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THESIS

MODELING RECONNAISSANCE SQUADRON WORKFLOW USING DISCRETE EVENT SIMULATION (DES) AND ANALYZING SEVERAL MEASURES OF EFFECTIVENESS

by

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Reconnaissance missions are not only one of the vital modes of intelligence-gathering methods, they are one of the most important contributors of military intelligence as well. They show the battlefield as it is to the commander.

A simplified reconnaissance cycle includes the arrival of reconnaissance requests, planning of reconnaissance flights, flying the mission and exploitation of the films or images, and then dissemination of the intelligence reports. The reconnaissance cycle is modeled for four different scenarios (peace and war as situations, RF-4 and F-16 as configurations). There are two points of view regarding this cycle. The first is the reconnaissance requesters' view: they want to know the estimated time it would take for a request to be answered, based on the resources and other factors, before an actual request was made. The second is the reconnaissance squadron commanders' perspective: they want to respond to as many reconnaissance requests as possible. For that reason, they want to know and revise the ideal numbers of personnel and equipment. Analysis includes regression models and partition trees. When results are considered, we see that there is no common rule to determine which factors (either decision or noise) are the key determinants for each scenario. But we noticed that noise factors have much more impact on several measures of effectiveness than decision factors in each model.

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MODELING RECONNAISSANCE SQUADRON WORKFLOW USING DISCRETE EVENT SIMULATION (DES) AND ANALYZING SEVERAL MEASURES OF EFFECTIVENESS

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ABSTRACT

Reconnaissance missions are not only one of the vital modes of intelligence-gathering methods; they are one of the most important contributors of military intelligence as well. They show the battlefield as it is to the commander.

A simplified reconnaissance cycle includes the arrival of reconnaissance requests, planning of reconnaissance flights, flying the mission and exploitation of the films or images, and then dissemination of the intelligence reports. The reconnaissance cycle is modeled for four different scenarios (peace and war as situations, RF-4 and F-16 as configurations). There are two points of view regarding this cycle. The first is the reconnaissance requesters' view: they want to know the estimated time it would take for a request to be answered, based on the resources and other factors, before an actual request was made. The second is the reconnaissance squadron commanders' perspective: they want to respond to as many reconnaissance requests as possible. For that reason, they want to know and revise the ideal numbers of personnel and equipment. For the purpose of answering these questions, satisfying these requests, and having a better understanding about the reconnaissance cycle, Reconnaissance Squadron Workflow is modeled, experimented and analyzed in this thesis.

Analysis includes regression models and partition trees. When results are considered, we see that there is no common rule to determine which factors (either decision or noise) are the key determinants for each scenario. But we noticed that noise factors have much more impact on several measures of effectiveness than decision factors in each model. Some of these noise factors could be controllable, including aircraft, camera and pod defect probabilities and their repair times. Therefore, some precautionary measures should be taken to reduce these defect probabilities and repair times.

Specifically, in the RF-4 configuration models, pilot filming error is a significant factor, which shows that training of the pilots cannot be ignored. When the F-16 models are considered, we see that data link defect probability is a significant factor too. This suggests that special precautions should be taken to keep this capability working.

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DISCLAIMER

The reader is cautioned that the computer program developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the planner.

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LIST OF ACRONYMS AND ABBREVIATIONS

DES	Discrete Event Simulation
DOE	Design of Experiments
E/O	Electro-Optic
FEL	Future Event List
GUI	Graphical User Interface
IMINT	Imagery Intelligence
IR	Infrared
MoE	Measure of Effectiveness
MOVES	Modeling, Virtual Environments, and Simulation
NOLH	Nearly Orthogonal Latin Hypercube
NPS	Naval Postgraduate School
RAM	Random Access Memory
SD	Standard Deviation
UAV	Unmanned Air Vehicle

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I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

Using intelligence gathering capabilities, military intelligence collects information about hostile, friendly and neutral forces. Intelligence activities are continuously processed at all levels, from tactical to strategic, in peacetime, the period of transition to war, and during a war itself.

Some of the military intelligence gathering capabilities include Human Intelligence (HUMINT), Signal Intelligence (SIGINT), Open Source Intelligence (OSINT), and Imagery Intelligence (IMINT).

The IMINT is conducted by unmanned or manned aerial vehicles. Those vehicles' missions also include reconnaissance, which is performed over specific targets at specific times. Reconnaissance missions are not just one of the intelligence gethering methods, but one of the most important contributors to military intelligence. Reconnaissance missions are highly important to military operations, since they are the only resources which show the commander the battlefield as it is. Reconnaissance missions provide insight for decison-makers and they are the key for victory.

To provide IMINT, a wide variety of sensors and platforms are in operational use in the theather. Platforms and sensors have evolved with the advent of aviation and photography, respectively. In the past, balloons, rockets, and kites were used as platforms. Previously, observers in the balloons, sketchers in the back of the planes, and optical devices that were taken into the air and handheld were early sensors used for reconnaissance. Now, sensors are mounted and used on platforms such as satellites, aircrafts, and unmanned air vehicles.

Aircraft have an advantage over other platforms since they can be deployed quicker and thus gather information about the area of interest much faster (Gething, Hewish, & Lok, 2003). The RF-4 and F-16, which are modeled in the thesis, are two aircraft that are used for the purpose of reconnaissance missions. The RF-4 has a specially designed nose in which optical sensors can be mounted, and can also carry recconnaissance pods, while the F-16 can do reconnaissance missions with reconnaissance pods only.

Sensors used in a reconnaissance mission can be film-based or Electro-Optic (E/O). The difference between a wet-film-based sensor and an E/O sensor is that the wet-based sensors need to be processed before the films are interpreted, thus requiring extra time. For the E/O sensor, target images can be downloaded to exploitation workstations via data link while the aircraft is still in the air, or downloaded directly to exploitation workstations after the aircraft lands. As Gething (2008) mentions, this reduces the 'sensor-to-shooter time.' That is, reconnaissance reports are provided faster with a net-based dissemination possibility of digital images, which is a great advantage to the decision makers (Gething, Hewish, & Lok, 2003). In this thesis, the RF-4 is modeled as a film-based reconnaissance aircraft, and the F-16 as an E/O pod-based aircraft.

Oxlee (1997) categorizes reconnaissance requirements as either strategic or tactical. Strategic reconnaissance is conducted in peacetime, times of conflict, or during war. Tactical reconnaissance is conducted during times of conflict and in war. One aspect of tactical reconnaissance is the importance of training during peacetime. Based on the "Train like you fight" principle, reconnaissance missions are simulated inside the borders of the country where both territory and targets are similar to the real targets. The aforementioned aircraft types can carry out both strategic and tactical reconnaissance missions with the appropriate types of sensors mounted.

A simplified recconnaissance cycle includes the arrival of reconnaissance requests, planning of reconnaissance flights, execution of the mission flights and exploitation of the films, and then the dissemination of the intelligence reports. Although there are commonalities, the reconnaissance cycle is different in peace and war situations. Therefore, strategic and tactical reconnaissance requirements are evaluated using different models for each situation. Any delay in the loop of providing reconnaissance reports due to the shortage of aircrafts, cameras, pilots or image analysts can cause severe problems.

To have a better understanding about the reconnaissance system the Reconnaissance Squadron Workflow is modeled. Two situations are modeled: peace and war; and for each situation there are two configurations, namely the RF-4 and the F-16.

B. RELATED RESEARCH

One of the related thesis research studies (computer specialist shortage problem) was conducted by another Turkish Air Force officer, Serhat Camur (2009). Camur modeled computer system specialist non-commisioned officers' jobs on a Turkish Air Force Base by using event graph and discrete event simulation techniques to determine the average time for repairing an entity (mean delay time in system) and average number of entity failures (mean number in the queue) waiting for repair. Camur identified the factors that have the most significant effects on these two performance measures by making a nearly orthogonal Latin hypercube (NOLH) experimental design, running simulation for this design with 100 replications, and conducting statistical analysis on simulation output data. Camur concluded that "the results do show that increasing the staff is not the only solution for his particular research. There are some other factors that can be played with to decrease the time in the system and mean number in queue."

After comparing Camur's results to our thesis research, we see that we have a similar performance measure (mean delay time in system vs. average time elapsed between getting reconnaissance requests and providing reconnaissance reports), and nearly the same methodology. Camur's model is based on actual data and operations, though our model is based on notional data and realistic operations.

C. RESEARCH QUESTIONS

This thesis will attempt to answer the following research questions:

i. Given an operation scenario:

    i. What is the average time elapsed between getting reconnaissance requests and providing reconnaissance reports?

ii. What is the ratio of not responded reconnaissance requests over total arrived reconnaissance requests?

ii. What is the ideal number of aircrafts, cameras, pilots, and image analysts (between realistic minimum and maximum values) to support a given operation scenario?

D. THE SCOPE OF THE THESIS

The primary goal of this thesis is to develop a simulation tool that will enable planners at headquarters to estimate the measures listed below:

1. Average time to provide a reconnaissance report.
2. Parameters that affect the elapsed time between getting reconnaissance requests and providing reconnaissance reports.
3. Usage of the resources such as aircrafts, cameras, pilots and image analysts.
4. Bottleneck areas of the Reconnaissance Squadron Workflow.

A secondary goal of this thesis is to find the best configuration (i.e., the ideal number of aircraft, cameras, pilots, and image analysts) to support a given operation scenario.

Both a thirty-day war scenario and a peace scenario with two different kinds of structures (organizational or configurational) are investigated.

E. METHODOLOGY

The methodology used in this thesis is as follows:

1. Conduct research on current and past similar Decision Support Systems and tools. This will set a general guideline for the thesis and give further ideas.
2. Conduct research on current Reconnaissance Squadron Workflow to create a realistic model.

3. Develop and draw detailed event graph components for the discrete event simulation. These will set the basis for the Simkit implementation of the model.

4. Develop a simulation tool using Java programming language. That tool will be a DES implementation using the event graph components obtained in the previous step.

5. Verify (test and debug) and validate (adequately capturing the essence of the problem) the simulation with the help of feedback, ideas and recommendations coming from pilots, planners and image analysts working in the Turkish Air Force.

6. Analyze results. Develop a methodology on how to obtain and analyze the data produced by the tool. The purpose is to give a general guideline on how to extract the needed data and how to run the proper analysis methods.

F. BENEFITS OF THIS STUDY

A technological approach is used to assess the need for personnel for a specific branch (image analysts); this may be enlarged later to the other branches in the other facilities of the Turkish Air Force. An improved assignment can be achieved by using the DES technique.

Insight can be obtained from the effects of camera/aircraft failures, aircraft, pilot or image analyst shortages, etc., when it comes to providing a reconnaissance report. After making a trade-off study, alterations can be made in those areas to optimize the Reconnaissance Squadron Workflow.

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II. MODELING AND SIMULATION

"Modeling and Simulation is a discipline for developing a level of understanding of the interaction of the parts of a system, and of the system as a whole" (Bellinger, 2004). This chapter describes some of the major terms about modeling and simulation such as system, model, and simulation. It explains the modeling process in detail. Then it describes the Discrete Event Simulation (DES) and event graph methodology. Finally, it describes the Simkit package that was used to create the Reconnaissance Squadron Workflow model.

A. SYSTEM, MODEL AND SIMULATION

"A system is defined to be a collection of entities, e.g., people or machines, which act and interact together toward the accomplishment of some logical end" (Law, 2007). An example for a system is the queuing system, which is made up of customers, a queue, and a server. Physical entities of the system are the customers and server; on the other hand, the queue itself is a concept. All of the system entities and their attributes constitute the state of the system (Sanchez, 2007).

A model can be defined as the representation of a system used to study it (Law, 2007). There are many reasons for using a model of a system instead of using a system itself. For example, models can enable us to study how a prospective system will work before the real system has even been built. Building and studying a model is only a small portion of the cost of experimenting with the real system in many cases. A model has the ability to scale time or space in a favorable manner—for example, with a flight simulator, wind sheer conditions can be created on demand (Sanchez, 2007). In addition to all of these reasons, in some cases a model becomes a necessity because it is very dangerous and often impossible to conduct experiments using real systems.

> Since all models are simplifications of reality there is always a trade-off as to what level of detail is included in the model. If too little detail is included in the model one runs the risk of missing relevant interactions and the resultant model does not promote understanding. If too much

> detail is included in the model the model may become overly complicated and actually preclude the development of understanding. (Bellinger, 2004)

There are many variations of models. One type is physical representations (with or without scaling) such as wind tunnel mockups. Another variation consists of mathematical equations such as the equations of motion found in a typical physics book. Computer simulations (programs), such as the ones used in modern flight simulators, are also a variation of models (Sanchez, 2007).

Simulation can be defined as:

> a computerized version of the model which is run over time to study the implications of the defined interactions…Simulations are generally iterative in their development. One develops a model, simulates it, learns from the simulation, revises the model, and continues the iterations until an adequate level of understanding is developed. (Bellinger, 2004)

B. MODELING PROCESS

Modeling is an iterative process with feedback. It can be divided into several basic stages. In stage 1, the scope of the model is decided to identify what is meant by the system of interest. A descriptive model is built at the end of stage 1. In stage 2, the behaviors and interactions of all of the entities that comprise the system are described. A formal model is built at the end of stage 2. “If the formal model has a high degree of conformance with the real world system being modeled, analytic models and their solutions allow us to obtain insights and draw inferences about the real system as seen from Figure 1. ” (Sanchez, 2007).

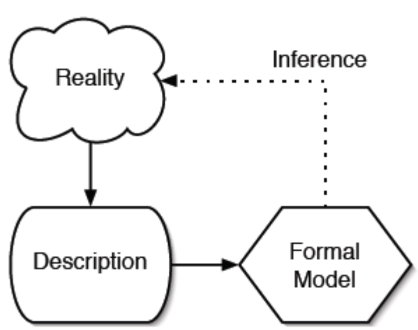


Figure 1. A Model Yields Insights and Inferences [From (Sanchez, 2007)]

Adding more realistic features such as non-homogeneous arrival and service rates, machinery breaking down, etc., leads to models that cannot be solved analytically. In many cases computer simulation can be created that describes these features algorithmically. The model described in Chapter III is an example of such a simulation model. The resultant simulation model often uses randomness as part of the modeling process so its output becomes a random variable. For this reason, statistics enters into the process and a statistical model of the computer model (built from the formal model) is built. The whole process is illustrated in Figure 2. (Sanchez, 2007).

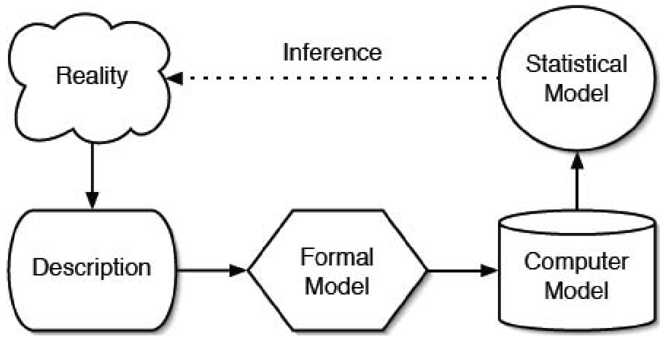


Figure 2. Simulation has a Longer Chain of Inference [From (Sanchez, 2007)]

Feedback enters the modeling process in the form of verification and validation (Sargent, 2003). Verification is a feedback loop between the computer model and the formal model that addresses the question "does my computer program do what I meant it to do?" and corresponds to the debugging of computer model. Validation is a feedback loop between the computer model and reality that addresses the question "does my computer program mimic reality adequately?" (Sanchez, 2007)

Sanchez (2007) gives some recommendations to model developers: start small, improve incrementally, test frequently and backtrack/simplify.

C. DISCRETE EVENT SIMULATION AND EVENT GRAPHS

Discrete Event Simulation (DES) is a methodology which models a system as the state change occurs at a discrete set of points along the time axis, rather than continuously (Sanchez, 2007). There are four basic elements of a DES model: states, events, scheduling relationships between events, and the parameters (Buss, 2010).

A state variable in a DES model is one that has the possibility of changing value at least once during any given simulation run. The number of customers in the queue for a queuing system is an example of a state variable. The collection of all state variables is called the state space, which gives a complete description of the simulation model at any point in time (Buss, 2010).

Law (2007) defines the event as “instantaneous occurrence that may change the state of the system.” The arrival of a customer for a queuing system is an example of an event. Each event is completely defined by specifying its state transition function and has an associated event time (Buss, 2010).

Scheduling relationships between events are the rules that determine what the next event will be. These relationships can be expressed as a graph (Buss, 2010).

The method of time advance in DES models is termed Next Event, which means simulation time moves in typically unequal increments, jumping from the scheduled time of one event to another. The Next Event algorithm is shown in Figure 3. (Buss, 2010).

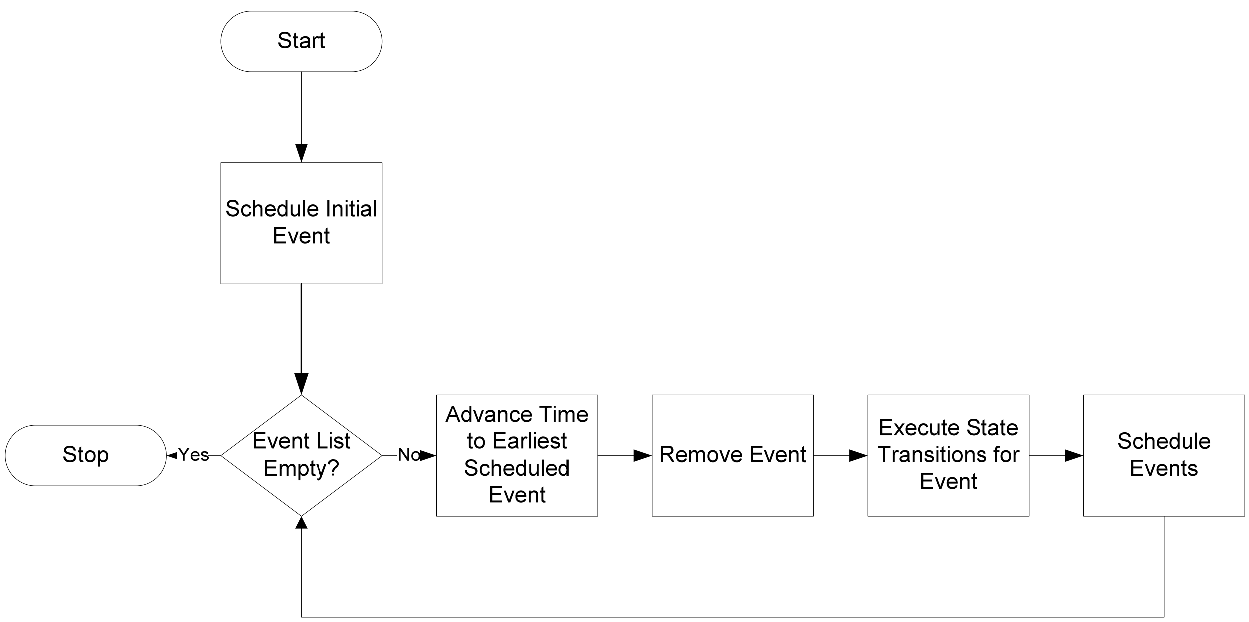


Figure 3. Next Event Algorithm [From (Buss, 2010)]

Minimum requirements for the Future Event List (FEL) in DES are: holding pending events, keeping them in order, adding new scheduled events, and removing the next scheduled pending event. If canceling of events is supported, it also needs to be able to find and remove the cancelled event (Buss, 2010). When DES terminates, the FEL gets emptied.

Parameters are the variables that do not change during a simulation run. The maximum number of servers in a queuing system is an example of a parameter (Buss, 2010).

There are several ways (terminating conditions) in which a DES run can be terminated. The simplest terminating condition is ending the simulation after a certain amount of simulation time has passed. Another terminating condition is ending the simulation after a particular event has been executed a preset number of times (Buss, 2010).

