refuel. Estimates of lateness of flights was used as input into a second MSim model, to be used to model flight planning/replanning staffing at an operations center. This second MSim model is the one described below.

3 CRCT

In the field of air traffic management, two major functions exist: ATC provides separation services between pairs of aircraft, or between an aircraft and airspace; traffic flow management (TFM), by contrast, manages system resources such as airports, routes, and airspace. It is the job of TFM to ensure that the demand for resources does not exceed the available capacity. Generally, in light of a predicted demand-over-capacity situation, aircraft can be moved in either time (via delay assignment) or space (via reroute, in the case of airspace congestion).

CRCT is a set of functions designed to assist TFM personnel in their quest to balance air traffic demand with the capacity of airspace resources to accommodate that demand. Using a graphical user interface, flow managers may visualize airspace and forecast air traffic, and assess potential airspace congestion. To ameliorate congestion, a traffic flow manager typically works with "flows" or aggregates, as opposed to individual flights. CRCT supplies a "what-if" capability, allowing a traffic flow manager to try various strategies, or variants on pre-stored initiatives, in a virtual mode. The traffic flow manager would consider not only resource capacities, but also the impact on air carrier preferences. For example, some air carriers prefer a route deviation over a ground delay. Once satisfied that a candidate initiative would likely succeed, the traffic flow manager would disseminate the solution to airspace managers and users, expecting compliance from users, such as pilots and commercial air carriers. Although CRCT was developed for real-time, real-world application, it also supports an offline mode which will support simulation studies.

Developed by the Center for Advanced Aviation System Development (CAASD) at The MITRE Corporation, CRCT currently exists on a research platform in the CAASD computer laboratories, and as a concept-evaluation platform at several federal ATC facilities. For this project, we accessed the offline and playbook features of the software system—all of the real-time, real-world traffic management functions in CRCT can be used for simulation modeling. In the parlance of simulation modeling (see [3]), we have a *dynamic, deterministic* simulation model. It is dynamic in that the situation (state of flights, sector demand, etc.) change over time. It is deterministic in that there are no random variables—a set of flight plan inputs create the same outputs each time the simulation model is run. Specifically, we used the following functions in our simulation modeling.

3.1 Traffic Flow and Demand Analysis

The CRCT adjunct supporting infrastructure performed flight plan and trajectory processing for the subject military flights. (A trajectory is the estimated future path of a flight, consisting of geographic position and altitude per time).

In addition to the subject military flight paths, multiple complete days of civilian traffic were modeled. Figure 1 gives a snapshot—a "freeze" in time—of this busy environment. In the lower right of the figure, the label "FUTURE" is displayed, indicating that the user is in forecast mode. Note the very busy nexus on the continent—these are busy civilian airports in cities such as Paris and Frankfurt. Note also the flows on the far left, headed west. This is the morning (10 a.m. local time) push of outbound flights to North America.

To assess sector congestion and the potential impact on military flights, an array of flight geometry information per sector was captured and analyzed. Per published equations and thresholds, sector loading was assessed using: traffic level, number of altitude transitions, number and type of pairwise aircraft proximity events, etc.

