Multi-Scale Modeling of the Air Operations Center

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Abstract

The goal of this effort is to use multi-scale modeling to understand the effect of operator-environment interaction and the global environment on Air and Space Operations Center (AOC) processes. Models were developed at 3 scales, including: 1) Operator interaction with computer interface (Agent-Based model); 2) Processing of Time Sensitive Targets (TST, Petri net model); and 3) Mission-scale objectives, strategy, and processes, including adversary response and global and US public perception (System Dynamics model). An existing Petri net model of the operational architecture of the AOC was updated for this study; all models were developed with subject matter experts.

Petri nets are well-suited for modeling systems that consist of a number of processes that communicate and need synchronization. The focus of the Petri net process model is critical event response time and manpower utilization. Information overflow indicators for operators (e.g., operator stress) and the effect of operator reduction on critical event processing both have high degrees of interdependence with the overall time critical event processing, and were found to be critical future research areas during the Joint Expeditionary Forces Experiment (JEFX) in 2006. AOC process models often focus on making operations as efficient as possible. However, without factoring in the global environment in which the AOC operates, locally optimum procedures may result in solutions that are not optimal for the global scale. Multi-scale modeling of the AOC is hypothesized to provide:

1. Insight into the impact that operator-scale constraints and environmental conditions have on processing critical events;
2. Insight into the effect that large-scale processes, such as world opinion and US political will, have on AOC operational performance; and
3. Insight into the long-term (2 month plus) dynamic behaviors evolving from the interplay between processes at these different scales.

Variables that link the AOC process model and mission-scale System Dynamics model include *average response time*, the *number of AOC operators*, the *priority of critical events*, and the *maximum personnel utilization rate*, which is used to estimate the probability of major errors in prosecution. Future work will include linking operator-environment interaction to the AOC model using the Agent-Based methodology. The currently-linked models provide insight that can be used by operators, AOC decision makers, and global stakeholders to understand what types of policies and procedures can improve operational outcomes, prior to their implementation into the AOC system (e.g.,

JEFX '08). This would provide a value-added prototype tool for determining options, as well as enabling ways to train operators, decision makers, and stakeholders. Results for the linked Petri net and System Dynamics model are presented, and technical issues are explored in linking the operator-environment model.

Background

A set of methods (or a Regimen) for Complex-System Engineering has been suggested (Kuras and White, 2005; White, 2005; Kuras and White, 2006), including: (1) Analyze and shape the environment, (2) Tailor developmental methods to specific regimes and scales, (3) Identify or define targeted outcome spaces, (4) Establish rewards (and penalties), (5) Judge actual results and allocate rewards, (6) Formulate and apply developmental stimulants, (7) Characterize continuously, and (8) Formulate and enforce fitness regulations (policing). These methods were hypothesized to focus and accelerate advantageous processes of system evolution at multiple scales. The goal of this study, was to develop a multi-scale model using real data and subject matter experts. The main research question is how to link the scales together. Once a model exists, it will be possible to apply all the methods listed above. As part of this study, analyzing and shaping the environment, tailoring development methods, judging results, characterizing continuously, and enforcing fitness regulations where all part of the modeling process. The remaining methods can be applied after successful linking and validation of the models.

For example, "fundamental concepts include the clear identification of desired outcome spaces, as opposed to outcomes (Kuras and White, 2006)." In System Dynamics modeling, a "behavior mode" describes a time-series change in behavior of a desired variable. Often this description defines an outcome space, rather than a specific outcome. As shown in Figure 1, a variable in which the behavior mode is growth over time is identified. This does not specify a particular outcome (e.g., value = 65), but instead a desired outcome space (growth in variable over time).

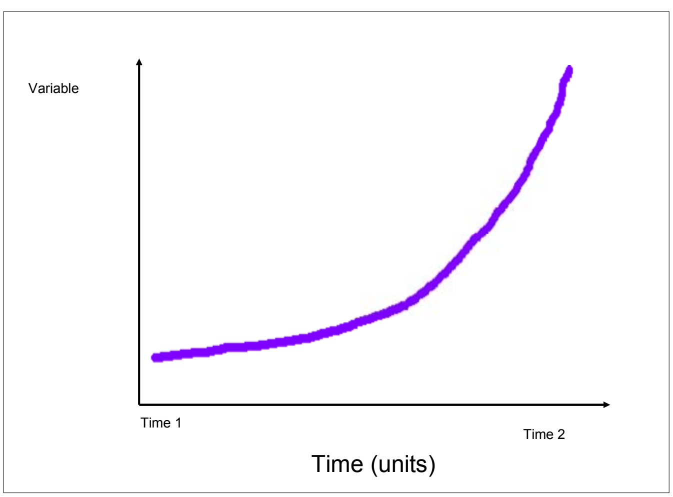

Figure 1. In System Dynamics, the "behavior mode" shows the outcome space.

The System Dynamics portion of the multi-scale model can be used to define and observe these outcome spaces. For instance, we may want the variable Theatre Ballistic Missile (TBM) launches to drop rapidly towards zero over time, realizing that a very few launches may occur into the future. A "behavior mode" of rapid reduction is expected, and then a slower reduction over time (e.g., an exponential decay), as shown in Figure 2.