Event graphs are an intuitive and powerful way to conceptualize DES models as well as a methodology for creating them. They consist of nodes and directed edges. Each node corresponds to an event, or state transition, and each edge corresponds to the scheduling of other events. Each edge can optionally have an associated Boolean condition and/or a time delay. The fundamental construct for event graphs is illustrated in Figure 4. It is interpreted as follows: the occurrence of Event A causes Event B to be scheduled after a *t* unit time delay, provided that condition (i) is true (Schruben, 1983).

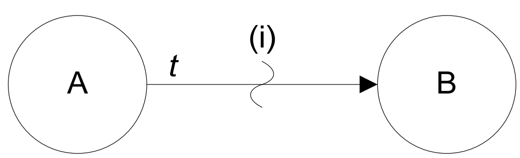


Figure 4. Fundamental Event Graph Construct [From (Schruben, 1983)]

There are two more useful concepts in event graph modeling to create simple and flexible models: the ability to cancel scheduled events, and the ability to pass arguments on scheduling edges and have these values received by the scheduled event as parameters (Buss, 2010).

A cancelling edge is illustrated in Figure 5. It is interpreted as follows:

Whenever Event A occurs, then (following its state transition), if condition (i) is true, then only the earliest scheduled occurrence of Event B is removed from the Event List. If no such Event had been previously scheduled, then nothing happens. (Schruben, 1983)

There is no time delay associated with a cancelling edge.

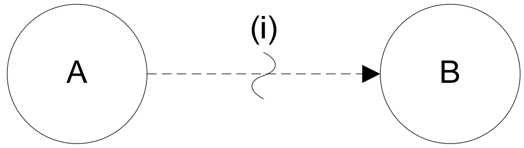


Figure 5. Prototypical Cancelling Edge [From (Schruben, 1983)]

The prototypes for a scheduling edge with arguments and an Event with parameters is illustrated in Figure 6. It is interpreted as follows:

When Event A occurs, then if condition (i) is true, Event B is scheduled to occur (placed on the Event List) after a delay of *t*, and when it occurs its parameter k will be set to the value of the expression j at the time it had been scheduled. (Buss, 2010)

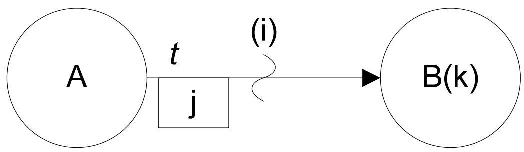


Figure 6. Scheduling Edge with Arguments and Events with Parameters [From (Schruben, 1983)]

Finally, there is one more useful concept in event graph modeling to create accurate models by breaking ties for events scheduled at exactly the same time: priorities on scheduling edges. This is done by setting a priority on the scheduling edge. By convention, higher numerical values represent higher priorities. A scheduling edge with priority p is illustrated in Figure 7. (Buss, 2010).

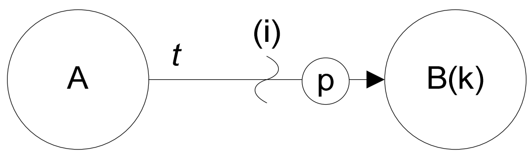


Figure 7. Scheduling Edge with Priority [From (Schruben, 1983)]

It is possible to build large models using only the basic event graph concepts presented so far. But modular simulation components are preferred for flexibility, extensibility and scalability reasons. We can build large-scale, complex models effectively by creating small and manageable components and connecting them. “An Event Graph component is simply an Event Graph “in miniature” — that is, an object that has its own parameters, state variables, and events.” All components share a common Event List that can keep track of which event was scheduled by which component. To make a DES model useful and interesting, the components do need to have some kind of interaction. That interaction is provided by the SimEventListener and Adapter patterns which are described below (Buss, 2010).

SimEventListening logic is as follows:

> One simulation component shows interest in another’s events by explicitly being registered as a SimEventListener to it. If there is a listener relationship (as in Figure 8.), then whenever an Event from Source occurs, then after it has executed its state transitions and scheduled Events, the Event is sent to Listener. If Listener has an Event that is identical (in both name and signature) to the one it “hears” then it processes that Event as if it had scheduled it. The listening component does *not* re-dispatch heard Events to its listeners, if it has any.” (Buss, 2010)

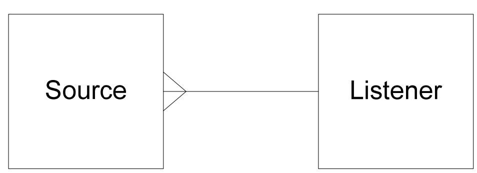


Figure 8. SimEventListener Relationship [From (Buss, 2010)]

If we desire an event of one name in a component to cause another event of a different name to occur in another component, we use the Adapter pattern. Unlike the Listener pattern, Adapter works on a single event only. The Adapter pattern seen in Figure 9. has this logic: Event A (source event) in the Source component causes Event B (adapted event) in the Listener component to occur whenever Event A occurs. The source and adapted events must have identical parameter lists for the Adapter to work (Buss, 2010).

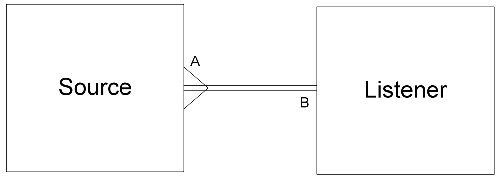


Figure 9. Prototype Adapter [From (Buss, 2010)]

D. SIMKIT

Simkit is a free software package designed to implement event graph models easily. Every element in an event graph model has a corresponding element in Simkit. Each event (except Run) in the event graph model is implemented by a corresponding method in a Simkit component (subclass) that starts with ‘do’ followed by the name of the event. Scheduling edges are implemented by calling waitDelay() method. The following Simkit code is the corresponding implementation of the event graph in Figure 6. (Buss, 2010).

```
public void doA() {
    int j = . . .;
    // State transitions for Event A
    if (i) {
        waitDelay(“B”, t, j);
    }
}
public void doB(int k) {
    // State transitions for Event B.
}
```

More information about Simkit and event graph model implementation examples in Simkit can be found in (Buss, 2010).

III. RECONNAISSANCE SQUADRON WORKFLOW MODEL

This chapter explains the Reconnaissance Squadron Workflow model that is implemented by using the Simkit package.

A. SCENARIO

A Simplified Reconnaissance Squadron Workflow Cycle is illustrated in Figure 10. The steps in this cycle are listed below:

- Reconnaissance requests for the following day arrive, in bulk, at the squadron in the late afternoon.
- Flight planning for the next day occurs. This entails creating aircraft, pilot, camera and flight time temporary assignments by considering the reconnaissance request attributes such as priority, due date, image type and angle type.
- Flight execution for the specific reconnaissance missions at take-off times. There are a few factors that affect the success of the flight execution, such as aircraft/camera defect(s), bad weather conditions, and pilot filming error. Except for aircraft defects, all of the other factors are determined when the evaluation of the film is started.
- Assessment (processing and interpretation) of films after aircraft landing and then report generation based on the reconnaissance request requirements. Generated reports are sent to the intelligence users.

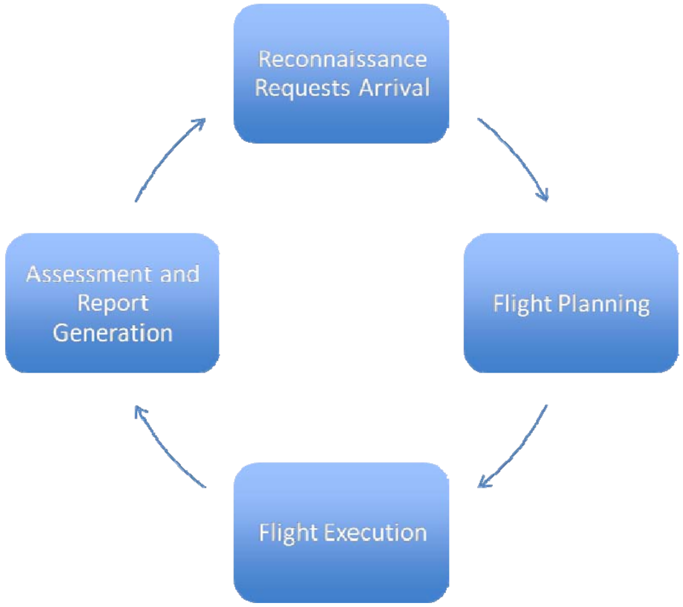


Figure 10. Simplified Reconnaissance Squadron Workflow Cycle

Table 1 shows four different scenarios in Reconnaissance Squadron Workflow Cycle based on situations and configurations. There is a specific model for each scenario.

Situation	Configuration	
	Type 1	Type 2
War	RF-4	F-16
Peace	RF-4	F-16

Table 1. Situation/Configuration Table for Different Scenarios

Figure 11. shows the flight planning for a peace-time situation with RF-4 configuration. The notional Air Base is located at the (0, 0) coordinate. The notional target zone has (-65, 20) as the upper left coordinate and (-35,-50) as the lower right coordinate. Each coordinate in this target zone represents a target. Each reconnaissance request has a specific target. In this peace situation, reconnaissance requests that have adjacent targets are combined into one mission if their camera requirements are the same, which means requiring the same image and angle type. Combining adjacent targets provides more training time for pilots and efficient usage of resources.

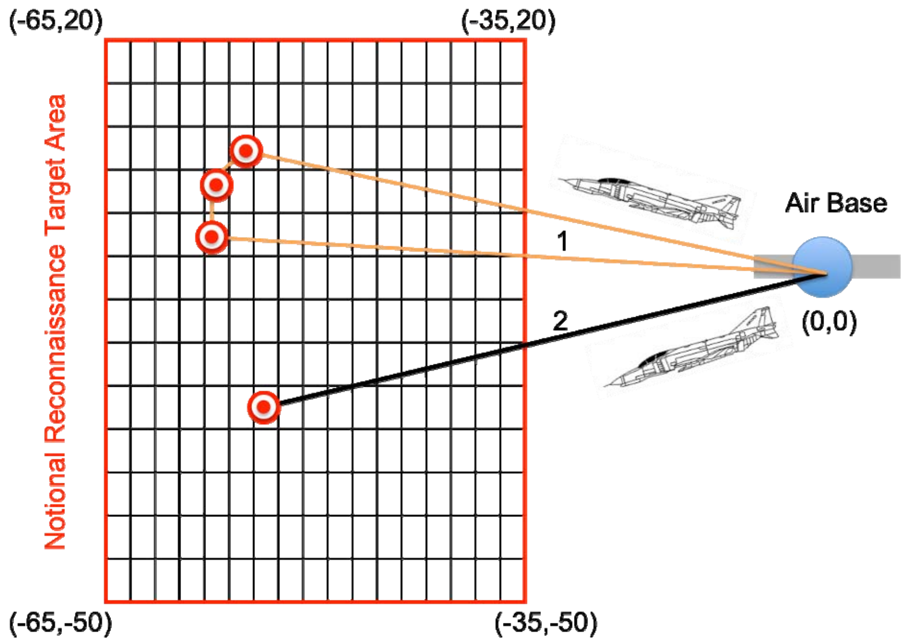


Figure 11. Flight Leg Planning for RF-4, Peace Situation Reconnaissance Missions

Figure 12. shows the reconnaissance planning for war situation. RF-4 aircraft missions include only one reconnaissance request (that is, no target combining occurs).

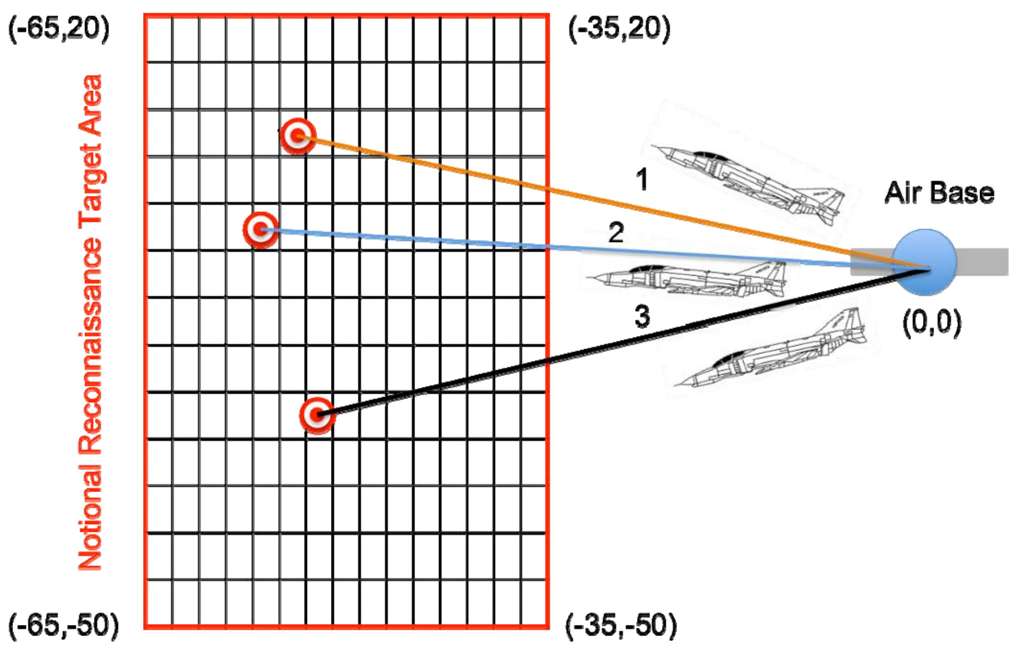


Figure 12. Flight Leg Planning for RF-4, War Situation Reconnaissance Missions

Figure 13 shows the reconnaissance mission planning for peace situation. In a peace situation, reconnaissance requests that have adjacent targets are combined into one mission if their camera requirements are the same, which means requiring the same image and angle type. F-16 aircrafts carry an EO/IR pod, which can take both EO and IR imagery simultaneously. Besides, when the aircraft is in the line of sight with the antenna and within its uplink/downlink parameter, new missions can be uploaded or imagery can be downloaded. In this study, only the downlink capability is modeled.

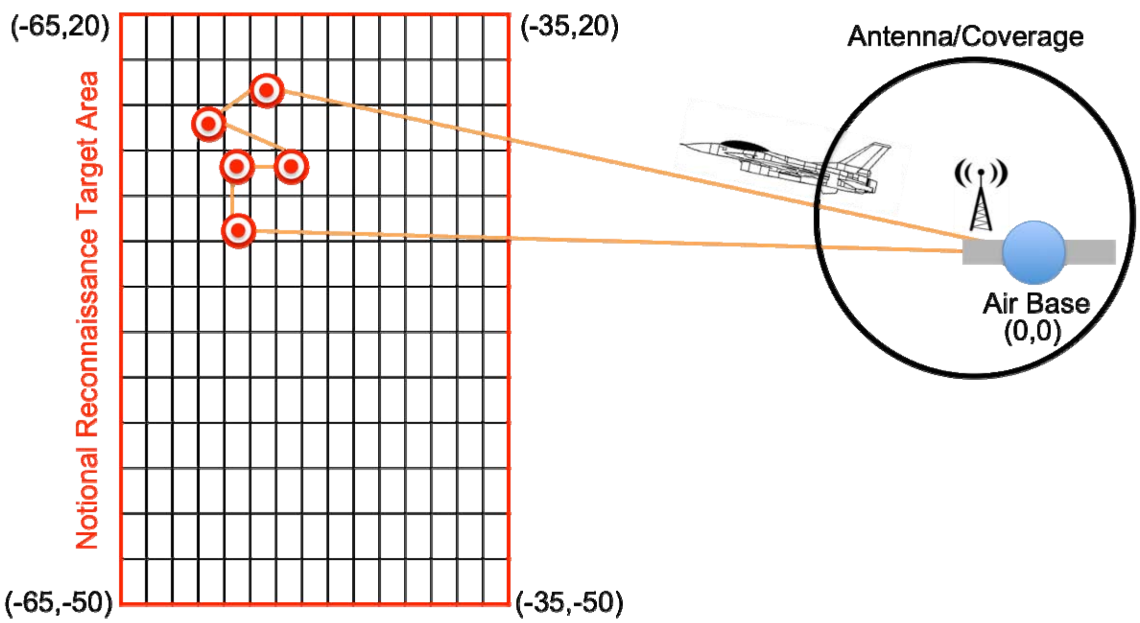


Figure 13. Flight Leg Planning for F-16 Reconnaissance Missions

B. ASSUMPTIONS

Common assumptions used in all models are listed below:

- Bulk reconnaissance requests arrive to the squadron every day at 17:00 for the following day's flight planning.
- The duration of a flight is calculated by using a heuristic algorithm (calculateFlightDuration method of FlightsPlanner class) that is based on a standard flight pattern; this is explained in the event graphs section.
- On average, aircrafts cover one mile in 0.3 minutes.

- There is a fifteen minutes gap between consecutive flights.
- After entering the target area for each target, it takes ten minutes of flight time to capture the images of the target.
- Even though both day (requires optic imagery) and night (requires infrared imagery) reconnaissance missions are conducted in specific, limited times, there is no specific or limited time for the evaluation of the films/imagery. Image analysts interpret and evaluate films/imagery when they arrive and they do this job until all of the imagery in the queue is evaluated.

Scenario specific assumptions are listed separately in order to highlight the differences between the four models.

1. Configuration of the RF-4

- RF-4 aircraft flights require two pilots for reconnaissance missions.
- For the evaluation of the films, two image analysts are assigned for each target.
- Only one sensor (camera) is mounted to the RF-4 aircraft for the reconnaissance mission. There is no spare sensor planning.
- All requests require new reconnaissance missions. There is no usage of responding requests from existing image library.

a. Situation: Peace

- Reconnaissance missions requiring optic imagery can only be conducted between 10:00 and 16:00.
- Reconnaissance missions requiring infrared (IR) imagery can only be conducted between 18:00 and 24:00.

- Main flight planning occurs at 03:00 each day. Any other required, additional flight planning occurs during flight executions after specific events such as aircraft defect(s), camera defect(s) or pilot filming error.

- During flight planning, reconnaissance requests that have adjacent targets are combined into one mission if their camera requirements are the same, which means requiring the same image and angle type (see Figure 11.).

- Pilots are required to take two hours of break ($t_{restingTimeForPilots}$) after successful flights, due to crew rest policies.

- After an RF-4 aircraft lands, it takes ten minutes to take the aircraft to the hangar and stop the engines. If aircraft lands without defect(s), it goes to seventy-five minutes routine maintenance (turnaround time).

- Due dates are assigned according to the priorities of the reconnaissance requests. The highest priority reconnaissance requests have the earliest due dates.

b. Situation: War

- Reconnaissance missions requiring optic imagery can only be conducted between 10:00 and 17:00, which is one hour more than in the peace situation.

- Reconnaissance missions requiring infrared (IR) imagery can only be conducted between 19:00 and 02:00. The night mission hours are shifted one hour from the peace situation.

- Main flight planning occurs at 05:00 each day. Any other required, additional flight planning occurs during flight executions after specific events such as aircraft defect(s), aircraft interception, camera defect(s) or pilot filming error.

- In contrast to the peace situation, reconnaissance requests that have adjacent targets are not combined into one mission (see Figure 12.).

- War situation requires extreme measures, so that pilots can be assigned to consecutive flights without any rest time.

- After an RF-4 aircraft lands, it takes ten minutes to take the aircraft to the hangar and stop the engines. If the aircraft lands without defect(s), it goes to one hour routine maintenance (turnaround time).

- All reconnaissance requests have the same due date, which is creation time plus one day. In war situations, due dates are more restrictive than peace situations.

- When the aircraft is intercepted, all of the resources (camera, aircraft and pilots) are assumed to be lost.

2. Configuration of the F-16

- The F-16 aircraft is modeled as a single seat, that is, it requires only one pilot.

- For the evaluation of images, one image analyst is assigned for each target.

- Only one sensor (camera) is mounted to the F-16 aircraft pod. This pod is dual band, that is, it can take both IR and Optic images simultaneously. There is no spare sensor planning.