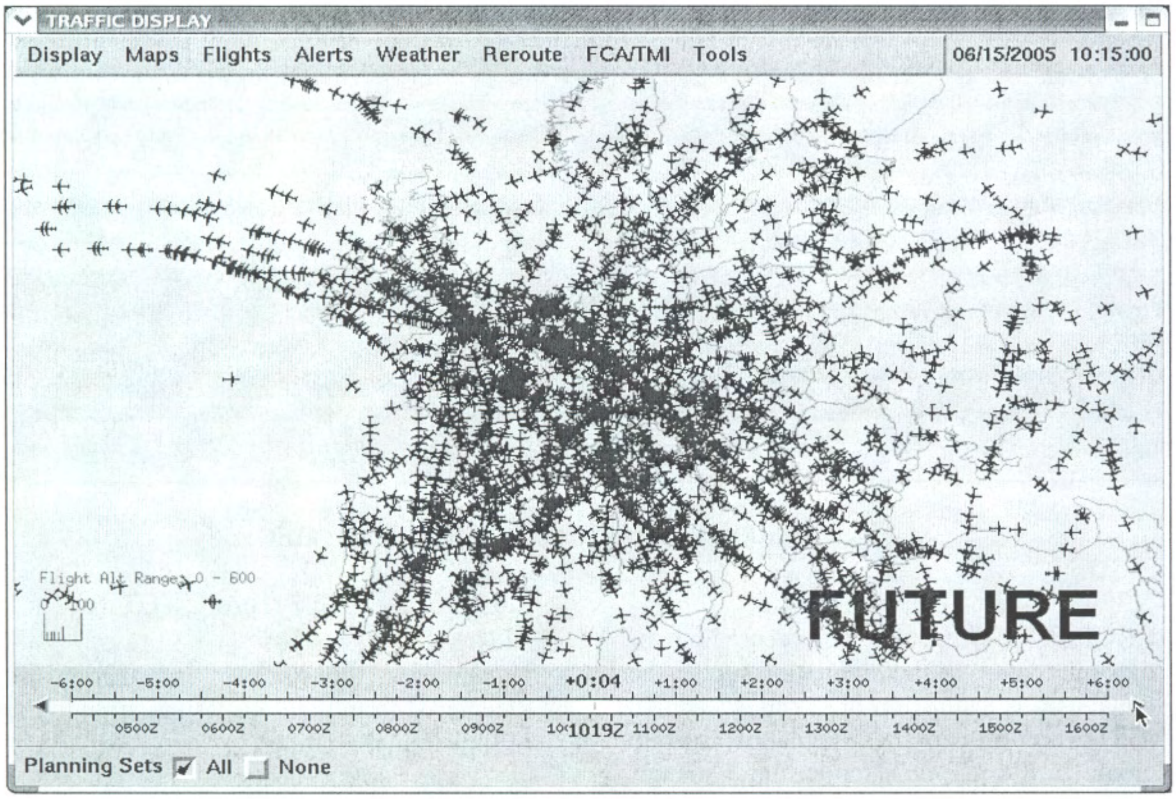

Fig. 1 CAPER Traffic Display for Europe

3.2 Aircraft Reroute Definition

It was decided, for our model representation, that military flights would avoid congested sectors by re-routing around them. It was hence necessary to determine the additional flight time for congestion-avoiding flights. The re-routes would not be represented dynamically in the CRCT modeling—rather, a probability distribution of typical re-route times was developed: several analysts played the role of traffic managers. Using the CRCT graphical user interface (GUI), the analysts selected 30 sectors at random, and worked-out re-route paths around these sectors. These 30 delay times were then fitted to a log-normal distribution, and used in MSim, as described below. Figure 2 shows military routes overlaid on civilian traffic, at a zoom-in magnification greater than that of Figure 2.