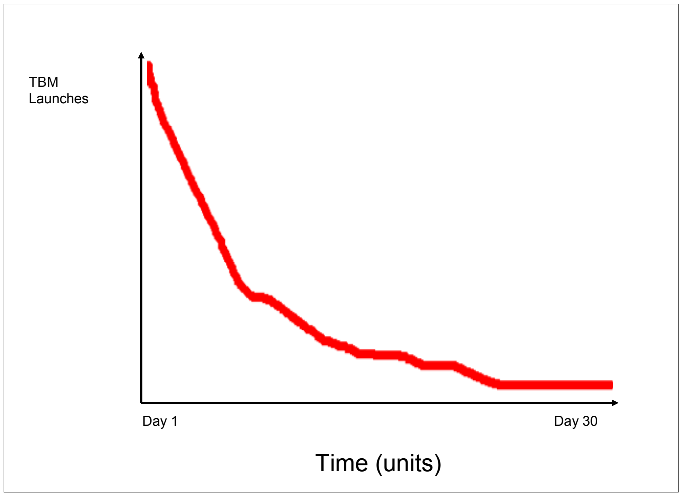

Figure 2. The desired outcome space of Theatre Ballistic Missile (TBM) launches.

The "shape" of the desired outcome space can be compared to model-simulated values. Outcome measures (e.g., Measures of Effectiveness, MOEs) can be defined rapidly in the System Dynamics portion of the model and then examined after the multi-scale simulation has proceeded. For example, the Petri net portion of the multi-scale model may have rules and rewards applied to individual decision makers, while the System Dynamics portion can contain large-scale objectives and goals of the organization.

Air Operations Center Process Model

The existing Air and Space Operation Center (AOC) process model (Figure 3), updated for this study, describes Situation Awareness and Assessment (SA&A) and Time Sensitive Targeting (TST) operations, including human resources. The models represent 2001-2003 operations (Schuh, 2003) with updates made in 2005 to allow for improved processing introduced in JEFX '04. As discussed in Wigfield et al. (2005), the model was based on staffing levels taken from an unclassified 2001 AOC Manpower Reduction Study, and represent a nominal AOC staffing level of 421 staff for two 12-hour shifts. Critical events were extracted from an unclassified scenario (first day of 1990 Gulf War) and implemented in THUNDER (2006, two-sided, theater level, conventional air and ground warfare simulation tool). The day had 446 Air Tasking Order (ATO)-planned missions.

The strike and support missions included six different types of critical events: 1) Theatre Ballistic Missile (TBM) launch; 2) TBM Detection; 3) Combat Search and Rescue (CSAR, a "pilot down" situation); 4) Surface to Air Missile (SAM) radar emissions; 5) Choke Point (enemy assets constrained by terrain); and 6) Air Tasking Order (ATO) retasking. All events were given the same priority with the exception of a CSAR event, which was given a higher priority. The effect of this was that the higher priority event preempted work on any other event type being processed in the same resource. All events trigger Time Sensitive Targeting (TST) responses by the Dynamic Targeting Cell (DTC) of the AOC in addition to their responsibilities of monitoring the progress of the Air Tasking Order (ATO).

The focus of this study is on the DTC in the AOC. The DTC operates during the execution of the campaign as targets of opportunity become available. These targets are discovered and assigned to be executed. As shown in Figure 3, the notional TST process model starts with *"Monitoring Operations,"* where AOC personnel discover critical events. The critical events are immediately sent to the DTC where emerging targets are monitored and researched.