- During flight planning, reconnaissance requests that have adjacent targets are combined into one mission if their angle types are same (see Figure 13).

a. Situation: Peace

- Reconnaissance missions requiring optic imagery can only be conducted between 10:00 and 16:00. Also, IR imagery requests can be planned during these hours.

- Reconnaissance missions for night are only possible with IR imagery, and can only be conducted between 18:00 and 24:00.
- Main flight planning occurs at 03:00 each day. Any other required, additional flight planning occurs during flight executions after specific events such as aircraft defect(s), camera defect(s) or pilot filming error.
- Pilots are required to take two hours of break ($t_{restingTimeForPilots}$) after successful flights, due to crew rest policies.
- After an F-16 aircraft lands, it takes ten minutes to take the aircraft to the hangar and stop the engines. If an aircraft lands without defect(s), it goes to one hour routine maintenance (turnaround time).
- Due dates are assigned according to the priorities of the reconnaissance requests. Highest priority reconnaissance requests have the earliest due dates.
- If so specified, reconnaissance requests can be responded to using information from old missions, that is, from an imagery archive, if the previous mission is not older than one week. If recent images are not available, then a flight mission is planned.

b. Situation: War

- Reconnaissance missions requiring optic imagery can only be conducted between 10:00 and 17:00.
- Reconnaissance missions requiring IR imagery can only be conducted between 19:00 and 02:00.
- Main flight planning occurs at 05:00 each day. Any other required, additional flight planning occurs during flight executions after specific events such as aircraft defect(s), aircraft interception, or pod defect(s).
- Pilots can be assigned to consecutive flights without any rest time.

- After an F-16 aircraft lands, it takes ten minutes to take the aircraft to the hangar and stop the engines. If the aircraft lands without defect(s), it goes to one hour routine maintenance (turnaround time).
- All reconnaissance requests have the same due date, which is the creation time plus one day.
- When the aircraft is intercepted, all of the resources (pod, aircraft and pilot) are assumed to be lost.

C. LIMITATIONS, CONSTRAINTS AND REQUIREMENTS

In the model, bulk reconnaissance requests arrive to the squadron every day at 17:00. The model does not consider the exact creation time of each reconnaissance request or the creators of the reconnaissance request who affect the priority or report type of the reconnaissance request.

After report writing is completed, it is assumed that the mission is successfully finished. However, in reality, there are a few more steps in this process such as transmission and evaluation of the reports. In this thesis, only the steps through the report writing are modeled.

The RF-4 aircraft can carry more than one sensor in its specially-designed nose compartment. In addition to these sensors, it can carry a sensor pod as well. Since a successful reconnaissance mission requires only one reliable sensor, the peace and war situation RF-4 models assume that there is only one sensor mounted on the aircraft. In reality, spare sensors are also mounted on the aircraft in order to increase the probability of mission success.

There are also some restrictions about the operational usage of the sensors, such as the minimum operational altitude or ground speed. However, the model does not take those limitations into account.

The model does not also take into account the different types of sensors, nor the logistic needs for sensors and aircrafts. While making experiments on the model, defect probabilities and maintenance times for aircrafts and sensors are assigned based on authors' experience.

All targets are assumed to be fixed targets; that is, they are not mobile and their coordinates are fixed. This allows for planning in advance for the next day. There is no reconnaissance request during the flight hours for emerging targets.

In this study, different scenarios and configurations are modeled to address the purpose of this study – namely, to find out what important factors are affecting the two different reconnaissance systems. Comparing the two different reconnaissance systems is not the purpose of this study.

D. EVENT GRAPHS

The event graphs in the figures below do not indicate state transitions; these are discussed in the paragraphs above the figures.

1. Configuration of the RF-4

a. Situation: Peace

Figure 14 shows the main components of the RF-4 configuration in a peace situation model. There are five main components in the model: RecSquadronWorkflow, RecRequestsCreator, FlightsPlanner, FlightsExecutor and ReportsGenerator. These main components are independent of each other, but they are connected by using listener and adapter patterns to make the whole model run accurately. Each main component is explained below in detail.

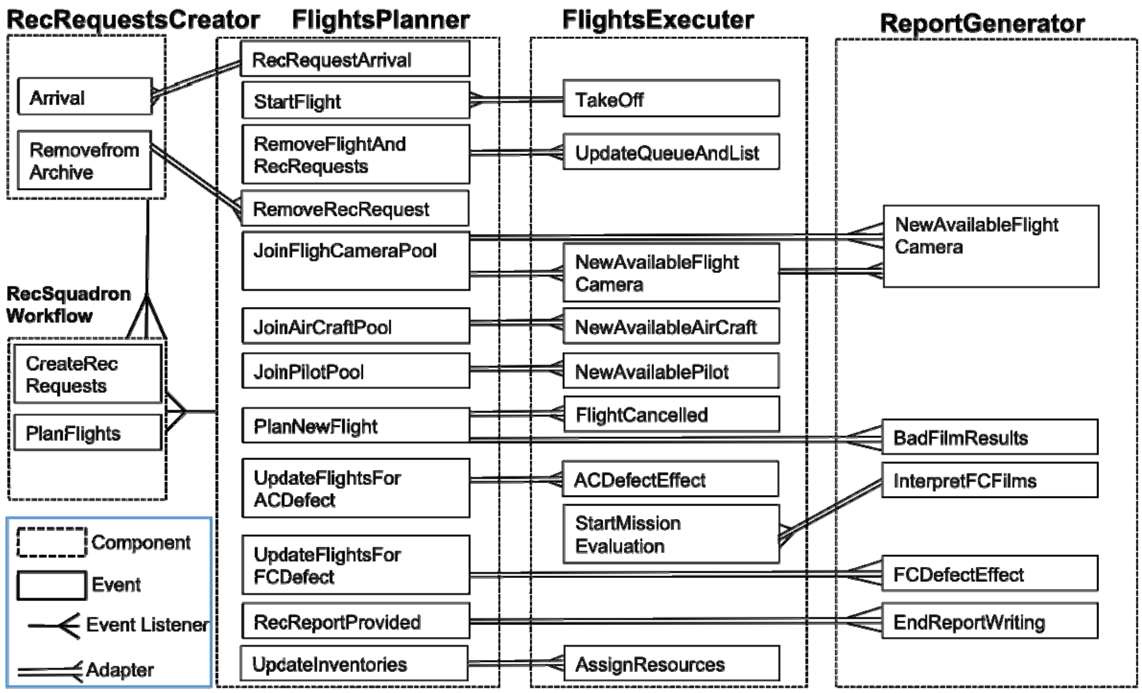


Figure 14. Conf.: RF-4 / Sit.: Peace - Components with Listener and Adapter Patterns

Figure 15 depicts the event graph of the RecSquadronWorkflow class. The RecSquadronWorkflow class works as a simulation clock. It triggers the creation of bulk reconnaissance requests and main flight planning every day at the same hour during the simulation run. Simulation starts at 00:00 with the Run event. This schedules a CreateRecRequests event with a $t_{recReqCreTime}$ time delay (which corresponds to 17:00), and PlanFlights event with $t_{planflightsTime}$ time delay (which corresponds to 03:00 the next day). The delay values are in minutes, e.g., $\frac{1020}{24} = 17$ hours. Both CreateRecRequests and PlanFlights events schedule themselves to occur every day at the same time by using $t_{minutesInADay}$ delay which equals twenty-four hours.

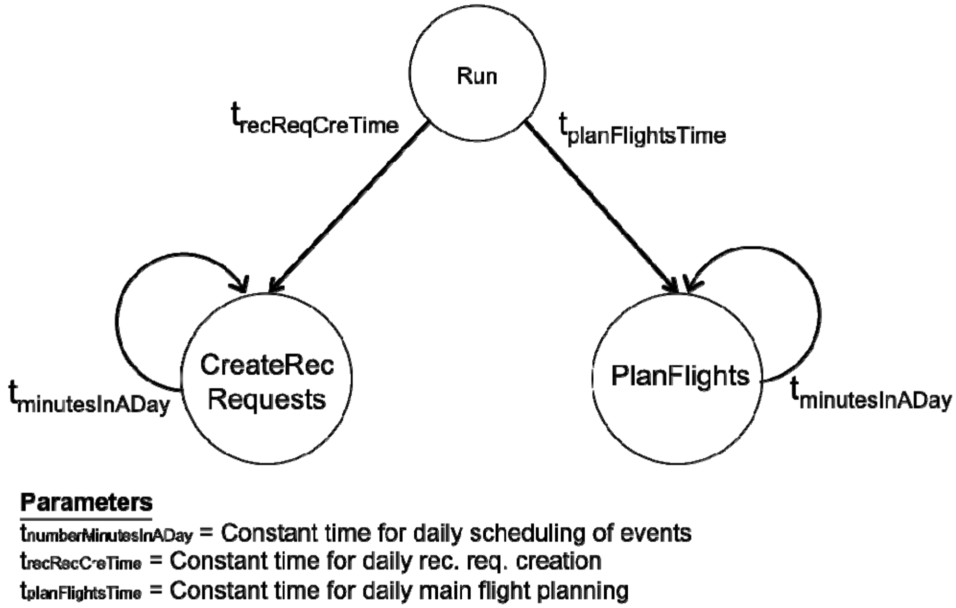


Figure 15. Conf.: RF-4 / Sit.: Peace - Reconnaissance Squadron Workflow Event Graph

Figure 16 shows the event graph of the RecRequestsCreator component. The RecRequestsCreator component deals with the creation of daily bulk reconnaissance requests, recording of successful reconnaissance request mission targets to the target archive, and removal of unresponded reconnaissance request targets from the target archive.

The CreateRecRequests() event generates a rounded random number (n) based on a triangular distribution whose parameters are set to the input taken from the user. Then it passes zero and this random number to the CreateRecRequest(i,m) event as parameters. The CreateRecRequest(i,m) event creates reconnaissance request (r) by calling the createNewRecRequest() method, schedules an Arrival event with created reconnaissance request (r), and schedules itself m times with increasing i. The createNewRecRequest() method creates an instance of reconnaissance request class, RecRequest, which includes fields such as priority index, due date, camera type and target location. The RemovefromArchive event allows the allocation of cancelled reconnaissance request (r) targets to newly-created reconnaissance requests.

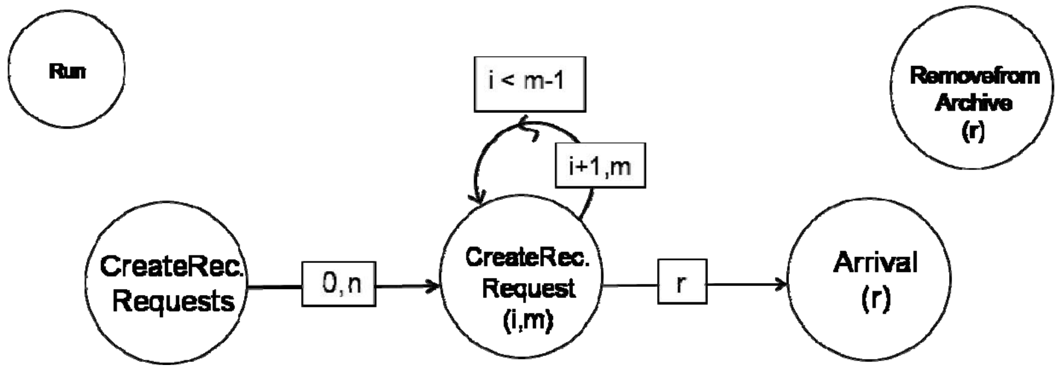


Figure 16. Conf.: RF-4 / Sit.: Peace - Reconnaissance Requests Creator Event Graph

Figure 17 shows the event graph of the FlightsPlanner component. The FlightsPlanner component plans reconnaissance flights dynamically based on availability of resources such as aircraft, pilots, and cameras. During flight planning it combines reconnaissance requests that have adjacent targets into one flight and calculates flight durations. FlightsPlanner keeps track of:

- Aircraft, pilot, and camera inventories.
- Planned flights list.
- Two separate queues for daylight and night reconnaissance requests.

In the RecRequestArrival(r) event, the arrival time of a reconnaissance request is stamped and then this reconnaissance request (r) is added to the relevant queue. The *numberRecRequestArrivals* state variable is incremented by one. Then the RecRequestArrival(r) event schedules the RemoveRecRequest(r) method with a $t_{dueDate\ -\ simTime}$ delay. Each reconnaissance request should be responded to before its due date passes. The RemoveRecRequest event removes reconnaissance requests from the relevant queue and increments the *numberRemovedRecRequests* state variable by one.

The RecReportProvided event first updates the *totalTimeAtWorkFlow* state variable. Then it cancels the RemoveRecRequest event for relevant reconnaissance requests.

The PlanFlights event makes the main flight planning based on availability of cameras, aircraft, and pilots within daily flight hours for both day and night flights.

During flight planning, it combines reconnaissance requests that have adjacent targets into one flight and calculates flight durations. The PlanFlights event schedules StartFlight events for planned flights (f) with relevant $t_{plannedFlightTime\ -\ simTime}$ delays.

The duration of a flight is calculated by using a heuristic algorithm in the calculateFlightDuration method. In this algorithm, it is assumed that the aircraft flies from base to targets which are sorted in ascending order according to their reconnaissance request due dates. The algorithm first initializes the flight duration to zero. Then it calculates the total distance traveled during a flight by adding distances between flight points. The distance between two flight points is calculated by using a variant of the Pythagorean Theorem (Purple Math, 2010). The total distance is multiplied by the *averageTimePerMile* constant and added to the flight duration. The number of targets in the flight mission is multiplied by the *averageTimeForTarget* constant and the result is also added to the flight duration.

The UpdateFlightsForFCDefect event first cancels the flights (f) which cannot be completed at their scheduled time because of camera defect(s) and then tries to plan new flights for those canceled ones by using the planNewFlight method.

The UpdateFlightsForACDefect event first cancels the flights (f) which cannot be completed at their scheduled time because of aircraft defect(s) and then tries to plan new flights for those canceled ones by using the planNewFlight method.

The PlanNewFlight event tries to plan a new flight for its argument flight by using the planNewFlight method. It also adds the reconnaissance requests (r) of the cancelled or unsuccessful flight to the relevant queue.

The planNewFlight private method tries to plan a new flight (nF) for a cancelled or unsuccessful flight by using available resources (cameras, aircrafts and pilots). If a new flight can be planned it schedules the StartFlight event with $t_{plannedFlightTime\ -\ simTime}$ delay and updates the flights list.

The JoinFlightCamerasPool event updates cameras’ availability times.

The JoinPilotsPool event updates pilots’ availability times.

The JoinAirCraftsPool event updates availability time for the aircraft.

The UpdateInventories event updates inventories of cameras, pilots, and aircraft after an aircraft takes off for a reconnaissance mission.

The RemoveFlightAndRecRequests event updates the flights list and relevant reconnaissance request queue after an aircraft takes off for a reconnaissance mission.

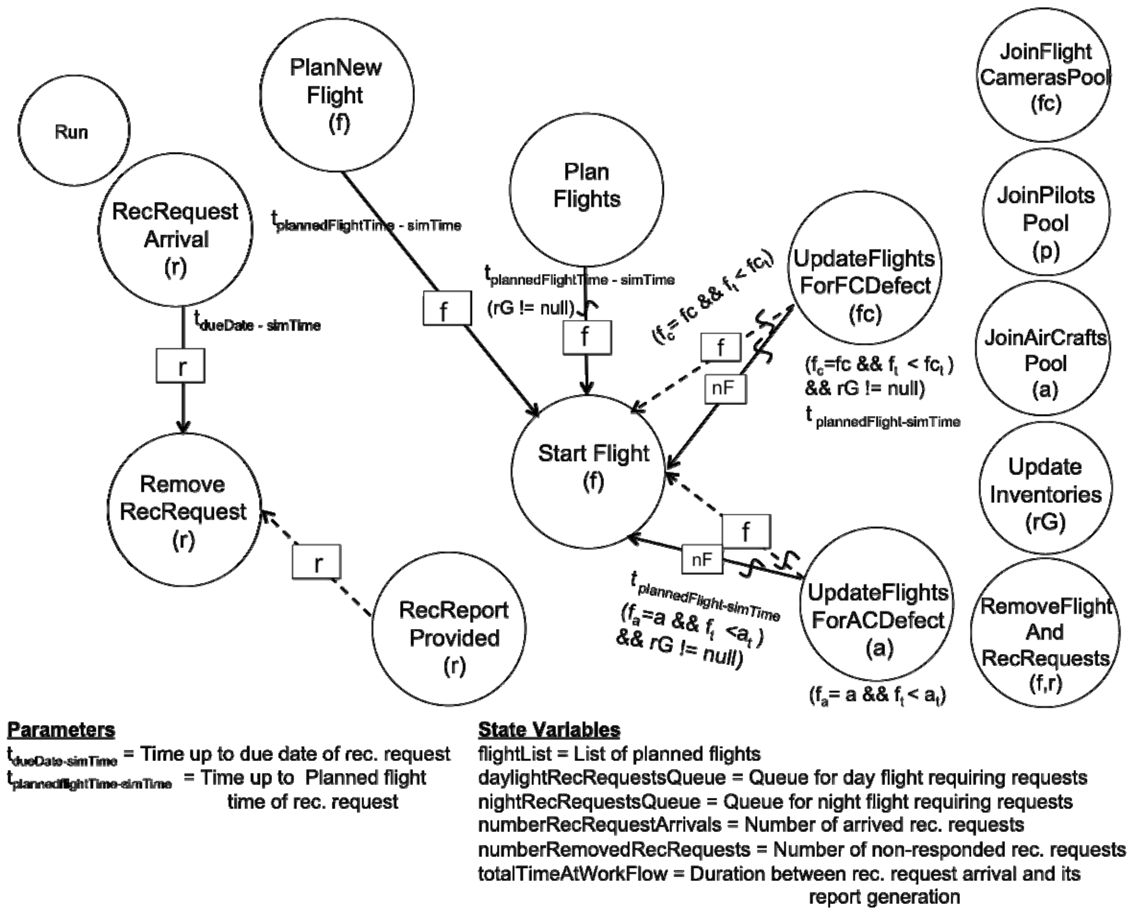


Figure 17. Conf.: RF-4 / Sit.: Peace - Flights Planner Event Graph

Figure 18 shows the event graph of the FlightsExecutor component. The FlightsExecutor component deals with reconnaissance flights after flight operations and most of the state variable changes in the whole model.

First, the TakeOff event schedules the UpdateQueueAndList event with the relevant flight (f) and resource group (rG) parameters.

Second, the TakeOff event schedules the AssignResources event with resource group (rG) parameter. Unless the simulation time is less than the availability times of any resource group component (camera, aircraft and pilots), the TakeOff event decrements the relevant *numberAvailableFlightCameras* and *numberAvailableAirCrafts* state variables by one and decrements the *numberAvailablePilots* state variable by two.

Third, the TakeOff event generates a random number for aircraft defect probability (p). If this number is less than or equal to the user input for aircraft defect probability, the TakeOff event schedules LandForACDefect by passing relevant flight (f) with $t_{aircraftDefectRecogTime}$ delay. If p is greater than the user input for aircraft defect probability, then the TakeOff event schedules the Land event by passing relevant flight (f) with $t_{flightDuration}$ delay.

Finally, if the simulation time is less than the availability times of any resource group component (camera, aircraft, and pilots) the TakeOff event schedules the FlightCancelled event by passing relevant flight (f).

The Land event schedules three events. First, it schedules the StartMissionEvaluation event by passing relevant flight (f) with a $t_{averageEngineStopTime}$ delay, which is the time between aircraft landing and turning off the aircraft engines. Films can be removed after the aircraft engines stop. Second, it schedules the StartACMaintenance event by passing relevant aircraft (a) with a $t_{averageEngineStopTime}$ delay. Third, it schedules the NewAvailablePilots event by passing relevant pilots (p) with a $t_{restingTimeForPilots}$ delay.