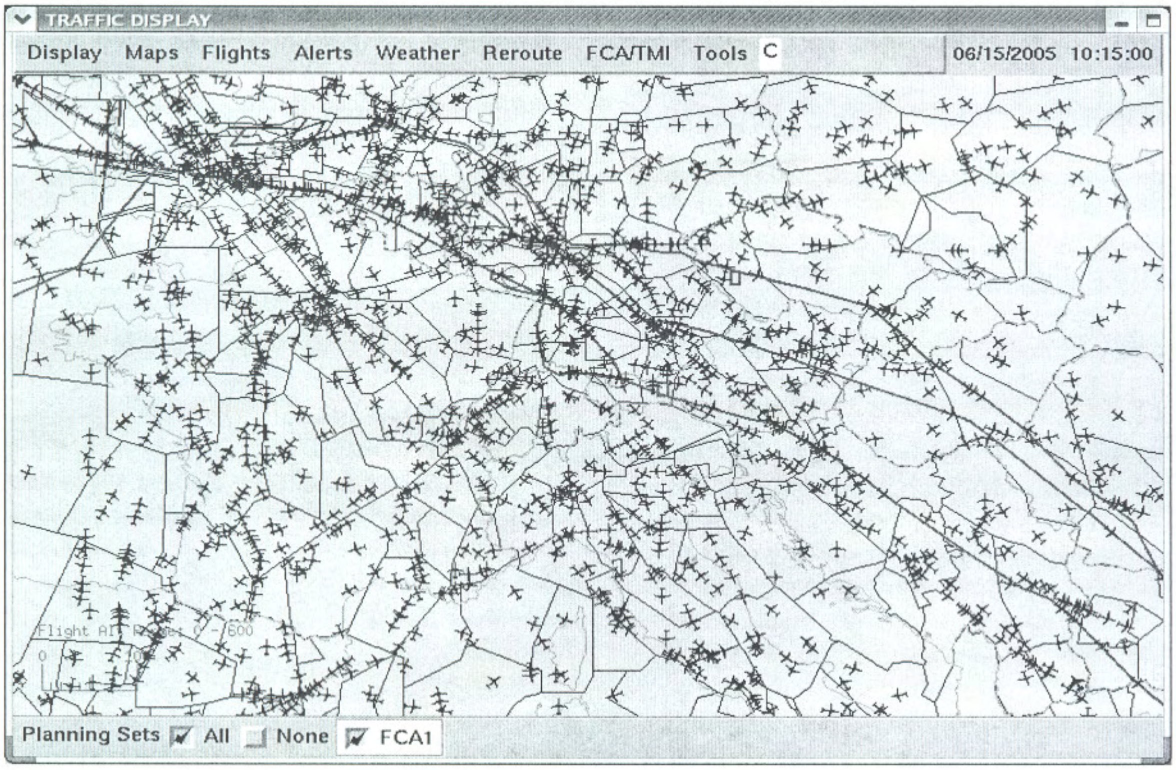

Fig. 2 Military Routes Overlaid on Civilian Traffic

3.3 Capture of Dynamic Data

CRCT allows capture and recording of dynamic data. In the simulation mode, the dynamism is a function of events scheduled and executed per the simulation system clock (In the real-time mode, the dynamics are obviously a function of real-world actions and events unfolding). Dynamic data on sector-specific flight geometries were captured and evaluated to determine times and locations of congested sectors.

3.4 Data Transfer from CRCT to MSim

In summary, three sets of information are transferred from the CRCT simulation to the MSim simulation runs:

- Times and locations of congested sectors
- Parameters for the probability distribution representing congested sector delays
- Military flight trajectories with sequences of sector entry and exit times

MSim uses these datasets, in concert with information about tanker capacities, their en route locations, to model the dynamical time ordering of events, in light of a complex network of interacting entities. The goal is to assess the probability of rendezvous of specific sets of airborne assets, i.e., the number of late arrival flights. As a second application of MSim, these lateness estimates are used to help estimate the requirements for flight planning staff, as described below.

4 MSim and the AOC Process Model

In the USAF, flight planning/replanning takes place at an Air and Space Operations Center (AOC). An elaborate sequence and synchrony of information flows and decisions must precede any execution of coordinated flight planning activities.

An AOC process model was developed using MSim, which is based on Petri net methodology. Petri nets were developed for systems in which communication, synchronization, and resource sharing play an important role. See Figure 3 for the simplest atomic example. Starting from the left, when the two input places (note Input Place 1 has two precedent activities) have a token, then the transition fires, and tokens are moved to output places. The transition can be configured to consume some amount of simulation clock time.

MSim is a prototype simulation tool that was developed at The MITRE Corporation, initially, to model the performance of distributed computer systems, but later used to analyze the performance of business processes [4]. MSim may be categorized as a *dynamic, stochastic* simulation model. It is dynamic in that the situation (rendezvous success rate, requirement for flight planning staff, etc.) changes over time. It is stochastic in that random variables, e.g., time to refuel or time to re-plan a coordinated flight package, create "chance effects" and a probabilistic outcome.