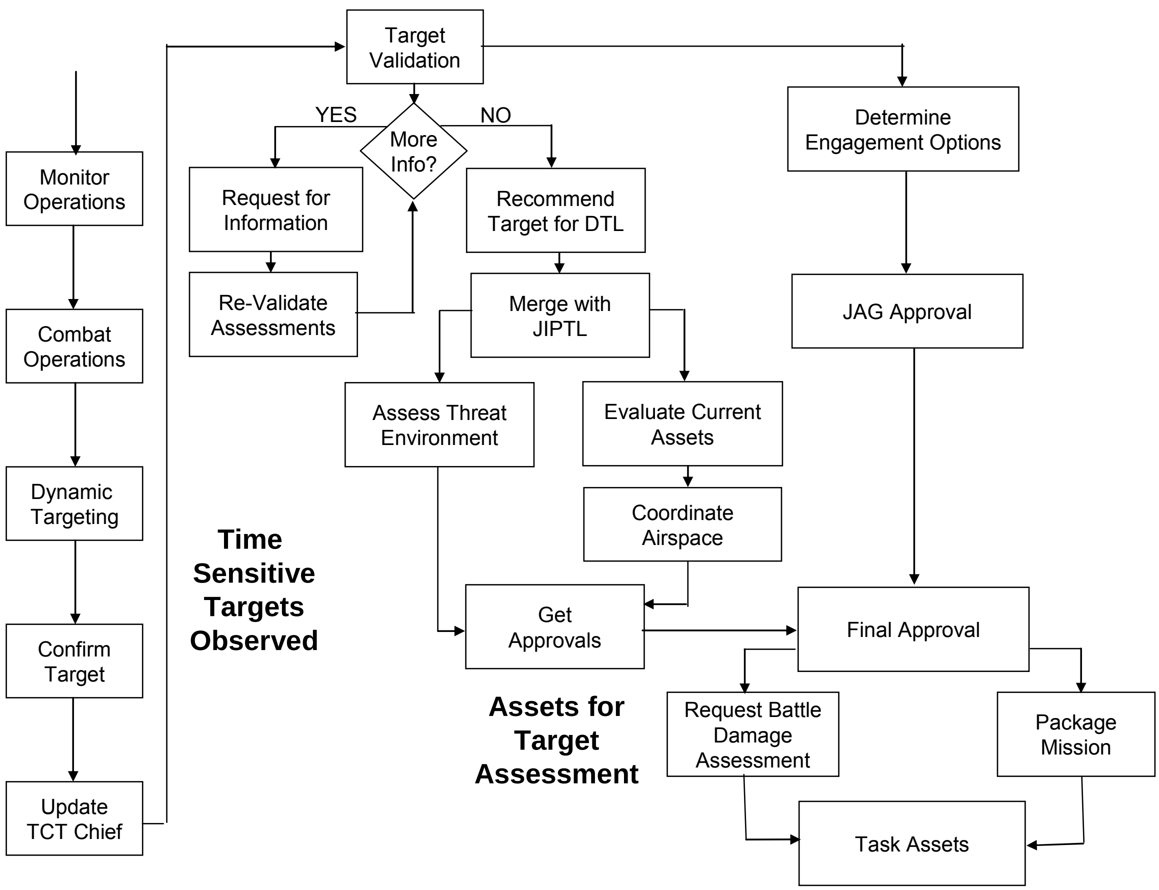

Figure 3. Air Operations Center (AOC) Petri net process model. The rectangles indicate tasks and arrows indicate the flow of critical events (DTL: Dynamic Target List; JIPTL: Joint Integrated Prioritized Target List; JAG Judge Advocate General).

Once the secret and top secret cells agree on *"Target Validation,"* a first attempt at weaponeering is done and a decision is made whether addition data is necessary. If so, a *"Request for Information"* is made to the Intelligence, Surveillance, and Reconnaissance (ISR) cell to obtain data from an available sensor. Meanwhile, an initial effort is done to *"Assess Treat Environment."* Depending on the results of the ISR information, this assessment may be re-done at a high priority level. The assessment results are given to the "*Judge Advocate Genera*l" for target approval. Finally, the results of the efforts to *"Evaluate Current Assets," "Assess Threat Environment,"* and *"Coordinate Airspace"* are brought before decision makers using a web voting mechanism that was introduced in JEFX '04 to eliminate a synchronization point. The approved target-weapon pairing is matched with appropriate assets (*"Package Mission"*) and coordinated by ISR for *"Request Battle Damage Assessment."* At this point, it is sent for execution—*"Tasked Assets."*

MSim Prototype

The AOC process model was developed using MSim, which is based on Petri net methodology. It 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 (James and Schaffner, 1994).

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 (Kuhl et al., 1999) through integration using High Level Architecture (HLA) such that federation time and MSim time are synchronized.

MSim-Supported Petri Nets for Modeling the AOC

Petri nets were developed for systems in which communication, synchronization, and resource sharing play an important role. In MSim, the user graphically specifies process behavior using a Petri net. MSim also utilizes the high level definition of system-threads to specify the routing of tokens in the Petri net. A thread corresponds to the UML "scenario;" it is a thread through the model of the system for a given system-stimulus. 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. This is different than what is possible with the UML sequence diagram—Petri nets allow the user see how all the threads interact in tasks where as UML allows only 1 thread.

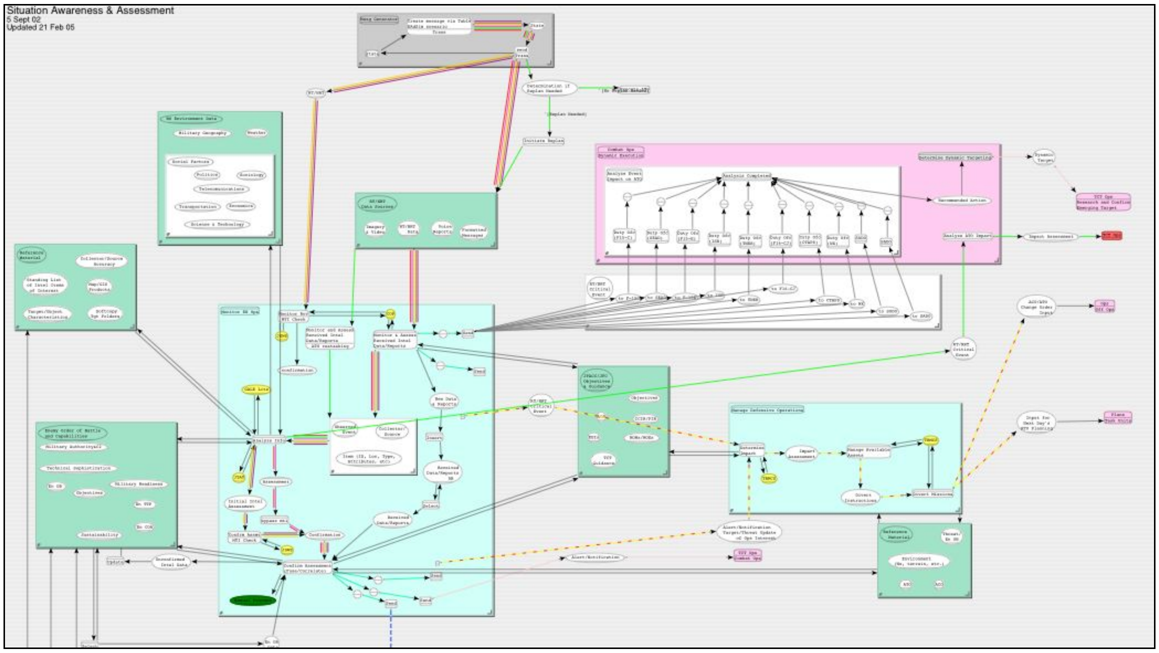

Figure 4. Portion of AOC Petri net model—Monitor Operations and Combat Operations.