The LandForACDefect event schedules four events. First, it schedules the NewAvailableFlighCamera event by passing relevant camera (fc) with a $t_{averageEngineStopTime}$ delay. Second, it schedules the NewAvailablePilots event by passing relevant pilots (p). Third, it schedules the StartACDefectRepair event by passing relevant aircraft (a) with a $t_{averageEngineStopTime}$ delay. Fourth, it schedules the FlightCancelled event by passing relevant flight (f) with a $t_{averageEngineStopTime}$ delay.

First, the StartACDefectRepair event updates aircraft inventory. Second, it schedules the ACDefectEffect event. Finally, it schedules the EndACDefectRepair event by passing relevant aircraft (a) with a $t_{airCraftDefRepTime}$ delay.

The EndACDefectRepair event schedules NewAvailableAirCraft event by passing relevant aircraft (a). The StartACMaintenance event updates aircraft inventory. Then it schedules the EndACMaintenance event by passing relevant aircraft (a) with a $t_{avgMaintTimeForAirCrafts}$ delay. The EndACMaintenance event schedules the NewAvailableAirCraft event by passing relevant aircraft (a).

The NewAvailableFlightCamera event first increments the relevant *numberAvailableFlightCameras* state variable by one. The NewAvailableAirCraft event increments the *numberAvailableAirCrafts* state variable by one. The NewAvailablePilots event increments the *numberAvailablePilots* state variable by two.

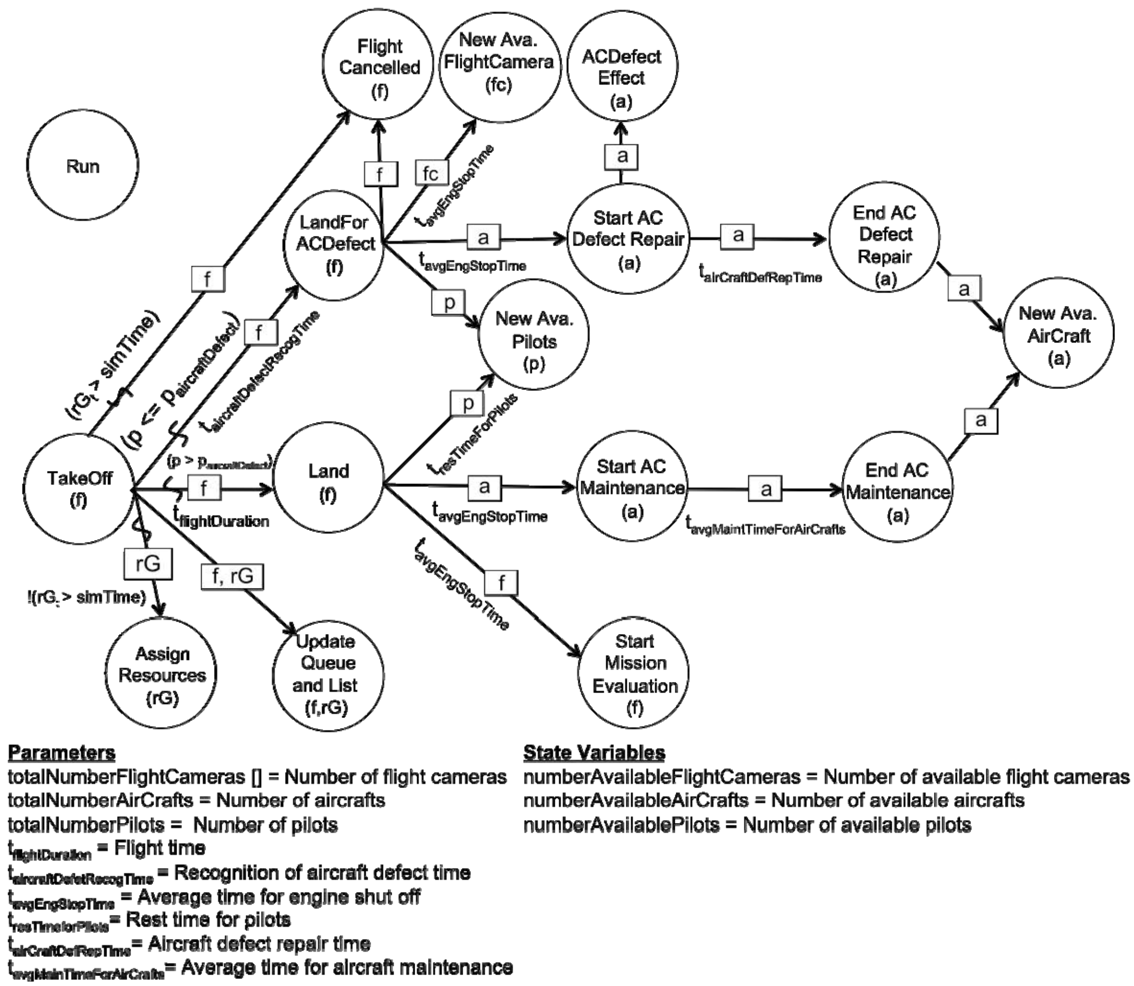


Figure 18. Conf.: RF-4 / Sit.: Peace - Flights Executor Event Graph

Figure 19 depicts the event graph of ReportsGenerator component. The ReportsGenerator component deals with the operations after a successful reconnaissance flight, that is, interpreting the films and writing reconnaissance reports based on their requirements.

The InterpretFCFilms event can schedule four different events. First, it generates a random number for camera defect probability (p1). If this number is less than or equal to the user input for the relevant camera defect probability, it schedules the StartFCDefectRepair event by passing relevant camera (fc). Second, if p1 is greater than the user input for relevant camera defect probability, then the InterpretFCFilms event schedules the NewAvailableFlightCamera event by passing the relevant camera (fc).

Third, based on generated random numbers, if there is a camera defect or pilot filming error or bad weather condition, then the InterpretFCFilms event schedules the BadFilmResults event by passing relevant flight (f). Fourth, based on generated random numbers, if there is no camera defect, no pilot filming error, and no bad weather condition, then the InterpretFCFilms event generates random report writing times for reconnaissance requests in the flight (f) and adds these reconnaissance requests to the reconnaissance requests queue. If there is an available image analyst, the InterpretFCFilms event schedules the StartReportWriting event.

First, the StartFCDefectRepair event updates the camera inventory. Second, it schedules the FCDeffectEffect event by passing relevant camera (fc). Finally, the StartFCDefectRepair event schedules the EndFCDefectRepair event by passing relevant camera (fc) with a $t_{flightCameraRepairTime}$ delay. The EndFCDefectRepair event schedules the NewAvailableFlightCamera event by passing relevant camera (fc).

The StartReportWriting event takes the first reconnaissance request (r) in the queue, removes it from the queue and schedules the EndReportWriting event by passing that reconnaissance request (r) with a $t_{reportWritingTime}$ delay. The StartReportWriting event also decrements the *numberAvailableAnalysts* state variable by two.

The EndReportWriting event increments the *numberProvidedRecRequests* state variable by one and the *numberAvailableAnalysts* state variable by two. If there is any reconnaissance request in the queue waiting for the report writing process, the EndReportWriting event schedules the StartReportWriting event.

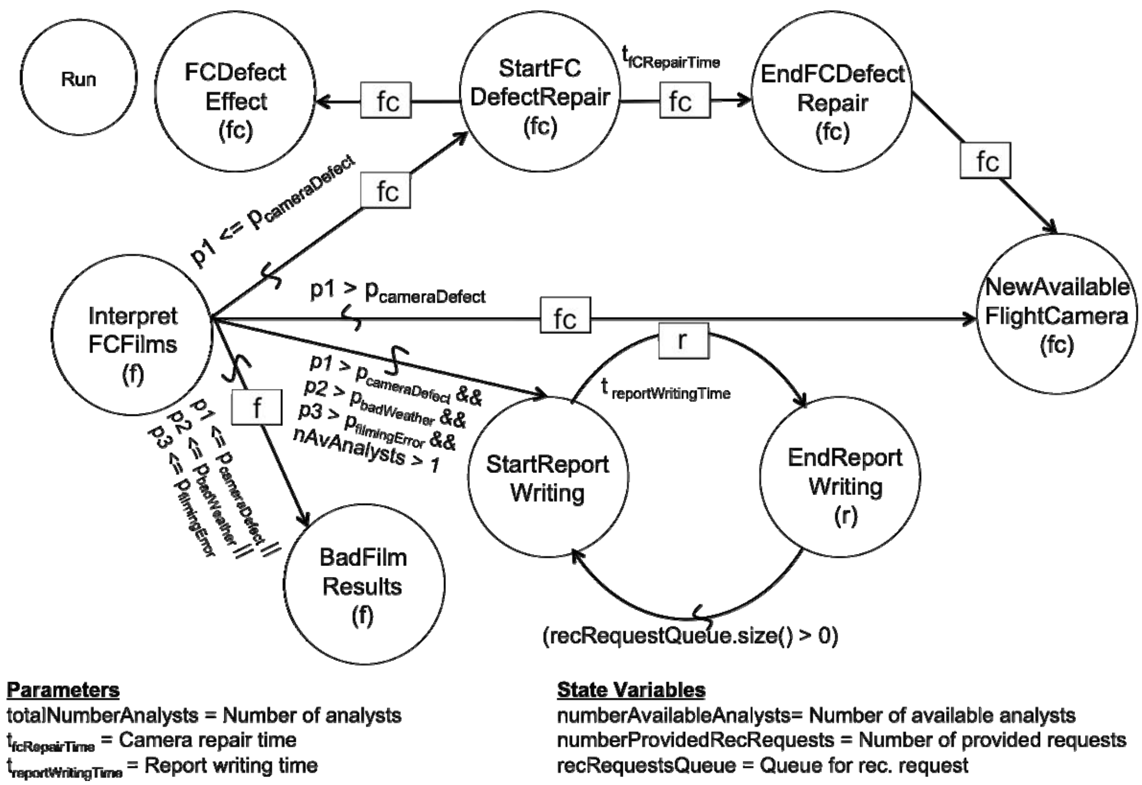


Figure 19. Conf.: RF-4 / Sit.: Peace - Reconnaissance Request Report Generator Event Graph

b. Situation: War

Figure 20 shows the main components of the RF-4 configuration in a war situation model. As in the peace situation, there are five main components in the model: the RecSquadronWorkflow, RecRequestCreator, FlightsPlanner, FlightsExecutor and ReportsGenerator. Even though, during the peace time, training is done according to "Train like you fight" principle, there are significant changes in the war situation. Events in red are either new or changed events specific to the war scenario. The rest of the events are the same as in the peace scenario. Each main component is explained below in detail.

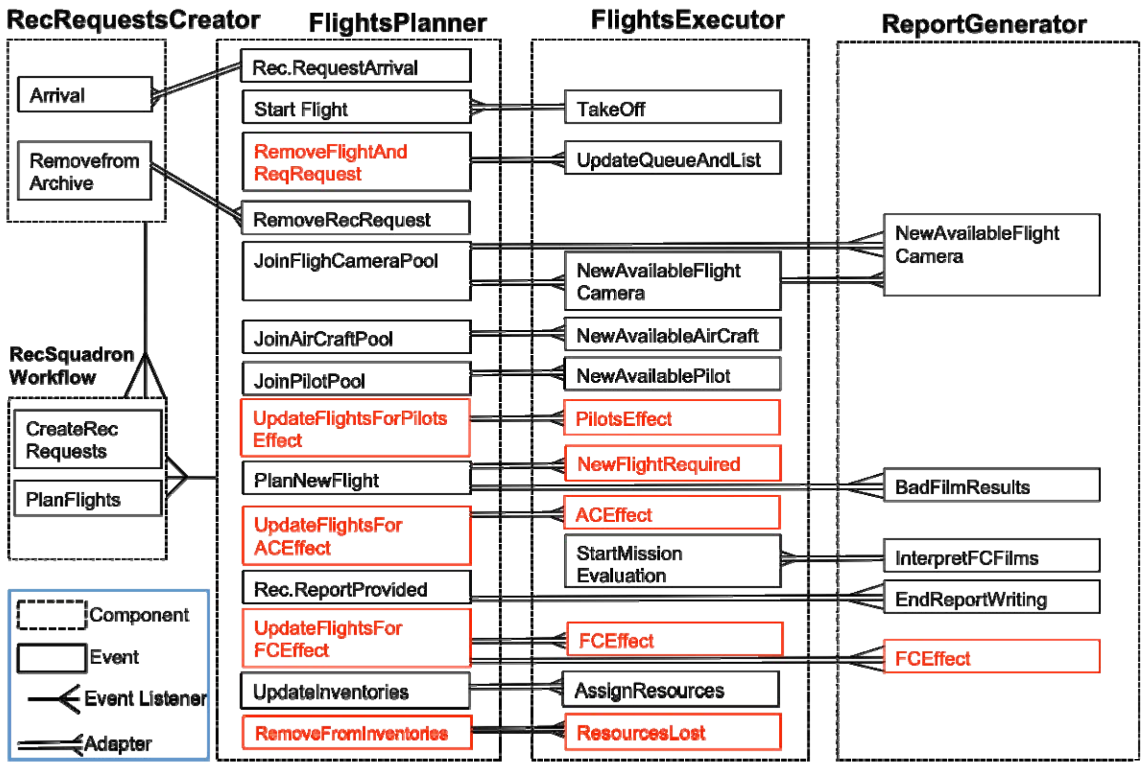


Figure 20. Conf.: RF-4 / Sit.: War - Components with Listener and Adapter Patterns

The RecSquadronWorkflow component of the RF-4 configuration war situation scenario is same as the RF-4 configuration peace situation scenario, except that the value for $t_{planflightsTime}$ time delay is incremented by two hours to allow for more flight hours.

The RecRequestsCreator component of RF-4 configuration war situation scenario is same as RF-4 configuration peace situation scenario. Only the due dates given to reconnaissance requests are different. In the peace scenario, the duration between arrival and due date of each reconnaissance request is random. In the war scenario, this duration is just one day.

Figure 21 shows the event graph of the FlightsPlanner component. Events in red are either new or changed events specific to the war scenario. The rest of the events are the same as in the peace scenario, except that the adjacent target combination possible in the peace scenario is not done in the war scenario.

The UpdateFlightsForFCEffect event first cancels the flights which cannot be completed at their scheduled times because of either camera defect(s) or camera loss (due to aircraft interception) and tries to plan new flights for those canceled ones by using the planNewFlight method.

The UpdateFlightsForACEffect event first cancels the flights which cannot be completed at their scheduled times because of either aircraft defect(s) or aircraft loss (due to aircraft interception) and tries to plan new flights for those canceled ones by using the planNewFlight method.

The UpdateFlightsForPilotsEffect event first cancels the flights which cannot be completed at their scheduled times because of pilot loss (due to aircraft interception), and tries to plan new flights for those canceled ones by using the planNewFlight method.

The RemoveFromInventories event updates inventories of cameras, pilots, and aircraft after an aircraft is intercepted. Also, if inventories of flight cameras and aircrafts drop to 0, or the inventory of pilots drops to 1, then the simulation stops. This means that the reconnaissance squadron cannot accomplish its duties because either there are no personnel or equipment.

The RemoveFlightAndRecRequest event updates the flights list and relevant reconnaissance request queue after an aircraft takes off for a reconnaissance mission.

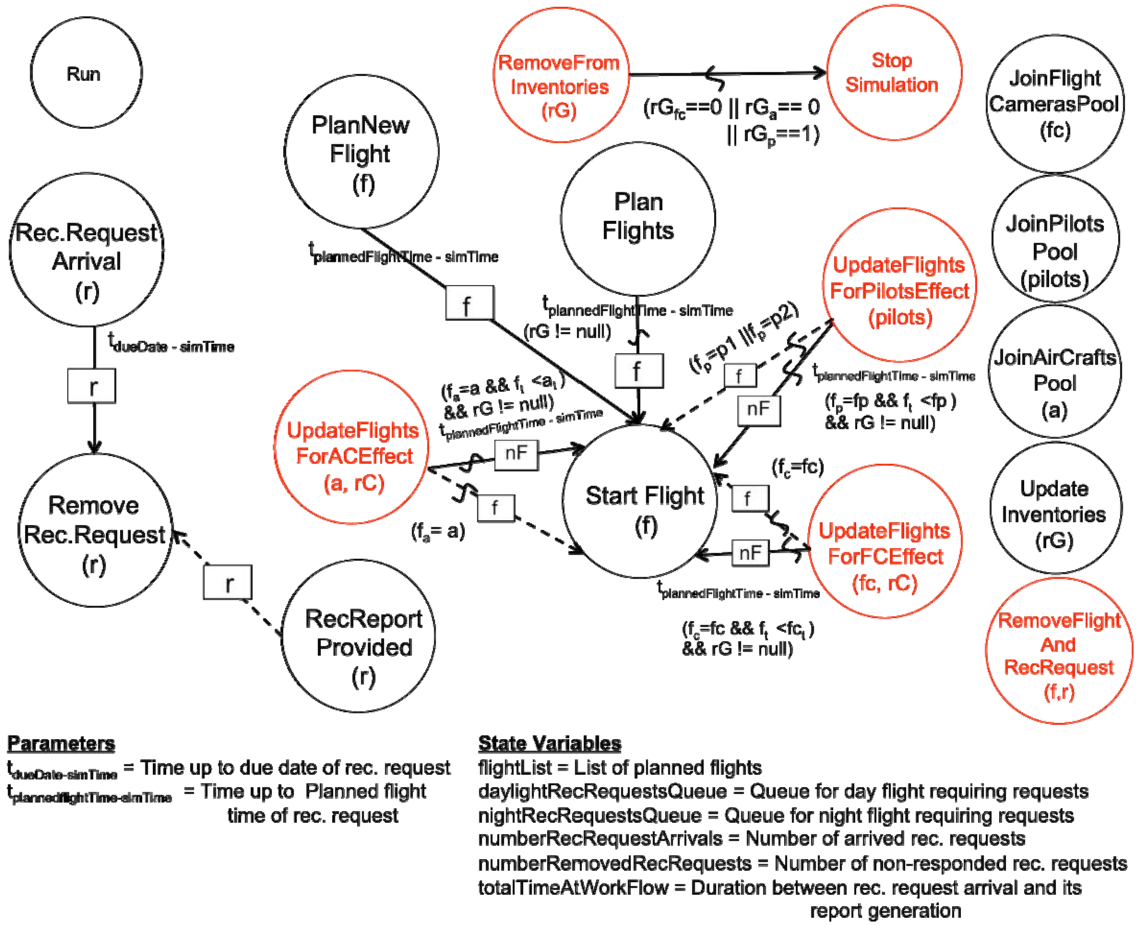


Figure 21. Conf.: RF-4 / Sit.: War - Flights Planner Event Graph

Figure 22 shows the event graph of the FlightsExecutor component. Events in red are either new or changed events specific to the war scenario. The rest of the events are the same as in the peace scenario, except the non-zero probability of reconnaissance aircraft interception by the enemy affects the entire reconnaissance cycle due to lost resources such as pilots, aircraft, and cameras.

The TakeOff event generates a random number for aircraft defect probability (p). If p is greater than the user input for aircraft defect probability, then the TakeOff event schedules the ArriveToTarget event by passing relevant flight (f) as a parameter with $t_{flightDuration/2}$ delay. If simulation time is less than the availability time of any resource group (rG) component (camera, aircraft and pilots), the TakeOff event schedules the NewFlightRequired event by passing relevant flight (f).

A random number for aircraft intercept probability (p) is generated and compared with the user input for aircraft intercept probability. If the aircraft intercept probability (p) is less than or equal to user threshold, then the ArriveToTarget event schedules the ACIntercepted event. If not, the ArriveToTarget event schedules the Land event with $t_{flightDuration/2}$ delay.

The ACIntercepted event schedules five events. First, it schedules the ResourceLost event by sending the pertinent resource group (rG). Second, it schedules the NewFlightRequired event by sending relevant flight (f). Third, it also schedules the ACEffect event by sending pertinent aircraft (a). Fourth, it also schedules the FCEffect event by sending pertinent flight camera (fc). Finally, the PilotsEffect event is scheduled by sending relevant pilots (p).