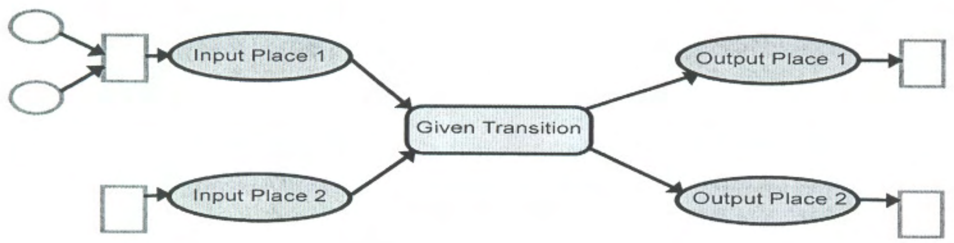

Fig. 3 A simple two-input, two output Petri Net

MSim also utilizes a high level definition of system "threads" to specify the routing of tokens in the Petri net. A thread is a path through the model of the system for a given system stimulus, (For readers familiar with the Unified Modeling Language (UML), this corresponds to the term "scenario," as used by the Object Management Group [5].) It may be open or closed and is drawn in the model diagrams by associating a thread of a specific color with a set of edges, as illustrated in Figure 4. Threads also have a name and a priority, and model diagrams can show multiple threads at the same time, which is a valuable feature, both for debugging and for appreciation of complex interrelationships.

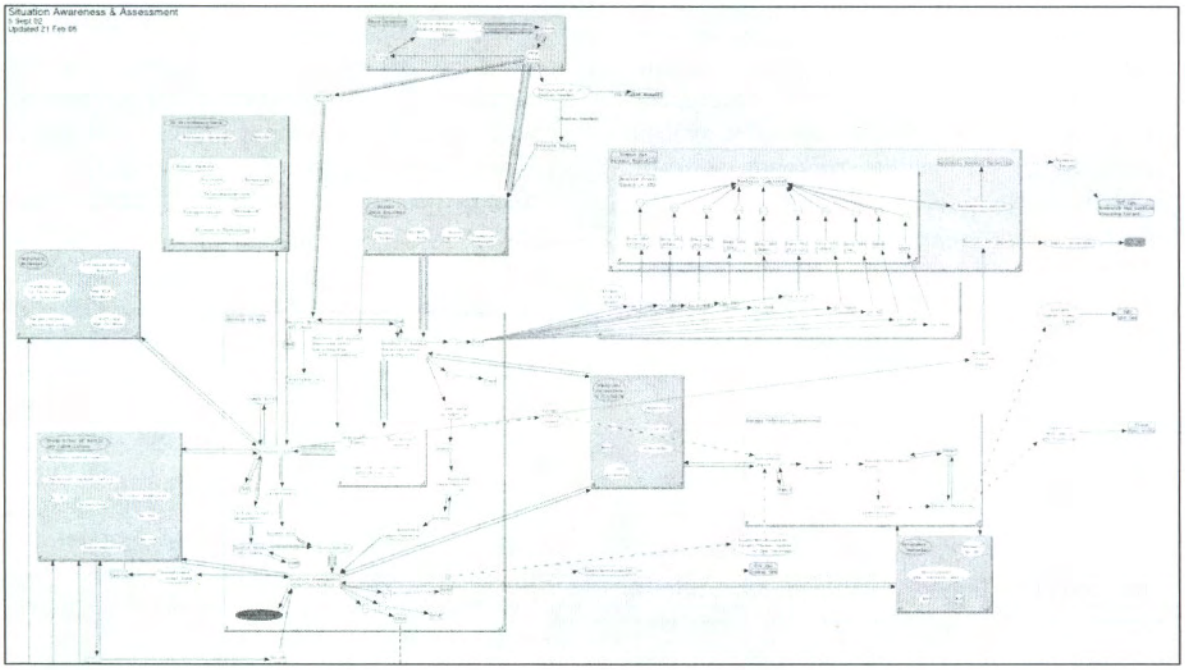

Fig. 4 Portion of AOC Petri Net Model

For a given scenario, MSim produces performance metrics such as resource utilization, component throughput, and thread response time. These metrics can be used to: (1) determine if the process modeled meets its operational performance requirements, (2) to find the performance bottlenecks, and (3) to evaluate the performance effectiveness of proposed process changes. Metrics may be exported directly to Excel for plotting and subsequent use in other automation products. MSim models can participate as a member of a simulation federation [6] through integration using High Level Architecture (HLA) such that federation time and MSim time are synchronized.