Figure 4 shows part of the AOC model that corresponds to *"Monitor Operations and Combat Operations"* in Figure 3. 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 Petri net paradigm is useful for modeling the performance of real-time distributed systems for several reasons. It models the dynamic system behavior with the ability to model concurrency and resource contention 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 architecture feature and 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 more usual process-oriented simulation paradigm, where models tends 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.

The AOC process model built using MSim explores and optimizes the operational processes of the DTC. The Petri net model is used to find efficient results for various indicators of performance regarding TST performed in the DTC, including: (1) Time from target appearance to target prosecution—critical event response time, (2) Workload in DTC—resource utilization, and (3) Number of operators in DTC. However, making the DTC as efficient as possible without considering global environment factors may lead to a problem where the "local" optimum produces a result at the system scale that is below the "global" optimum.

Table 1. MSim's 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 (Lawyer, 1976). 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

System Dynamics Global & Mission Models

The System Dynamics modeling process was used in two distinct manners to support modeling of DTC operations:

1. Informing the AOC Petri net model of global-scale dynamics, and
2. Linking the Petri net and System Dynamics models to achieve strategic mission and global-scale simulation.

System Dynamics can be used to model behavior at any scale, however, its great strength is macro-scale modeling based on its continuous time focus. In comparison to other simulation methodologies, System Dynamics is well positioned to model high level interaction, such as *"US political will"*—one of two primary driving variables in this model. In System Dynamics, the stocks (accumulations or state variables) are indicated using rectangles; the flows (rates of change) are indicated using pipes with valves; and the text variables indicate different constants and auxiliary computed variables.

A basic goal-seeking loop drives the system towards a reduction in adversary state until the Joint Forces Commander's (JFC) goals are achieved (Figure 5). The adversary system produces its own responses (Figure 7) by setting up and launching TBMs. The Joint Forces goal-seeking process can be halted if something causes *"US Political Will"* to become sufficiently low (Figure 8).

Quantitative information can enter the System Dynamics model from the Petri net through two variables: (1) *average response time* (Figure 5), and (2) *maximum personnel utilization* (Figure 6), which is used to determine the probability of major errors in prosecution. Figure 9 shows the response times for each event over the course of the day. This is the output of the AOC Petri net model at the end of day 1—average daily values for each event type are used to calibrate day 1 of System Dynamics model. The output from the System Dynamics model is a set of critical events for the next day. Therefore, the two models are run in succession to simulate the effect of global dynamics on AOC operation.

Some global processes may be important in influencing mission effectiveness (completing military operations to the JFC objectives). In this case, *"World Support"* for US operations, as well as *"US Public Support,"* both impact *"US Political Will,"* which in turn can turn down the degree of military actions to zero (see Figure 8).

Linking the two models (Petri net and System Dynamics) had the following challenges: (1) the Petri net model uses discrete time and the System Dynamics model uses continuous time, (2) the Petri net model was validated using data of the course on 1 day (1990 Gulf War), and the global scale model was run over a period of 4 months, and (3) the linking of the models was done using System Dynamics software due to its ease of use enabling rapid model creation, debugging, and model iterative development. However this required us to re-create partial abstractions of the AOC model in the Vensim® software.

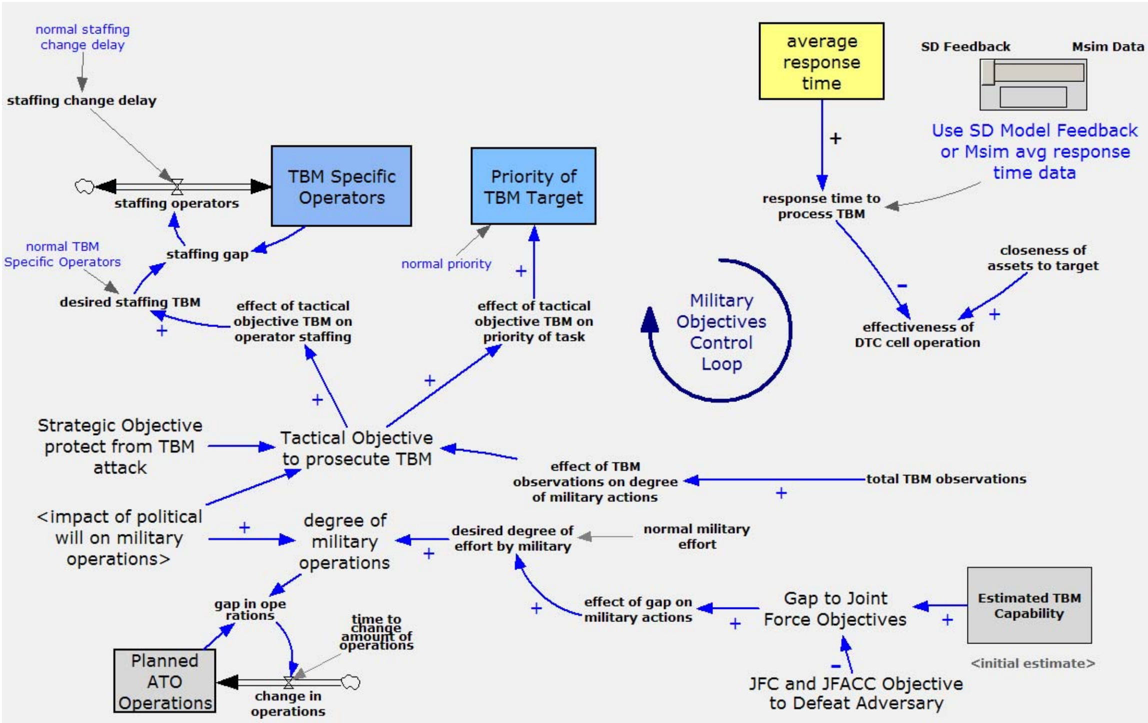

Figure 5. System Dynamics model of DTC operations for TST of adversary TBMs.