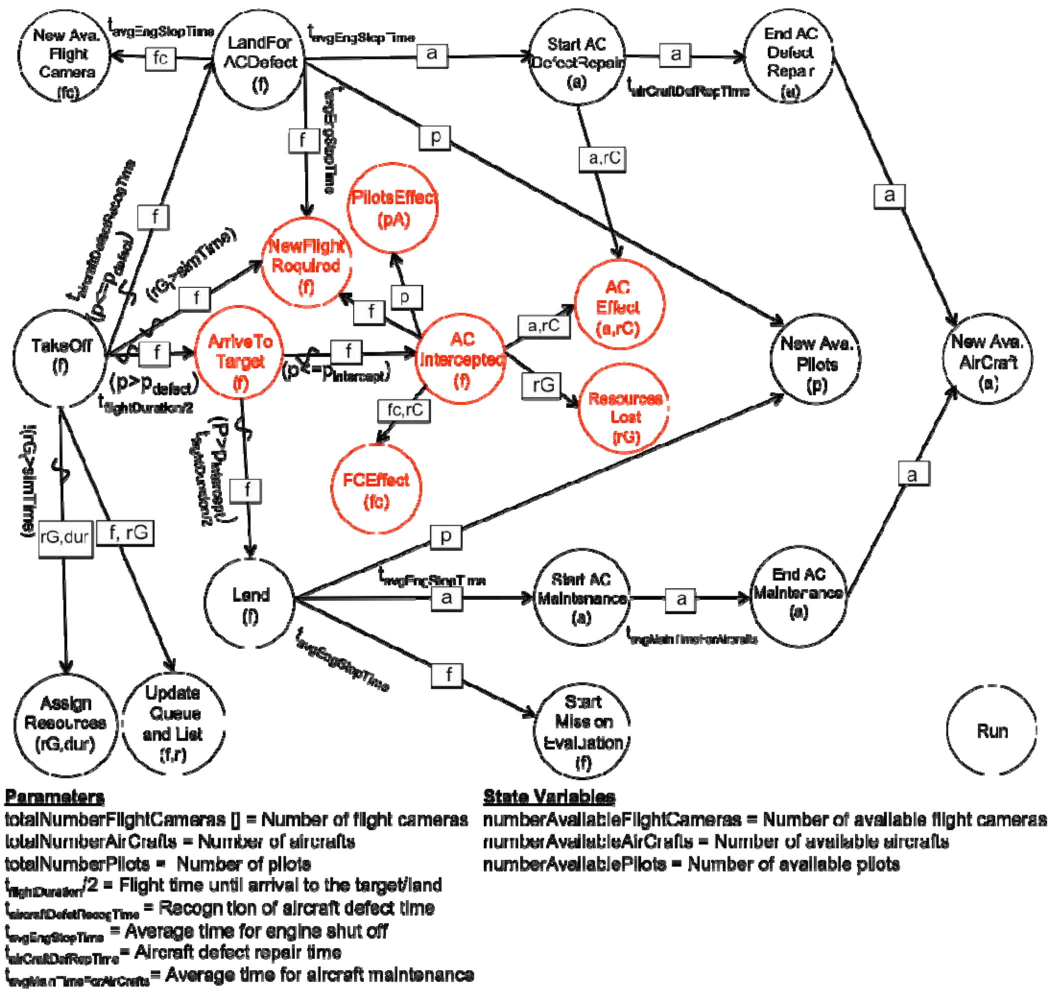


Figure 22. Conf.: RF-4 / Sit.: War - Flights Executor Event Graph

Figure 23 shows the event graph of the ReportsGenerator component. Event in red is a changed event specific to the war scenario. The rest of the events are the same as in the peace scenario. The FCEffect event triggers the UpdateFlightsForFCDefect event of FlightsPlanner component.

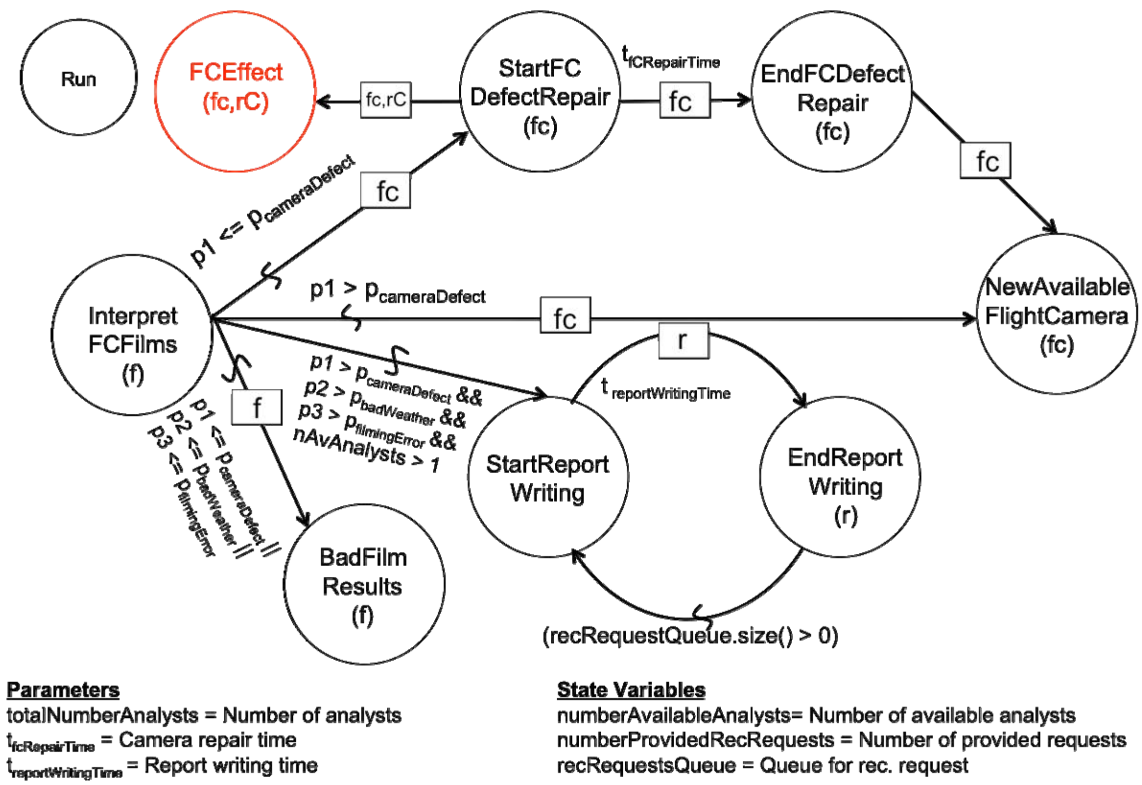


Figure 23. Conf.: RF-4 / Sit.: War - Reconnaissance Request Report Generator Event Graph

2. Configuration of the F-16

a. Situation: Peace

Figure 24 shows the main components of the F-16 configuration in the peace situation model. There are five main components in the model: RecSquadronWorkflow, RecRequestCreator, FlightsPlanner, FlightsExecutor and ReportsGenerator. These main components are independent of each other, but are connected by using listener and adapter patterns to make the whole model run accurately. Each main component is explained below in detail.

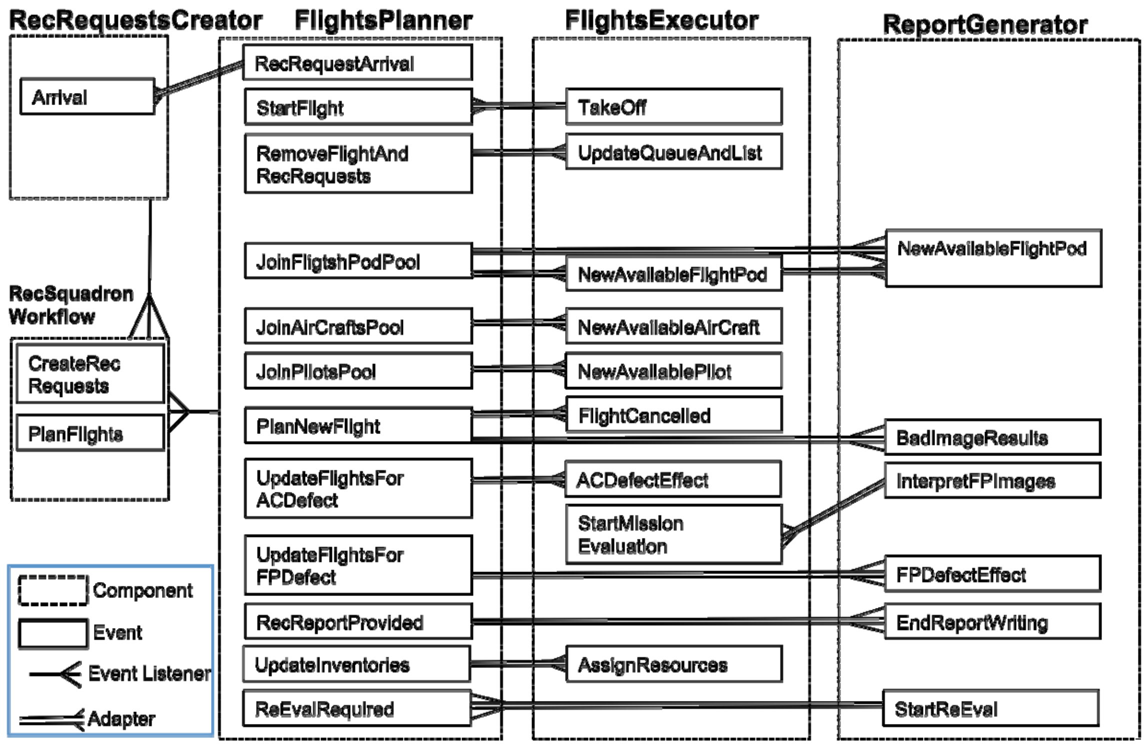


Figure 24. Conf.: F-16 / Sit.: Peace - Components with Listener and Adapter Patterns

The RecSquadronWorkflow component of the F-16 configuration peace situation scenario is same as in the RF-4 configuration peace situation scenario.

Figure 25 shows the event graph of the RecRequestsCreator component. The RecRequestsCreator component of the F-16 configuration peace situation scenario is almost the same as in the RF-4 configuration peace situation scenario. RecRequestsCreator component of F-16 configuration peace situation scenario do not have RemovefromArchive events, and they use the FilmingType class (which has updatedRepRequired and addToArchive extra fields) instead of CameraType class as one of the fields for the RecRequest class.

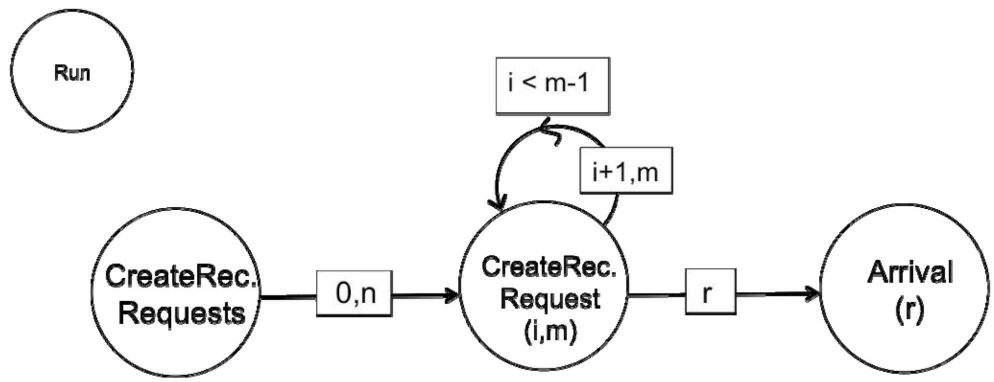


Figure 25. Conf.: F-16 / Sit.: Peace - Reconnaissance Requests Creator Event Graph

Figure 26 shows the event graph of the FlightsPlanner component. The FlightsPlanner component plans reconnaissance flights dynamically based on availability of resources such as aircrafts, pilots, and pods (cameras). During flight planning it combines reconnaissance requests that have adjacent targets into one flight and calculates flight durations. FlightsPlanner also records successful reconnaissance request mission target locations to the relevant target location archive, and removes obsolete target locations from the relevant target location archive. FlightsPlanner keeps track of:

- Aircraft, pilot, and camera inventories.
- Planned flights list.
- Two separate queues for day and night reconnaissance requests.
- Two separate archives (optic and infrared) for storing target locations filmed by reconnaissance missions.

In the RecRequestArrival event the arrival time of reconnaissance request (r) is stamped, and then the *numberRecRequestArrivals* state variable is incremented by one. If the reconnaissance request does not require an up-to-date image of the target and the relevant target location archive (aI) contains the target of reconnaissance request (Pt), the RecRequestArrival event schedules the ReEvalRequired event with a $t_{timeBetArrivalAndWorkingStart}$ delay. Otherwise the reconnaissance request (r) is added to the relevant queue and the RecRequestArrival event schedules the RemoveRecRequest event with $t_{dueDate\ -\ simTime}$ delay. Each reconnaissance request should be responded to before its due date passes. The RemoveRecRequest event removes reconnaissance requests from the relevant queue and increments the *numberRemovedRecRequests* state variable by one.

If the target of the reconnaissance request (Pt) is going to be added to the relevant target location archive (aI), the RecReportProvided event schedules the AddToArchive event and cancels the RemoveRecRequest event for the relevant reconnaissance request (r). The RecReportProvided event also updates the *totalTimeAtWorkFlow* state variable.

If the relevant target location archive (aI) contains the target location (Pt), the AddToArchive event cancels the RemoveFromArchive event for that target location. Otherwise, the target location (Pt) is added to the relevant target location archive (aI). The AddToArchive event also schedules the RemoveFromArchive event with $t_{reportUptoDateTime}$ delay for same target location (Pt). The RemoveFromArchive event removes the target location (Pt) from relevant target location archive (aI).

The PlanFlights event makes the main flight planning based on availability of cameras, aircrafts and pilots within daily flight hours for both day and night flights. During flight planning it combines reconnaissance requests that have adjacent targets into one flight (f) and calculates flight durations. The PlanFlights event schedules the StartFlight events for planned flights with relevant $t_{plannedFlightTime - simTime}$ delays.

The duration of a flight is calculated the same as in the RF-4 configuration peace situation model.

The UpdateFlightsForFPDefect event first cancels the flights (f) which cannot be completed at their scheduled times because of camera defect(s) and tries to plan new flights for those canceled ones by using the planNewFlight method.

The UpdateFlightsForACDefect event first cancels the flights (f) which cannot be completed at their scheduled times because of aircraft defect(s) and tries to plan new flights for those canceled ones by using the planNewFlight method.

The PlanNewFlight event tries to plan a new flight for its argument flight (f) by using the planNewFlight method. It also adds the reconnaissance requests of the cancelled or unsuccessful flight to the relevant queue.

The planNewFlight private method tries to plan a new flight (nF) for a cancelled or unsuccessful flight by using available resources (cameras, aircraft, and pilot). If a new flight can be planned it schedules the StartFlight event with a $t_{plannedFlightTime - simTime}$ delay and updates the flights list.

The JoinFlightPodsPool event updates cameras' availability times. The JoinPilotPool event updates pilots' availability times. The JoinAirCraftsPool event updates aircraft availability times.

The UpdateInventories event updates inventories of cameras, pilots, and aircraft after an aircraft takes off for a reconnaissance mission.

The RemoveFlightAndRecRequests event updates the flights list and relevant reconnaissance request queue after an aircraft takes off for a reconnaissance mission.

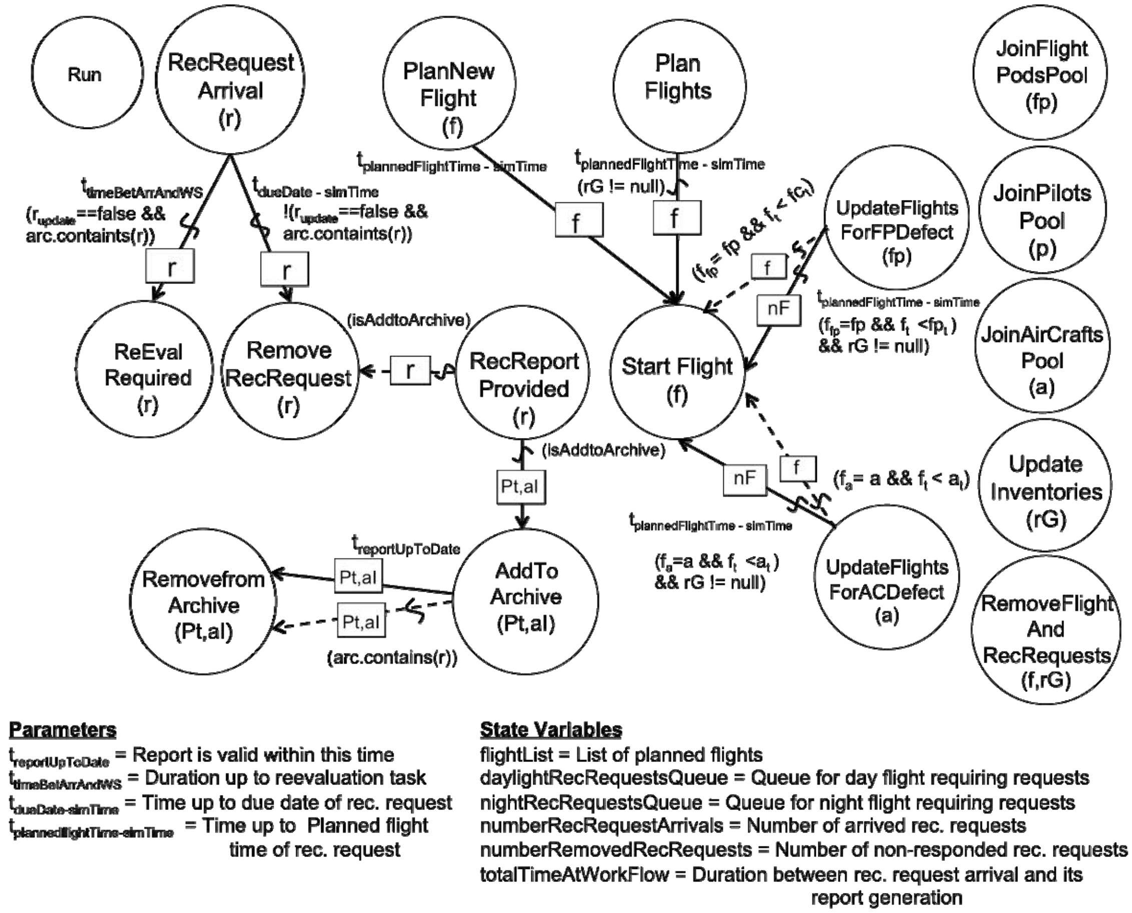


Figure 26. Conf.: F-16 / Sit.: Peace - Reconnaissance Flights Planner Event Graph

Figure 27 shows the event graph of the FlightsExecutor component. The FlightsExecutor component deals with reconnaissance flights, after flight operations, and most of the state variable changes in the whole model.

First, the TakeOff event schedules the UpdateQueueAndList event with the relevant flight (f) and resource group (camera, aircraft, and pilot) parameters.

Second, the TakeOff event schedules the AssignResources event with resource group (rG) parameter. Unless the simulation time is less than the availability times of any resource group component (camera, aircraft and pilot), the TakeOff event decrements relevant *numberAvailableFlightCameras, numberAvailableAirCrafts* and *numberAvailablePilots* state variables by one.

Third, the TakeOff event generates a random number for aircraft defect probability (p). If p is less than or equal to user input for aircraft defect probability, the TakeOff event schedules LandForACDefect by passing the relevant flight (f) with a $t_{aircraftDefectRecogTime}$ delay. If p is greater than the user input for aircraft defect probability, then the TakeOff event schedules the Land event by the passing relevant flight (f) with a $t_{flightDuration}$ delay and generates a random number for data link defect probability (q). If q is less than or equal to user input for data link defect probability, the TakeOff event schedules the StartMissionEvaluation event by passing the relevant flight (f) and true with a $t_{flightDuration + avgEngStopTime}$ delay. If q is greater than user input for data link defect probability, the TakeOff event schedules the StartDLCom event by passing the relevant flight (f) with a $t_{flightDuration - landDLCom}$ delay.