Figure 4 shows part of the AOC model that is implemented in MSim. Petri net *Transitions* (rectangular box) model the activities that do work and produce outputs. *Places* (circles or ellipses) represent the type of data that the *Transition* needs for input and the type of data that the *Transition* produces as output. Tokens represent the instances of data created and consumed by the *Transitions*. Tokens are also associated with thread types and their movement is restricted along *Arcs* that are associated with the same types.

The execution behavior of an ordinary Petri net follows two simple rules: (1) Once all the input *Places* to a given *Transition* have a token, then the *Transition* can fire (occur) and is said to be enabled, and (2) When a *Transition* fires, it takes a token from each input place and puts a token in each output *Place*. A timed Petri net allows discrete event simulation to be modeled, and in this case, *Transitions* usually have timing functions that introduce time delays in processing.

The timed Petri net methodology is useful for modeling the performance of real-time distributed systems partly because of the ability to analyze concurrency and resource contention in a manner appropriate to real-time systems. The unique contribution of MSim is that it distinguishes between data and resource tokens and provides priority preemptive scheduling on the resources within the tool. Moreover it utilizes system threads to route the tokens. This is a fundamental architectural feature that should not be hidden in low-level logic. Finally, it provides in-place hierarchy to represent model hierarchy. This makes the context easier to understand when the current focus is down several levels. The models that result from using the Petri net paradigm are similar to the physical design that they represent. This is an alternative to the models developed from the process-oriented simulation paradigm, where models tend to be an abstraction based on the execution flow, and are harder to correlate to the physical design. This closeness of the MSim model to the real design makes the model easier to verify. Table 1 identifies the MSim's Petri net features, which are more general than ordinary Petri nets.

In summary, MSim was successfully used to model military flight arrivals under conditions of a rendezvous requirement, as well as the staffing requirements for the flight planning/replanning function.

Table 1 The MSim Petri net features

Feature	Description
High level Petri net	--A *Place* is marked by a multi-set of structured tokens. The tokens have a thread type and can carry a data structure as well as a synchronization value (i.e., control fork and join operations)
Timed Petri net	--The *Transition* firing takes a user-defined amount (i.e., distribution) of time
Arcs	--Associate thread type with the *Arc* of the net and only allow movement of tokens along edges having the same type as the token
Transitions	--Every *Transition* has a code expression that can have a Boolean guard function that must evaluate to true for the *Transition* to fire. The code expression can change the tokens type and set values in the data structure within the token
Specify the Petri net	--Allows fused *Places* and *Transitions* so that a Petri net can be made up of a set of pages with common features. --Hierarchy is used as a short hand way to specify a set of *Places* connected to a given *Transition* or a *Place* connected to a set of *Transitions*. --Binding is a set of input data tokens—one from each input place. It represents the necessary data and resources required to do the work in a *Transition*. It has an inherent thread type associated with its tokens and an associated priority as defined by the thread-type. The inherent thread type of a Ready-to-Run *Transition* controls the type of resource tokens used by the firing of the *Transition*. Thus, a different resource could be used depending on the type of data flowing through the *Transition*
Resource allocation algorithm	--A built in, optional resource allocation algorithm determines the highest priority bindings that should be running with the required resources. The algorithm is a variation of a standard combinatorial problem called the Provisioning Problem [7]. Each binding corresponds to the items being provisioned and the resources are the provisions. Their cost is the binding's priority. This algorithm is run whenever there are *Transitions* that could fire to select the *Transitions* that will be running next

5 Conclusion

Simulation modeling is one of the most prominent analytical solutions available for modern, complex applications. It has been said: "When all else fails, simulate", suggesting that closed-form and other algorithmic solutions, though desirable, may be inadequate to represent the vagaries of the real world.

Two quite different simulation models have been described. CRCT was developed as a real-time tool for air traffic managers, but offers a wide array of offline facilities that can support simulation modeling.

These facilities were used for our European airspace study – civilian traffic for two future years, and associated sector congestion, and flight path trajectory of military flights pursuing a rendezvous point with minimal delay.

MSim, by contrast, was used to represent time sequencing and dynamic processes such as: queuing for refueling resources, or demand for flight planning/replanning staff. Using a Petri net technology, MSim supports classical discrete event simulation, plus allows transparency with respect to "threads" or transaction sequence paths through multiple heterogeneous processes.

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