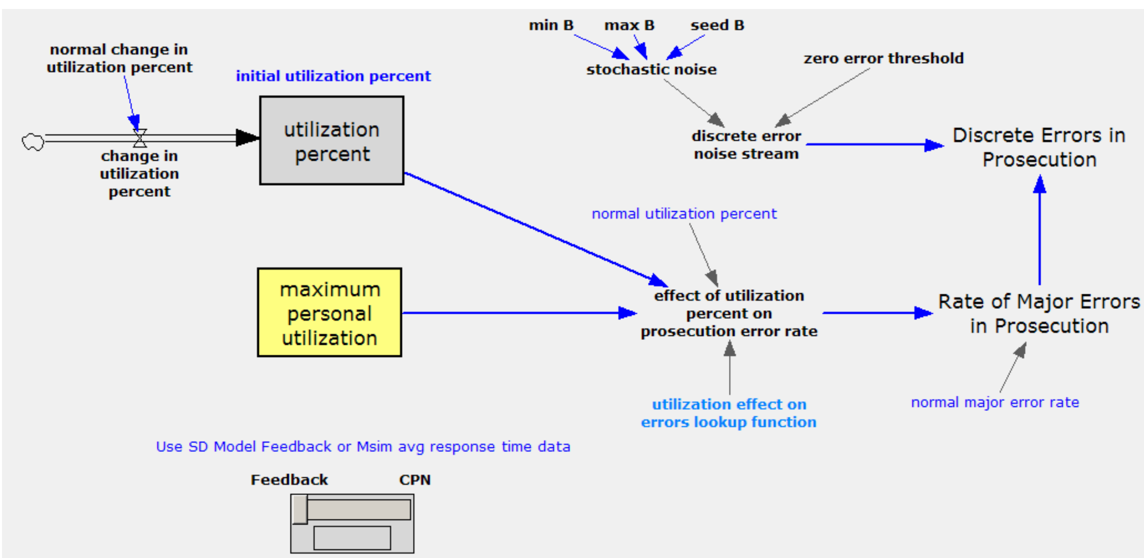

Figure 6. The maximum personnel utilization is used to estimate the rate of errors in prosecution.

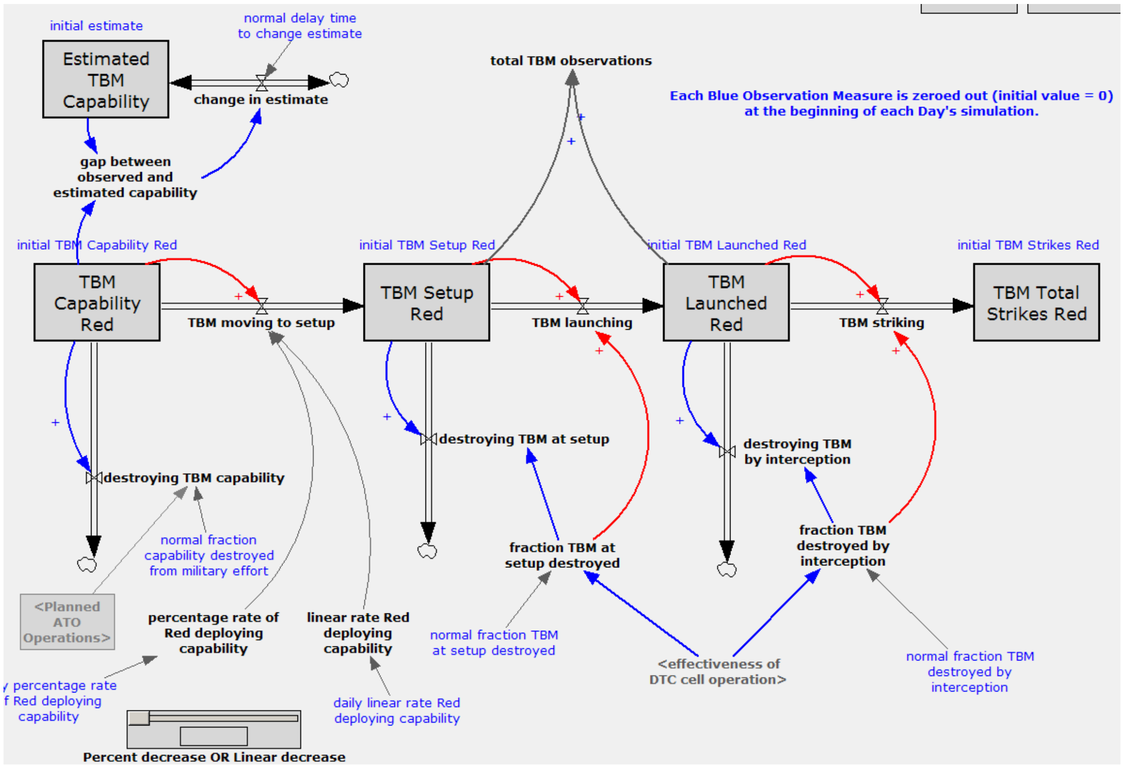

Figure 7. The adversary system deploys TBMs at varying rates during the mission.