Finally, if the simulation time is less than the availability times of any resource group component (camera, aircraft, and pilot) the TakeOff event schedules the FlightCancelled event by passing the relevant flight (f) as a parameter.

The Land event schedules the StartACMaintenance event by passing the relevant aircraft (a) with a $t_{avgEngStopTime}$ delay. Then it schedules the NewAvailablePilot event by passing the relevant pilot (p) with $t_{restTimeForPilots}$ delay.

The StartDLCom event schedules the StartMissionEvaluation event by passing relevant flight (f) and false with $t_{DLComTime}$ delay.

The LandForACDefect event schedules four events. First, it schedules the NewAvailableFlighPod event by passing the relevant pod (fp) with a $t_{avgEngStopTime}$ delay. Second, it schedules the NewAvailablePilot event by passing the relevant pilot (p). Third, it schedules the StartACDefectRepair event by passing relevant aircraft (a) with a $t_{avgEngStopTime}$ delay. Fourth, it schedules the FlightCancelled event by passing relevant flight (f) with a $t_{avgEngStopTime}$ delay.

The StartACDefectRepair event updates aircraft inventory. Then it schedules the ACDefectEffect event. Finally, it schedules the EndACDefectRepair event by passing relevant aircraft (a) with a $t_{airCraftDefRepTime}$ delay.

The EndACDefectRepair event schedules the NewAvailableAirCraft event by passing relevant aircraft (a). The StartACMaintenance event updates aircraft inventory. Then it schedules the EndACMaintenance event by passing relevant aircraft (a) with $t_{avgMaintTimeForAirCrafts}$ delay. The EndACMaintenance event schedules the NewAvailableAirCraft event by passing relevant aircraft (a).

The NewAvailableFlightPod event increments the relevant *numberAvailableFlightPods* state variable by one. The NewAvailableAirCraft event increments the *numberAvailableAirCrafts* state variable by one. The NewAvailablePilot event increments the *numberAvailablePilots* state variable by one.

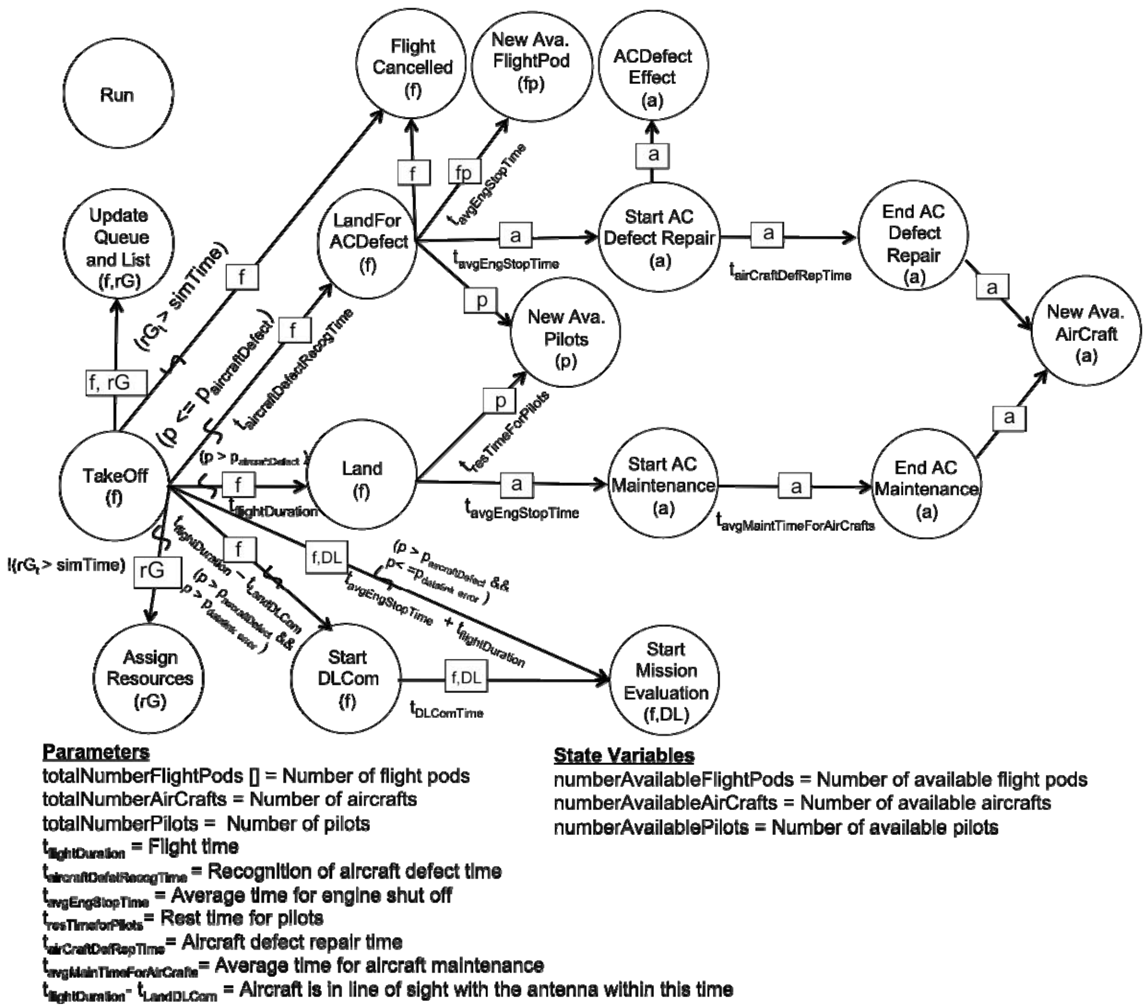


Figure 27. Conf.: F-16 / Sit.: Peace - Reconnaissance Flights Executor Event Graph

Figure 28 depicts the event graph of the ReportsGenerator component. The ReportsGenerator component deals with the operations after successful reconnaissance flights, which are interpretation of the images and writing reconnaissance reports based on their requirements.

The InterpretFPImages event can schedule four different events. First, it generates a random number for camera defect probability (p1); if this number is less than or equal to user input for relevant camera defect probability, it schedules the StartFPDefectRepair event by passing relevant pod (fp). Second, if p1 is greater than the user input for relevant camera defect probability, then the InterpretFPImages event schedules the StartFPMaintenance event by passing relevant pod (fp).

Third, based on generated random numbers, if there is a camera defect or bad weather condition, then the InterpretFPImages event schedules the BadImageResults event by passing relevant flight (f). Fourth, based on generated random numbers, if there is no camera defect and no bad weather condition, then the InterpretFPImages event generates random report writing times for reconnaissance requests in the relevant flight (f) and adds them to the reconnaissance requests queue. If there is available image analyst, the InterpretFPImages event schedules the StartReportWriting event.

The StartReEval event adds the reconnaissance request (r) to the reconnaissance requests queue. If there is available image analyst, it schedules the StartReportWriting event. The StartFPMaintenance event updates camera inventory. Then it schedules the EndFPMaintenance event by passing the relevant pod (fp) with $t_{avgMaintTimeForFPs}$ delay.

The EndFPMaintenance event schedules the NewAvailableFlightPod event by passing relevant pod (fp).

The StartFPDefectRepair event updates camera inventory. Then it schedules the FPDeffectEffect event by passing the relevant pod (fp). Finally, the StartFPDefectRepair event schedules the EndFPDefectRepair event by passing relevant pod (fp) with $t_{flightPodRepairTime}$ delay. The EndFPDefectRepair event schedules the NewAvailableFlightPod event by passing relevant pod (fp).

The StartReportWriting event takes the first reconnaissance request (r) in the queue, removes it from the queue and schedules the EndReportWriting event by passing that reconnaissance request (r) with $t_{reportWritingTime}$ delay. The StartReportWriting event also decrements the *numberAvailableAnalysts* state variable by one.

The EndReportWriting event increments the *numberProvidedRecRequests* and *numberAvailableAnalysts* state variables by one. If there is any reconnaissance request in the queue waiting for the report writing process, the EndReportWriting event schedules the StartReportWriting event.

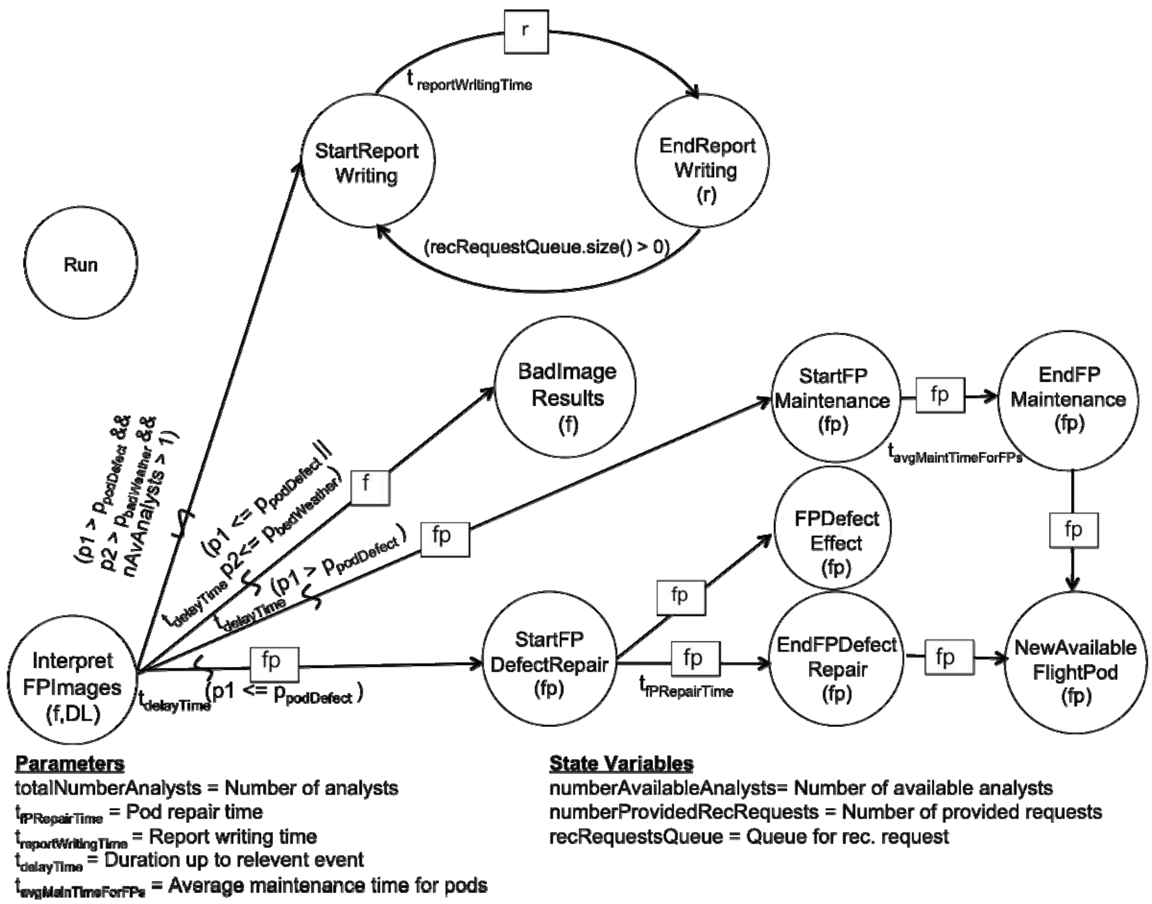


Figure 28. Conf.: F-16 / Sit.: Peace - Reconnaissance Reports Generator Event Graph

b. Situation: War

Figure 29 shows the main components of the RF-4 configuration in a war situation model. There are five main components in the model like peace situation:

RecSquadronWorkflow, RecRequestCreator, FlightsPlanner, FlightsExecutor and ReportsGenerator. Even though, during the peace time, training is done according to "Train like you fight" principle, there are significant changes in the war situation. Events in red are either new or changed events specific to the war scenario. The rest of the events are the same as in the peace scenario. Each main component is explained below in detail.

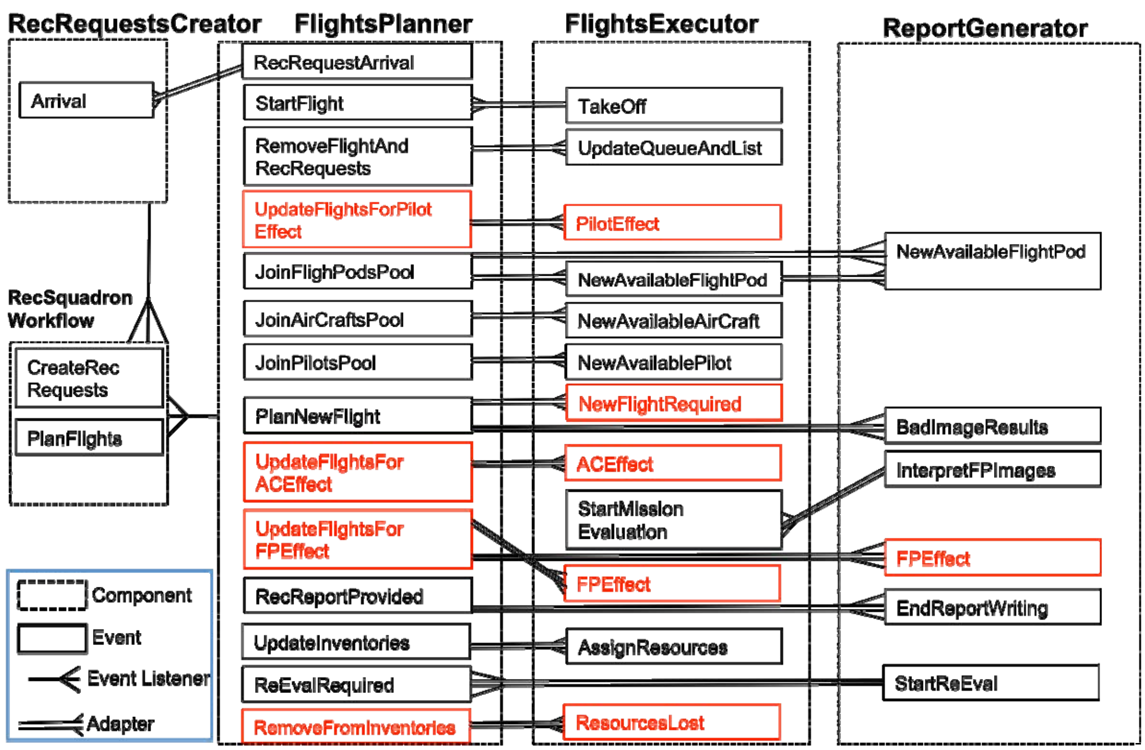


Figure 29. Conf.: F-16 / Sit.: War - Components with Listener and Adapter Patterns

RecSquadronWorkflow component of F-16 configuration war situation scenario is same as RF-4 configuration peace situation scenario. Only the value for $t_{planflightsTime}$ time delay is incremented two hours for more flight hours.

RecRequestsCreator component of F-16 configuration war situation scenario is same as F-16 configuration peace situation scenario. Only the due dates given to reconnaissance requests are different. In peace scenario duration between arrival and due date of each reconnaissance request is random but in war scenario this duration is just one day.

Figure 30 shows the event graph of the FlightsPlanner component. Events in red are either new or changed events specific to the F-16 configuration war scenario.

The UpdateFlightsForFPEffect event first cancels the flights which cannot be completed at their scheduled times because of either camera defect(s) or camera loss (due to aircraft interception) and then tries to plan new flights for those canceled ones by using the planNewFlight method.

The UpdateFlightsForACEffect event first cancels the flights which cannot be completed at their scheduled times because of either aircraft defect(s) or aircraft loss (due to aircraft interception) and then tries to plan new flights for those canceled ones by using the planNewFlight method.

The UpdateFlightsForPilotEffect event first cancels the flights which cannot be completed at their scheduled times because of pilot loss (due to aircraft interception), and then tries to plan new flights for those canceled ones by using the planNewFlight method.

The RemoveFromInventories event schedules the StopSimulation event when either there is no aircrafts, cameras or pilots left, which means the reconnaissance squadron cannot operate.

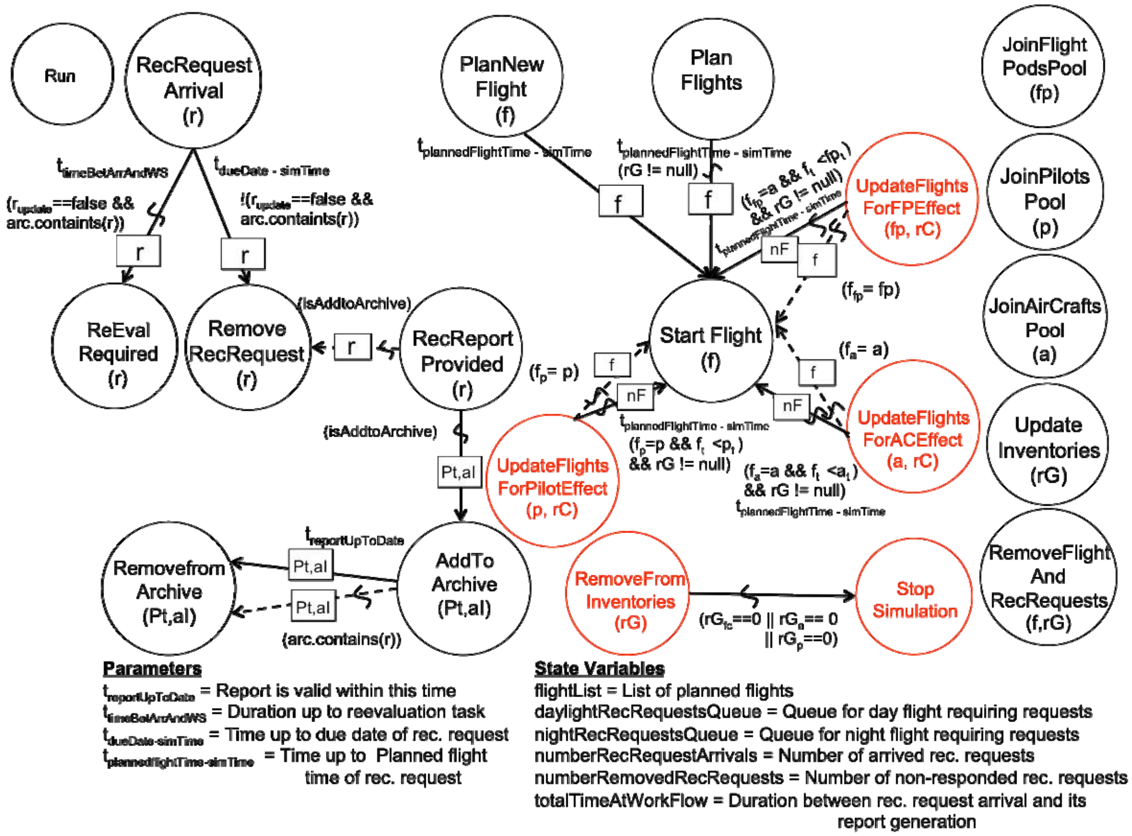


Figure 30. Conf.: F-16 / Sit.: War - Reconnaissance Flights Planner Event Graph

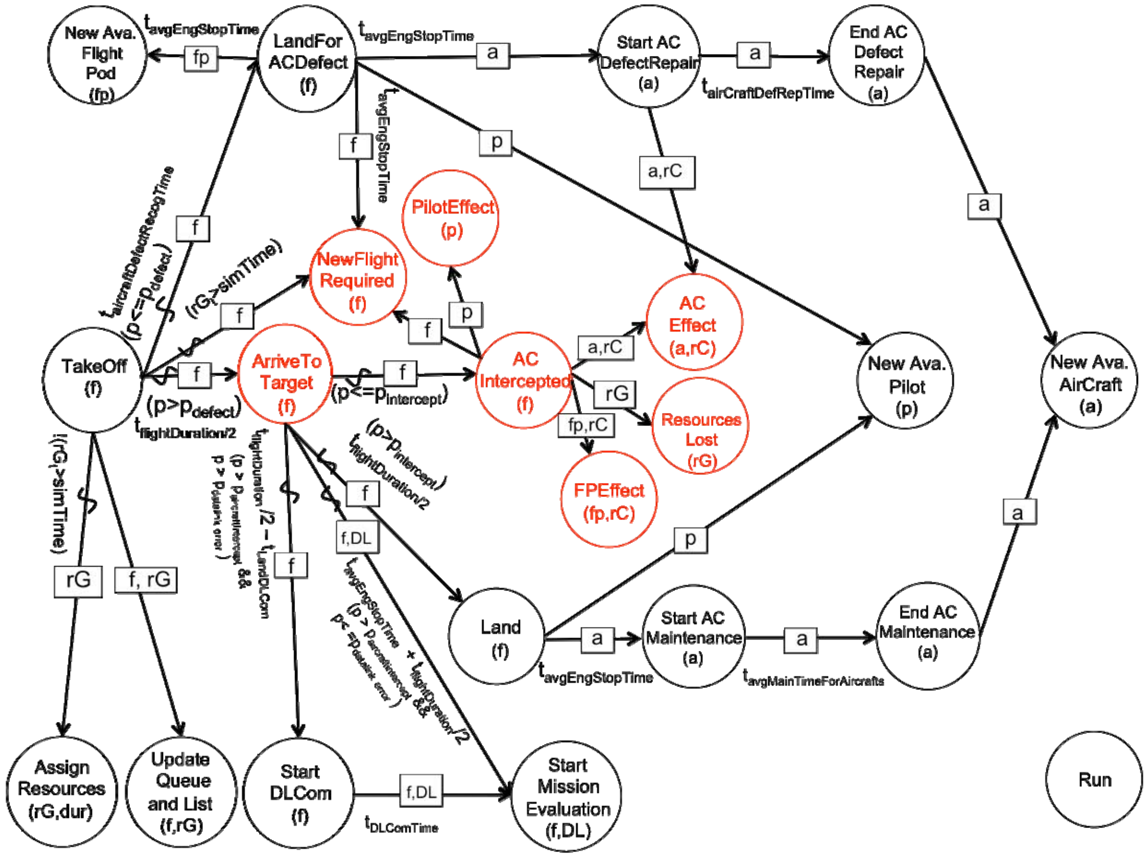
Figure 31 shows the event graph of the FlightsExecutor component. Events in red are either new or changed events specific to the F-16 configuration war scenario. The rest of the events are the same as in the F-16 configuration peace scenario except the probability of reconnaissance aircrafts' interception by enemy which affects the entire reconnaissance cycle due to lost resources such as pilots, aircrafts and cameras.

The TakeOff event generates a random number for aircraft defect probability (p). If p is greater than the user input for aircraft defect probability, then the TakeOff event schedules ArriveToTarget event by passing relevant flight (f) with $t_{flightDuration/2}$ delay. If the simulation time is less than availability times of any resource group component (camera, aircraft and pilots) the TakeOff event schedules the NewFlightRequired event by passing relevant flight (f).

A random number for aircraft intercept probability (p) is generated and then compared to the user input for aircraft intercept probability. If the aircraft intercept probability (p) is less than or equal to the user threshold, then the ArriveToTarget event schedules the ACIntercepted event. If not, it schedules three events. First, the ArriveToTarget event schedules the Land event with $t_{flightDuration/2}$ delay. Second, it schedules the StartDLCom event if the data link error (p) is greater than the user threshold $p_{datalinkError}$, in $t_{flightDuration}/2$ - $t_{LandDLCom}$ time delay. Finally, it schedules StartMissionEvaluation if the data link error (p) is less than or equal to the user threshold, with $t_{avgEngStopTime}$ + $t_{flightDuration}/2$ time delay.

The ACIntercepted event schedules five events. First, it schedules the ResourceLost event by sending pertinent resource group (rG). Second, it schedules the NewFlightRequired event by sending relevant flight (f). Third, it schedules the ACEffect event by sending pertinent aircraft (a) and reason code (rC). The reason code differentiates aircraft interception from aircraft defects. Fourth, it schedules the FPEffect event by sending pertinent flight pod (fp) and reason code (rC). Finally, the PilotsEffect event is scheduled by sending related pilot (p).

The LandForACDefect event schedules the NewFlightRequired event by passing relevant flight (f) with $t_{averageEngineStopTime}$ delay.



Parameters

totalNumberFlightPods [] = Number of flight pods
totalNumberAirCrafts = Number of aircrafts
totalNumberPilots = Number of pilots
$t_{flightDuration}/2$ = Flight time until target/land
$t_{aircraftDefetRecogTime}$ = Recognition of aircraft defect time
$t_{avgEngStopTime}$ = Average time for engine shut off
$t_{resTimeforPilots}$ = Rest time for pilots
$t_{airCraftDefRepTime}$ = Aircraft defect repair time
$t_{avgMainTimeForAirCrafts}$ = Average time for aircraft maintenance
$t_{flightDuration}/2 - t_{LandDLCom}$ = Aircraft is in line of sight with the antenna within this time
$t_{DLComTime}$ = Average data comunicaton time
$t_{avgEngStopTime} + t_{flightDuration}/2$ = Mission evaluation start time if Datalink doesn't work

State Variables

numberAvailableFlightPods = Number of available flight pods
numberAvailableAirCrafts = Number of available aircrafts
numberAvailablePilots = Number of available pilots

Figure 31. Conf.: F-16 / Sit.: War - Reconnaissance Flights Executor Event Graph

Figure 32 shows the event graph of the ReportsGenerator component. Event in red is a changed event specific to the war scenario. The rest of the events are the same as in the peace scenario. The FPEffect event triggers the UpdateFlightsForFPDefect event of FlightsPlanner component.

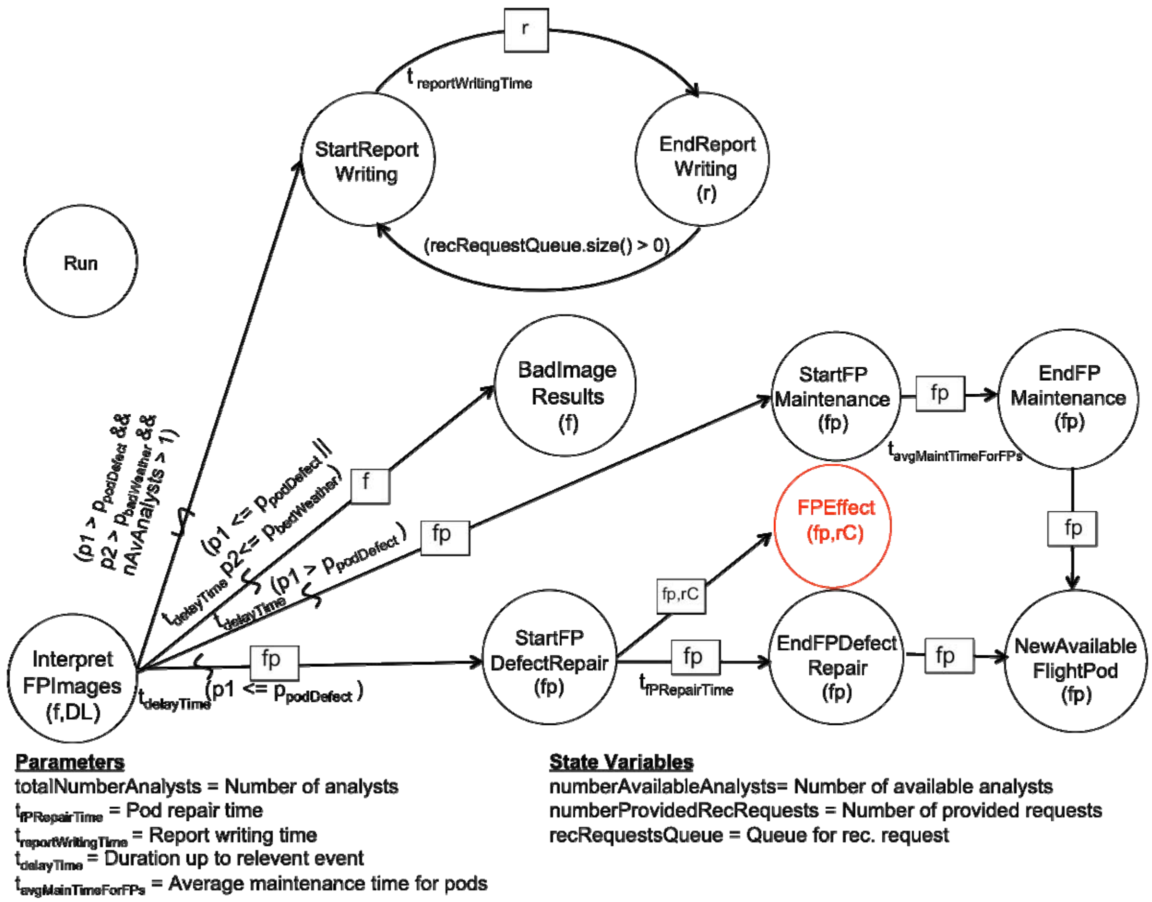


Figure 32. Conf.: F-16 / Sit.: War - Reconnaissance Report Generator Event Graph

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IV. DESIGN OF EXPERIMENTS

> Simulation analysts and their clients might seek to (i) develop a basic understanding of a particular simulation model or system, (ii) find robust decisions or policies, or (iii) compare the merits of various decisions or policies (Kleijnen et al., 2005).

Simulation experiments are needed to provide solutions for these aims listed above that are all related to our research questions.

There are many classic experimental designs. When the number of factors is large, more effective and efficient designs are required. Sanchez (2008) says, “A well-designed experiment allows the analyst to examine many more factors than would otherwise be possible, while providing insights that cannot be gleaned from trial-and-error approaches or by sampling factors one at a time.” One more benefit of well-designed experiments is getting insight and information in a relatively short amount of time (Sanchez, 2008).

A. INPUT FACTORS

One of the initial steps an experimenter must take to design a good experiment is identify the experimental factors. Factors are the input (or independent) variables that might have some impact on responses (i.e., experimental outputs). Generally, an experiment might have many factors, each of which might get a variety of values, called levels of the factor in DOE (Design of Experiments) terminology. Identifying which of the factors are really important for which responses, and which are not and can thus be dropped from further consideration, greatly reduces the experimental effort and simplifies the task of interpreting the results of experiment (Sanchez, 2008).

All of the input factors (decision and noise factors) of interest for different scenarios of Reconnaissance Squadron Workflow are shown in Table 2 and described below. These factors are anticipated, *a priori*, to be the factors with the greatest influence the Reconnaissance Squadron Workflow and so on the measures of effectiveness. Input and distributional parameters are based on authors’ experience, and are used to generate the minimum and maximum levels of each input factor for this study. Values of the input factors used in each experiment are presented in the Appendix.

Num		Parameters	Peace	War	Peace	War
			RF-4	RF-4	F-16	F-16
1	Decision	numT1Pods			•	•
2	Decision	numT2Pods			•	•
3	Decision	numT1Cam	•	•		
4	Decision	numT2Cam	•	•		
5	Decision	numT3Cam	•	•		
6	Decision	numT4Cam	•	•		
7	Decision	numT5Cam	•	•		
8	Decision	numACs	•	•	•	•
9	Decision	numPilots	•	•	•	•
10	Decision	numAnalysts	•	•	•	•
11	Noise	modeNumReq	•	•	•	•
12	Noise	halfDistNumReq	•	•	•	•
13	Noise	modeHighPriDueDays	•		•	
14	Noise	halfDistHighPriDueDays	•		•	
15	Noise	priDueDaysLowOverHighRatio	•		•	
16	Noise	opImgTProb	•	•	•	•
17	Noise	t1CamsDefProb	•	•		
18	Noise	t2CamsDefProb	•	•		
19	Noise	t3CamsDefProb	•	•		
20	Noise	t4CamsDefProb	•	•		
21	Noise	t5CamsDefProb	•	•		
22	Noise	t1PodsDefProb			•	•
23	Noise	t2PodsDefProb			•	•
24	Noise	aCDefProb	•	•	•	•
25	Noise	pilotFilErProb	•	•		
26	Noise	badWeatConProb	•	•	•	•
27	Noise	upRepReqProb			•	•
28	Noise	dataLinkDefProb			•	•
29	Noise	verAngTProb			•	•
30	Noise	nightFlightProb			•	•
31	Noise	aCInterceptProb		•		•
32	Noise	modeACRepTime	•	•	•	•
33	Noise	halfDistACRepTime	•	•	•	•
34	Noise	modePodsRepTime			•	•
35	Noise	halfDistPodsRepTime			•	•
36	Noise	modeTacCamsRepTime	•	•		
37	Noise	halfDistTacCamsRepTime	•	•		
38	Noise	camsRepTimeStraOverTacRatio	•	•		
Total			27	25	23	21

Table 2. Input Factors used in the Models

1. Number of Type 1 Pods

Type 1 pods are used for day and night flights on the F-16 aircrafts. Their image type is both optic and IR, and the angle type is vertical.

2. Number of Type 2 Pods

Type 2 pods are used for day and night flights on the F-16 aircrafts. Their image type is both optic and IR, and the angle type is oblique.

3. Number of Type 1 Cameras

Type 1 cameras are used for daytime flights on the RF-4 aircrafts. Their image type is optic and the angle type is vertical.

4. Number of Type 2 Cameras

Type 2 cameras are used for night flights on the RF-4 aircrafts. Their image type is optic and the angle type is vertical.

5. Number of Type 3 Cameras

Type 3 cameras are used for daytime flights on the RF-4 aircrafts. Their image type is optic and the angle type is vertical.

6. Number of Type 4 Cameras

Type 4 cameras are used for night flights on the RF-4 aircrafts. Their image type is infrared and the angle type is vertical.

7. Number of Type 5 Cameras

Type 5 cameras are used for daytime flights on the RF-4 aircrafts. Their image type is optic and the angle type is oblique.

8. Number of Aircraft

There are two types of aircraft used for different scenarios: the RF-4 and F-16.

9. Number of Pilots

For flight, the RF-4 aircraft requires two pilots and the F-16 aircraft requires one pilot to do reconnaissance missions.

10. Number of Image Analysts

Image analysts interpret and evaluate films when the films arrive. They do this job until all of the films in the queue are evaluated.

11. Number of Reconnaissance Requests

This input factor corresponds to number of reconnaissance requests arriving to the squadron every day. A symmetric triangular distribution is used for this input factor.

12. Half Distance Number of Reconnaissance Requests

This input factor is used for calculating the number of reconnaissance requests triangular distribution's minimum and maximum values by subtracting from and adding to the number of reconnaissance requests, respectively.

13. Number of Due Days for Reconnaissance Requests

They are five types of priorities for reconnaissance requests: "LOWEST," "LOW," "DEFAULT," "HIGH," and "HIGHEST." Priorities of reconnaissance requests are generated randomly, by using a discrete integer random variable. In our model, "HIGH" or "HIGHEST" priority reconnaissance requests are high priority and the other ones are low priority reconnaissance requests. Two symmetric triangular distributions are used to assign the mode of the number of due days for high and low priority reconnaissance requests in peace situation scenarios. In war situation scenarios, the number of due days for all reconnaissance requests is always one.

14. Half Distance Number of Due Days for Reconnaissance Requests

This input factor is used for calculating the number of due days for reconnaissance requests triangular distribution's minimum and maximum values by subtracting from and adding to the mode of the number of due days for reconnaissance requests.

15. Ratio of Low Priority Due Days Over High Priority Due Days

This input factor is used to calculate due days for low priority reconnaissance requests in both the RF-4 and F-16 configurations and only in peace situation scenarios. It is used as a scalar multiplier. For example, the mode of the number of due days for low priority reconnaissance requests is equal to this scalar factor multiplied by the mode of the number of due days for high priority requests. A similar process is used to compute the half distance number of due days for low priority reconnaissance requests.

16. Optic Image Type Probability

A reconnaissance request's image type can be either optic or infrared. A discrete integer random variable whose parameters are set by this input factor is used to assign reconnaissance requests' image types.

17. Type 1, 2, 3, 4 and 5 Cameras' Defect Probabilities

Different types of cameras have different, or sometimes nearly the same, defect probabilities. Discrete Bernoulli random variables whose parameters are set by using these input factors are used to decide whether or not there is/are camera defect(s) after reconnaissance missions.

18. Type 1, 2 Pods' Defect Probabilities

Different types of pods have different, or sometimes nearly the same, defect probabilities. Discrete Bernoulli random variables whose parameters are set by using these input factors are used to decide whether or not there is/are pod defect(s) after reconnaissance missions.

19. Aircraft Defect Probabilities

The RF-4 aircraft has a higher defect probability than the F-16 aircraft. Discrete Bernoulli random variables whose parameters are set by using these input factors are used to decide whether there is/are aircraft defect(s) in a small amount of time after takeoff for a reconnaissance mission.

20. Pilot Filming Error Probability

A discrete Bernoulli random variable whose parameter is set by using this input factor is used to decide whether there is pilot filming error during target filming.

21. Bad Weather Condition Probability

A discrete Bernoulli random variable whose parameter is set by using this input factor is used to decide whether there is a bad weather condition during target filming.

22. Requiring Update Reconnaissance Mission Probabilities

A discrete Bernoulli random variable whose parameter is set by using this input factor is used to decide whether reconnaissance requests can be responded to from previous missions or not. This parameter is used only in the F-16 configuration models.

23. Data Link Defect Probability

In the F-16 configuration models, target imagery can be downloaded using a data link. The corresponding input factor is a discrete Bernoulli random variable that is used to decide whether or not a data link is working.

24. Requiring Vertical Angle Reconnaissance Mission Probability

Reconnaissance requests can require vertical or oblique imagery. This parameter is used for deciding which requests are vertical or oblique.

25. Requiring Night Flight Reconnaissance Mission Probabilities

In the F-16 configuration models, IR imagery requiring requests can be flown both in day and night hours. This parameter is used for deciding which IR imagery requiring reconnaissance missions are flown during night flight time or during day flight time.

26. Aircrafts' Interception Probabilities

The RF-4 aircraft has a higher interception probability than the F-16 aircraft. Discrete Bernoulli random variables whose parameters are set by using these input factors are used to decide whether the aircraft was intercepted during entrance to the target area for a reconnaissance mission.

27. Aircraft Repair Time

The RF-4 aircraft has a different defect repair time than the F-16 aircraft. These defect repair times are short in war situation scenarios. A symmetric triangular distribution is used to assign aircraft defect repair time after recognized aircraft defect(s).

28. Half Distance Aircraft Repair Time

This input factor is used for calculating the aircraft repair time triangular distribution's minimum and maximum values by subtracting from and adding to the aircraft repair time.

29. Pods' Repair Times

Type 1 and Type 2 pods used on F-16 aircrafts have similar defect repair times. Two symmetric triangular distributions are used to generate pod defect repair times after recognized pod defect(s).

30. Half Distance Pod's Repair Time

This input factor is used for calculating the pod repair time triangular distribution's minimum and maximum values by subtracting from and adding to the pod repair time.

31. Tactic Camera Repair Time

Type 1, 2, 3 and 4 cameras (tactic) used on RF-4 aircrafts have a different defect repair time than Type 5 (strategic) camera used on RF-4 aircrafts. Two symmetric triangular distributions are used to generate camera defect repair times after recognized camera defect(s).

32. Half Distance Tactic Camera Repair Time

This input factor is used for calculating tactic camera repair time triangular distribution's minimum and maximum values by subtracting from and adding to the tactic camera repair time.

33. Ratio of Strategic Camera Repair Time Over Tactic Camera Repair Time

This input factor is used to calculate the repair time of strategic cameras in RF-4 configurations. It is used as a scalar with tactic camera repair time and half distance tactic camera repair time input factors.