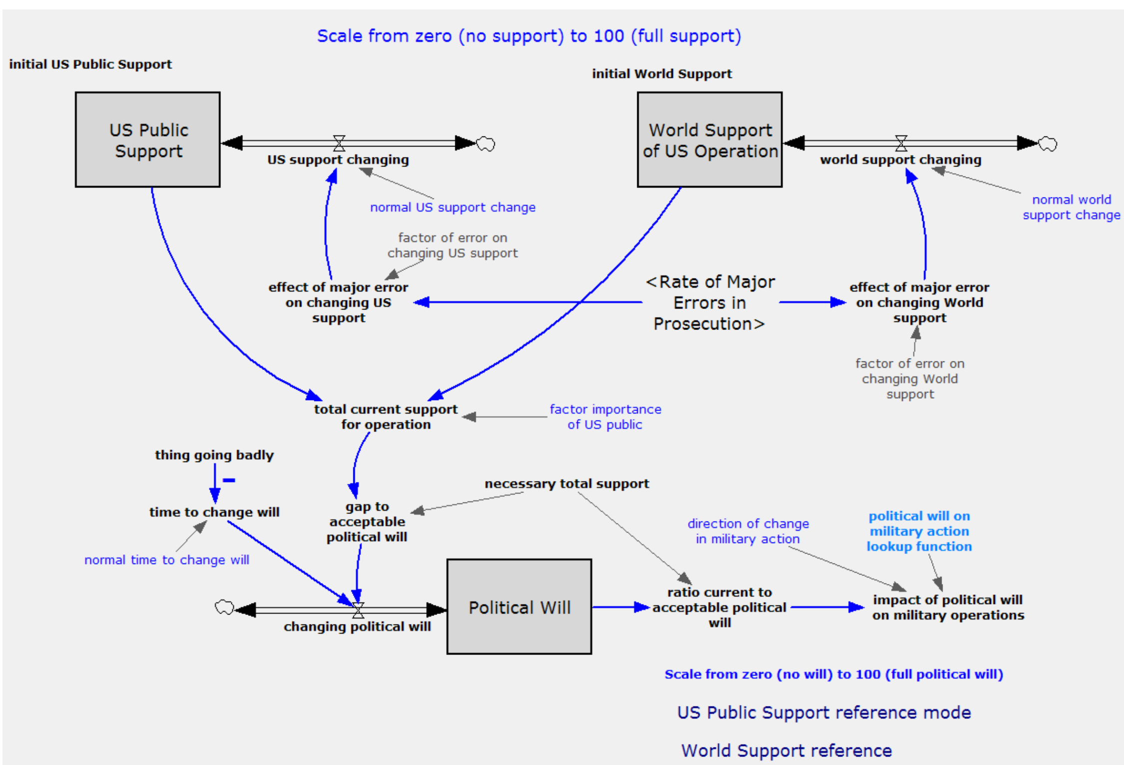

Figure 8. US and world public support and its effect on political will.

Results and Discussion

Figure 9 shows the response times from running the AOC model for the original data file of critical events—the baseline run. As more critical events occur over a given period of time, the longer the AOC response time to accomplish the tasks (e.g., see the period between 10 and 13 hours). This indicates that operators are increasingly busy and there is a queuing of tasks. As longer time between events occur over a given period of time, the queues are reduced and the response time is less (e.g., period after 13 hours). A weighted, average response time was calculated for the TBM launch and detect events. This value was used in the System Dynamics model—Figure 5 *"Average Response Time."*

The highest utilized operators in the AOC model were determined using the baseline run and are shown in Table 2. The maximum personnel utilization rate (e.g., 65%, Coordinate Airspace) was used in the System Dynamics model—Figure 6 *"Maximum Personnel Utilization."*

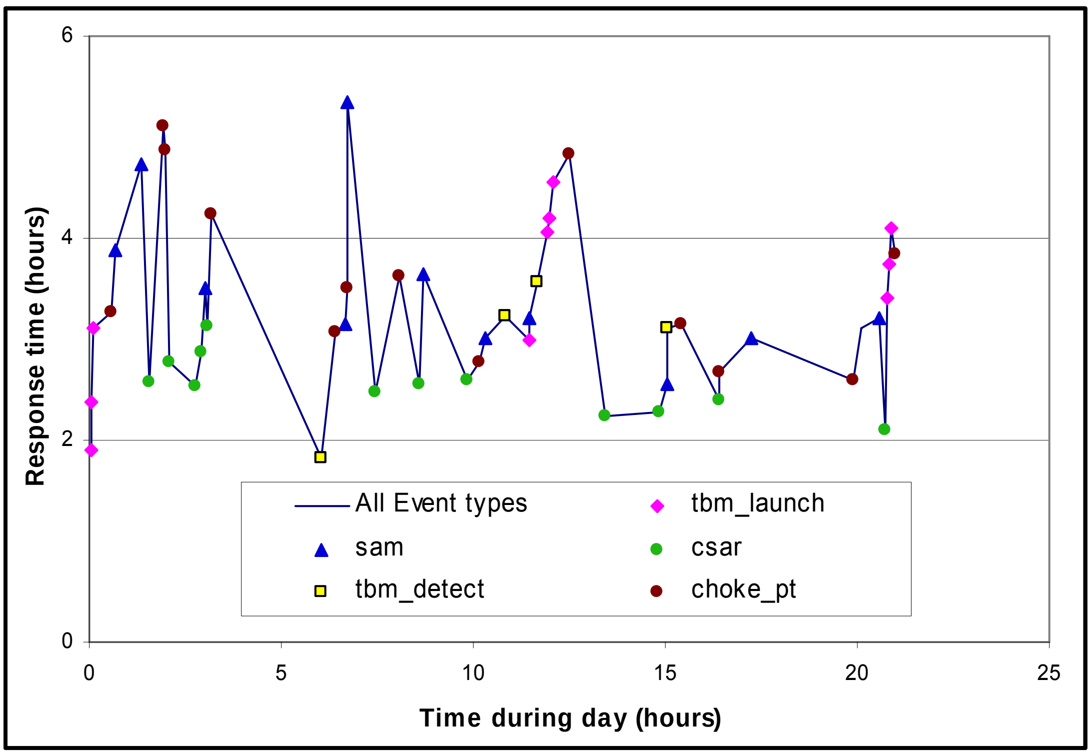

Figure 9. The response time for each type of event over the course of one day (baseline run). CSAR or pilot down has the highest priority and the remaining 4 events have the same lower priority.

Table 2. Highest utilized AOC operator from Petri net (day 1)—AOC cell correlates to Figure 3

Utilization Rate	**AOC Cell**	**Job Description**
65 %	*Coordinate Airspace*	Coordinate airspace
62 %	*Combat Operations* *Evaluate Current Assets* *Package Mission* *Get Approvals*	Analyze event impact on ATO
61 %	*Combat Operations* *Dynamic Targeting*	Determine impact; Research and monitor
60 %	*Combat Operations* *Dynamic Targeting*	Assess threat environment; Collect intelligence; Monitor emerging targets (top secret)
57 %	*Monitor Operations* *Dynamic Targeting*	Determine impact; Research and intelligence
55 %	*Combat Operations* *Evaluate Current Assets* *Package Mission* *Get Approvals*	Asset availability; Approve package for mission; Analyze event impact on ATO; Manage assets

Using the critical events in the baseline run, the AOC model was executed and data was passed to the System Dynamics model as outline above. The System Dynamics model was run for 1 day and the output of critical events was then used to run the AOC model again. This process was done 9 times and the System Dynamics results are shown in Figure 10. The *"Adversary Military Capability"* starts at 100% and is drawn down over the 9 days. The TBM setup and launches first increase and then decrease as the capability is drawn down. US and world public support both decrease and political will first increases slightly and then decreases. Figure 11 shows the critical event response time from the Petri net model for day 2 and day 9. At the beginning of the campaign, there are more critical events and the AOC model shows that there is queuing with a maximum response time of 8.5 hours. As the critical events are reduced by taking out "Adversary Military Capability," the AOC model shows that queuing is reduced and response time is consistently between 2 and 4 hours. These results show that the System Dynamics model has been calibrated to the Petri net model. This is the first step in model validation.

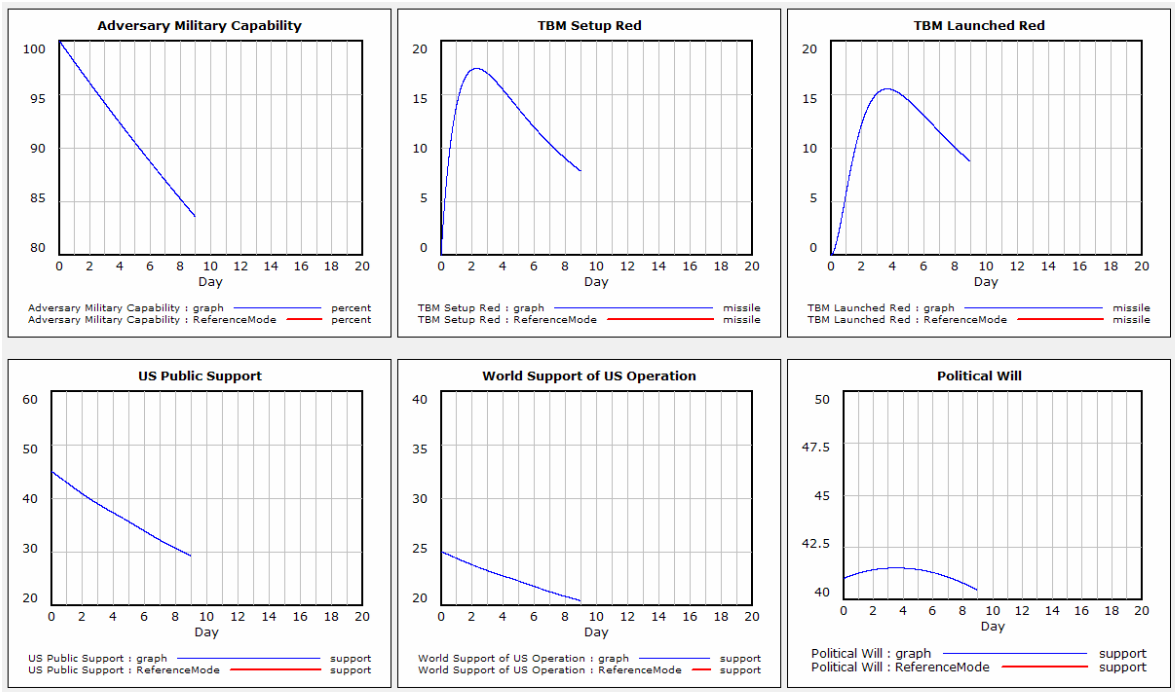

Figure 10. The response time for each type of event over the course of one day

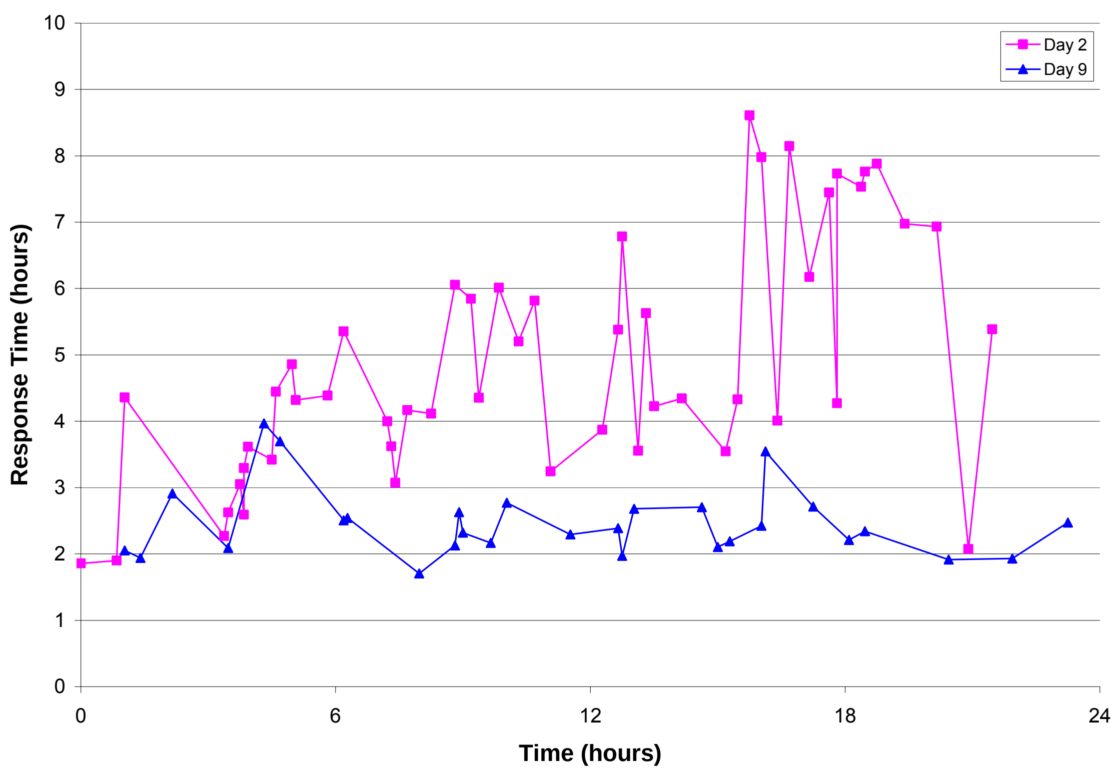

Figure 11. The response time for each type of event over the course of one day

Table 3. The average response time and maximum personnel utilization for each day with corresponding number of critical events.

Day	Response Time (hours)	Maximum Personnel Utilization (%)	Number of Critical Events
1	4.33	64.5	50
2	5.40	66.1	51
3	3.40	62.0	45
4	3.54	53.9	39
5	2.79	48.8	37
6	2.76	52.3	37
7	3.09	54.5	38
8	2.34	50.3	31
9	2.37	42.7	29

The critical events processed started at 50 on day 1 (Table 3) and were drawndown to 29 on day 9. The corresponding response time and maximum personnel utilization are also shown in Table 3, and are reduced as expected. This drawdown scenario was selected for the first step of validation. Future scenarios could include:

- Have *"Adversary Military Capability"* rise due to the purchase of weapons resulting in more critical events to handle. This would cause utilization to increase causing more errors in prosecution and possible effect on US and world opinion.
- Remove a particularly well-connected operator from the AOC resulting in more utilization and higher response times.
- Currently, the CSAR or pilot down is the highest priority event, but TBM events targeting a densely populated area could become the highest priority as dictated by the global model. This would result in faster response times for TBM, but may cause negative US opinion.

Operator-Environment Interaction Model—Future Work

The Human System Integration (HSI) effort from the Joint Expeditionary Forces Experiment (JEFX) in 2006 studied how operators rated their interaction with the AOC environment—in particular, the computer interface.

The MSim, Petri net process model of the AOC is currently being updated using this report and information from JEFX '06, in particular the job descriptions. Using this data, the Petri net model will be evaluated for use in determining information overflow indicators for operators (e.g., operator stress) and the effect of operator reduction on critical event processing. Both issues have high degrees of interdependence with the overall time critical event processing, and were found to be critical future research areas during JEFX '06.

Operator overflow and manpower reduction inherently have components that depend on individual characteristics. In order to gain insight into these issues, it is necessary to model individual scale dynamics. As stated above, removing a particularly well-connected operator from the AOC could cause disastrous effects on the overall process. Modeling the AOC at the operational process scale and operator interactions at the individual scale is hypothesized to provide insight into operator overflow and manpower reduction issues. The models and insight gained can be used by operators, decision makers, and new team members to understand the effects of polices that improve operations on the overall system. This would provide an excellent value-added tool for discussions among decisions makers and training for new team members.

The JEFX ’06 HSI data—individual and aggregate data—will be used as a case study to begin the validation of the operator-environment model. The 3 scale-model being developed here could be used in JEFX ’08 in real-time. Operators could provide daily feedback through surveys, which could be inputs to the multi-scale simulation model. The effect of the operators self-assessment in processing time critical events could be compared to the actual process time to determine operator stress indicators.

Conclusions

Work is on-going to achieve a multi-scale model that allows operator-environment interaction to be linked to an AOC process model for handling critical events. Furthermore, the AOC process model is linked (e.g., critical event process time and probability of errors) to a global-environment model that is driven by the political landscape in which the AOC operates. Feedback from the global model includes priority of targets and human resources available to the AOC. Each of the three scales has a focus on the operators.

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