B. PERFORMANCE MEASURES

As previously discussed, there are two performance measures:

1. Average Time at Workflow for Responded Reconnaissance Requests

This MoE shows the mean time elapsed after the creation of a reconnaissance request to the provided report for that reconnaissance request. This value should be small for an effective Reconnaissance Squadron Workflow configuration.

2. Removed Over Arrived Reconnaissance Requests Ratio

This MoE shows the ratio of reconnaissance requests not responded to (for reasons such as due date and available resources) over total arrived reconnaissance requests. This value also should be small for an effective Reconnaissance Squadron Workflow configuration.

C. DESIGN

A design is a matrix where every column corresponds to a factor, and the entries within the column are settings for this factor. Each row represents a particular combination of factor levels and is called a design point. If the row entries correspond to the actual settings that will be used, these are called natural levels. Table 3 shows a simple design in natural levels that could be used for an experiment involving two factors.

	Natural Levels	
Design Point	X_1	X_2
1	16	20
2	18	20
3	16	22
4	18	22
5	16	24
6	18	24

Table 3. Experimental Design in Natural Levels [After (Sanchez, 2008)]

As Sanchez (2008) says, "selecting a design is an art, as well as a science." The number of factors and the mix of different factor types (binary, qualitative or discrete with a limited number of levels, discrete with many levels, or continuous) play important roles for experimental designs. A desirable property for an experimental design is orthogonality, which means the pairwise correlation between any two columns (factors) is equal to zero. An orthogonal design makes the analysis of the output (Y's) we get from running our experiment simple, because estimates of the factors' effects and their contribution to the explanatory power (R^2) of the regression metamodel will not depend on what other explanatory terms are present in the regression metamodel (Sanchez, 2008).

Two designs (one for decision and one for noise factors) were generated for each scenario (model) by using "Generating and Improving Orthogonal Designs by Using Mixed Integer Programming tool" coded by Helcio Vieira Junior (see also Vieira et al., 2010). These two designs were crossed by using Paul Sanchez's *cross.rb* program to generate designs for each scenario. Each scenario's crossed design has 5,000 design points which gave them much of the space-filling and orthogonality properties of factorial designs with fine grids, but requiring orders of magnitude less sampling. Figure 33 shows a correlation table and a scatter-plot matrix built in JMP version 8.0 (SAS Institute Inc., 2008) software for some of the input factors of the RF-4 configuration peace situation scenario. As seen from the figure, crossed design is notably good at space-filling property and represents many combinations of input factors. It also shows that pairwise correlations of input factors are almost zero.

Multivariate

Correlations

	numT1Cams	numT2Cams	numT3Cams	numT4Cams	numT5Cams	numACs	numPilots	numAnalysts
numT1Cams	1.0000	-0.0002	0.0000	-0.0016	-0.0000	-0.0012	-0.0030	-0.0006
numT2Cams	-0.0002	1.0000	0.0000	0.0038	-0.0000	0.0002	-0.0013	0.0013
numT3Cams	0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	0.0031	0.0000
numT4Cams	-0.0016	0.0038	0.0000	1.0000	-0.0000	0.0016	0.0040	0.0030
numT5Cams	-0.0000	-0.0000	0.0000	-0.0000	1.0000	0.0000	0.0000	-0.0000
numACs	-0.0012	0.0002	0.0000	0.0016	0.0000	1.0000	0.0030	0.0006
numPilots	-0.0030	-0.0013	0.0031	0.0040	0.0000	0.0030	1.0000	0.0001
numAnalysts	-0.0006	0.0013	0.0000	0.0030	-0.0000	0.0006	0.0001	1.0000

The correlations are estimated by Pairwise method.

Scatterplot Matrix

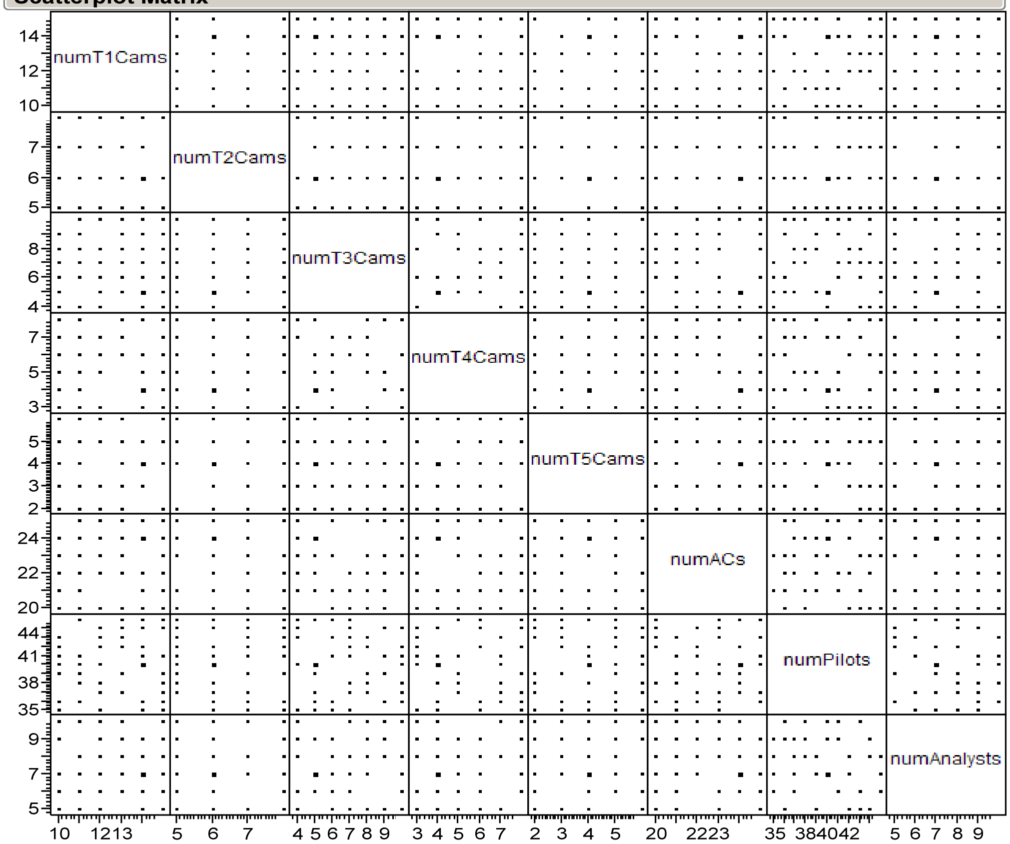

Figure 33. Correlations and Scatter-plot Matrix

D. SCENARIO REPLICATION

Simulation models come in many flavors. There are deterministic simulations (e.g., numerical solutions of differential equations, where the same set of inputs always produces the same output) and stochastic

> simulations (where the same set of simulation inputs may produce different output unless the random number streams are carefully controlled). (Sanchez, 2008)

Simulations modeling processes that occur over time can be characterized as terminating or non-terminating, depending on the stopping conditions. In terminating simulations, the simulation stops after either a pre-specified amount of simulation time has elapsed, or when a specific event or condition occurs (Sanchez, 2008). Different scenarios (models) of Reconnaissance Squadron Workflow are all stochastic and terminating. To study these models, replication should be used. Each repetition of the whole design matrix is called a replication and the replications are independent. We have 5,000 design points and 25 replications. Then the total number of experimental units for each scenario is 5,000 * 25 = 125,000 which takes approximately seven hours to run on a laptop equipped with Intel(R) 2.26GHz Core 2 Duo processor and 2GB RAM.

E. DATA DELETION

Time series models were fit by using JMP software to predict reconnaissance request's respond times (time elapsed after creation of a reconnaissance request to the provided report for that reconnaissance request) for all of the scenarios. We saw that the magnitude of autocorrelation drops below 0.40 after lag 1 and stays below. Therefore, we did not perform any data deletion.

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V. ANALYSIS AND RESULTS

This chapter presents the analysis of the output from the simulation models discussed in Chapter IV. The reader should note the fact that these results do not constitute a definitive solution to the research questions for specific squadron operations; although we use data based on authors' experience, the actual data are classified. Future analysts should conduct their own experiments for each simulation with updated inputs to be more confident in the answers to the research questions. After the run of each simulation experiment is over, the resultant data (.csv files) is saved to the hard drive. Duplicates of headers in these files are removed by using *stripheaderdups.rb* program written by Paul Sanchez. The resultant data was imported into JMP software for analysis.

A. REGRESSION ANALYSIS

Mathematically, let $X_1, \ldots, X_k$ denote the k factors in an experiment, and let Y denote a response of interest. Generally, we are interested in constructing response surface metamodels that approximate the relationships between the factors and the responses with statistical models (typically regression models). First, suppose that the X_i's are all quantitative, although they can be discrete or continuous. A first-order (main-effects) model means we assume:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \varepsilon,$$

where the ε's are independent random errors with mean zero (Sanchez, 2008).

To explore any quadratic effects, we include terms like X_1^2 as potential explanatory variables for Y. For two-way interactions, we include terms like X_1X_2. A second-order model includes quadratic effects and two-way interactions as below (Sanchez, 2008):

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{i,i}(X_i - \overline{X}_i)^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{i,j}(X_i - \overline{X}_i)(X_j - \overline{X}_j) + \varepsilon.$$

Regression models were formulated to identify the impact of the factors (explanatory variables) on the responses (e.g., increasing, linear, quadratic), and whether the levels of some factors influence the effects that other factors have (called factor interactions). Fitting regression models is an interactive process. Each scenario's experiment data was summarized (all the decision and noise factors as the group, mean of each MoE as statistics) in JMP software to fit regression models and partition trees. Several different regression models were fit for each MoE by using stepwise regression analysis in JMP. For war situation scenarios, regression models for avgTimeAtWFForResRecRequests were not built because the due date of all arriving reconnaissance requests is one day after they arrive. The significance thresholds for entering and leaving the model used in these analyses are both 0.01 and direction is mixed. Some effective regression models and partition trees were provided in the relative sections below.

B. ROBUST DESIGN

Robust design is a system optimization and improvement process which states that a system should not be evaluated on the basis of mean performance alone. In addition to giving an acceptable mean performance, a "good" system must be relatively insensitive to uncontrollable sources of variation present in the system's environment and nature. The purpose of robust design is to lead to better decisions in terms of implementation, level and consistency of performance, cost, and insight into the drivers of system performance (Sanchez, 2000).

Factors are classified as decision factors, noise factors, or artificial factors. The decision factors are controllable in the real world setting modeled by the simulation. Noise factors are not easily controllable or are controllable only at great expense in the real world setting such as aircraft and camera defect probabilities. Artificial factors are simulation-specific variables such as initial state of the system, termination conditions and random number streams (Sanchez, 2000).

For performance evaluation, the analyst specifies some performance characteristic of special interest, and an associated target value *t*. The cost of the performance characteristic's fluctuation around the target value is measured in order to optimize or improve the system. An ideal configuration would result in the performance characteristic's mean equal to *t* and its variance equal to zero. A quadratic loss function is a common way to trade off performance mean and variability. Let x and Y(x) denote a vector of decision factor settings and the associated performance characteristic, respectively. Then, assuming no loss is incurred when Y(x) is equal to *t*, the quadratic loss function can be written as: $l(Y(x)) = c[Y(x) - t]^2$ where c is the scaling constant to convert losses into monetary units. Using the quadratic loss function, the expected loss associated with configuration x is $E(loss) = c[var_{Y(x)} (\mu_{Y(x)} - t)^2]$ (Sanchez, 2000).

Robust design has two important benefits. First, because of a chosen system configuration's robustness, it is likely to work well across a variety of realizations of noise factor values. Second, there will be an improved communication between the analyst and client via expected loss (Sanchez, 2000).

To find out robust configurations for the reconnaissance squadron in different scenarios, each scenario's experiment data was summarized (all the decision factors as the group, mean and standard deviation of MoE as statistics) in JMP. The target value selected for remOverArrRecRequestsRatio in each scenario is 0.0. The target value selected for avgTimeAtWFForResRecRequests in each scenario is the minimum observed avgTimeAtWFForResRecRequests during a relevant experiment.

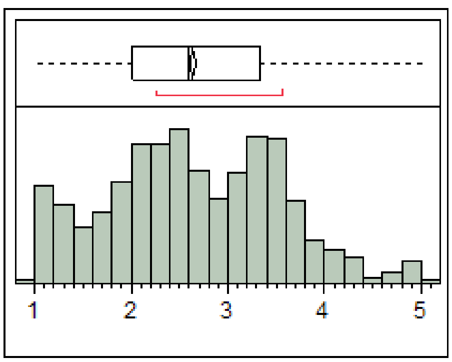
C. OUTPUT ANALYSIS FOR CONFIGURATION: RF-4 / SITUATION: PEACE

1. Average Time at Workflow for Responded Reconnaissance Requests

a. Basic Statistics

Figure 34 shows the basic statistics for the average time at workflow for responded reconnaissance requests (avgTimeAtWFForResRecRequests). With the realistic values used by the authors, the mean of avgTimeAtWFForResRecRequests is 2.64 days with a standard deviation of 0.886. The distribution of avgTimeAtWFForResRecRequests is almost symmetric but not unimodal.

avgTimeAtWFForResRecRequests



Quantiles

100.0%	maximum	5.0582
99.5%		4.9256
97.5%		4.3105
90.0%		3.7077
75.0%	quartile	3.3229
50.0%	median	2.5857
25.0%	quartile	2.0115
10.0%		1.3612
2.5%		1.0870
0.5%		1.0343
0.0%	minimum	0.9836

Moments

Mean	2.6401497
Std Dev	0.8855038
Std Err Mean	0.0125229
Upper 95% Mean	2.6647001
Lower 95% Mean	2.6155993
N	5000

Figure 34. Distribution of avgTimeAtWFForResRecRequests

b. Regression Model Built by Using Only Main Effects

After performing stepwise regression analysis by using only the main effects of 27 input factors, a regression model for the avgTimeAtWFForResRecRequests was built. Figure 35 shows the actual by predicted plot of this model. The p-value of this model is less than 0.0001, which means the model is statistically significant. The R^2 value of 0.89 indicates that 89% of the variability in the response variable is explained by the model.

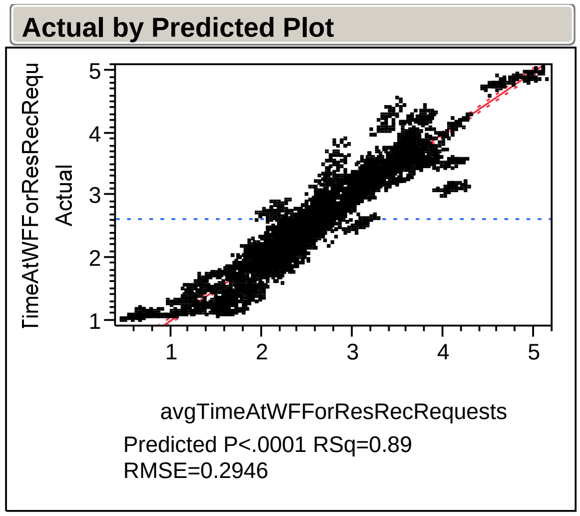


Figure 35. Actual by Predicted Plot of Model for avgTimeAtWFForResRecRequests

Figure 36 shows Summary of Fit (SoF) and Analysis of Variance (AoV) tables of the regression model.

Summary of Fit

RSquare	0.889662
RSquare Adj	0.889308
Root Mean Square Error	0.294611
Mean of Response	2.64015
Observations (or Sum Wgts)	5000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	16	3487.2975	217.956	2511.138
Error	4983	432.5032	0.087	**Prob > F**
C. Total	4999	3919.8007		0.0000*

Figure 36. SoF and AoV Tables of Model for avgTimeAtWFForResRecRequests

As seen from Figure 37, there are sixteen statistically significant terms in the model sorted by their importance on response.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
modeNumReq	0.2798772	0.002094	133.65	0.0000*
aCDefProb	5.650032	0.071454	79.07	0.0000*
modeHighPriDueDays	0.32994	0.005129	64.33	0.0000*
pilotFilErProb	3.9362399	0.071454	55.09	0.0000*
opImgTProb	4.7570963	0.095277	49.93	0.0000*
badWeatConProb	3.0027538	0.071453	42.02	0.0000*
t1CamsDefProb	1.0819422	0.035726	30.28	<.0001*
modeACRepTime	0.0002001	6.616e-6	30.25	<.0001*
t3CamsDefProb	1.0552377	0.035732	29.53	<.0001*
t5CamsDefProb	0.8492586	0.035728	23.77	<.0001*
t2CamsDefProb	0.7443508	0.035729	20.83	<.0001*
t4CamsDefProb	0.924482	0.047635	19.41	<.0001*
numACs	-0.041932	0.00242	-17.33	<.0001*
numT5Cams	-0.0415	0.003007	-13.80	<.0001*
priDueDaysLowOverHighRatio	0.4822559	0.035731	13.50	<.0001*
camsRepTimeStraOverTacRatio	-0.430398	0.035737	-12.04	<.0001*

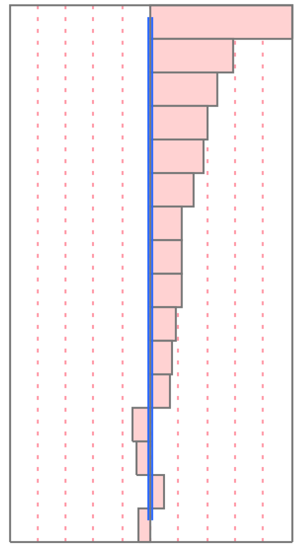


Figure 37. Sorted Parameter Estimates of Model for avgTimeAtWFForResRecRequests

As seen from Figure 37, coefficients for mode number of requests, aircraft defect probability, mode of high priority reconnaissance requests' due days, pilot filming error probability, optic image type reconnaissance requests probability, bad weather condition probability, all of the cameras' defect probabilities, mode of aircraft repair time and due days ratio of low over high priority reconnaissance requests are all positive, which makes sense. The positive effects of a few terms on avgTimeAtWFForResRecRequests —namely, the mode of high priority reconnaissance requests' due days, optic image type reconnaissance requests probability, and due days ratio of low over high priority reconnaissance requests—may seem counter-intuitive. As the mode of high priority reconnaissance requests' due days and due days' ratio of low over high priority reconnaissance requests increase, arrived but not responded reconnaissance requests will wait in resources in the reconnaissance workflow for long time. So this effect will increase avgTimeAtWFForResRecRequests. As optic image type reconnaissance requests probability increases, reconnaissance requests waiting for daytime missions will increase and requests waiting for night missions will decrease. There is not enough time for accomplishing all daytime missions in a day. So arrived but not responded reconnaissance requests requiring daylight missions will wait in the reconnaissance workflow for long time, and this effect will increase avgTimeAtWFForResRecRequests. Coefficients for the number of aircraft, the number of type 5 cameras (single strategic camera), and the ratio of strategic over tactic cameras' repair time are all negative, which also makes sense. The ratio of strategic over tactic cameras' repair time's negative effect on avgTimeAtWFForResRecRequests seems counter-intuitive. But as it increases, the number of reconnaissance requests waiting for resources decreases and number of removed reconnaissance requests increases. Our MoE deals with only responded reconnaissance requests; avgTimeAtWFForResRecRequests decreases too.

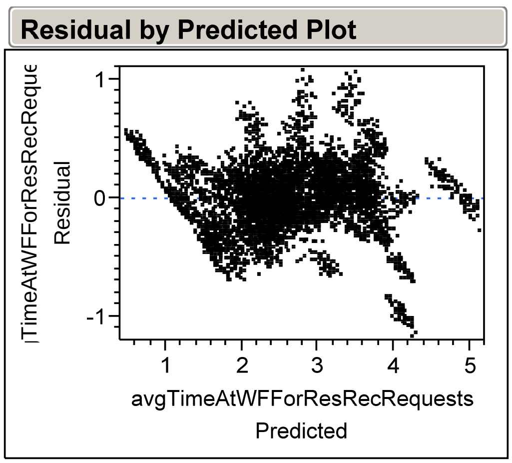


Figure 38. Residual by Predicted Plot of Model for avgTimeAtWFForResRecRequests

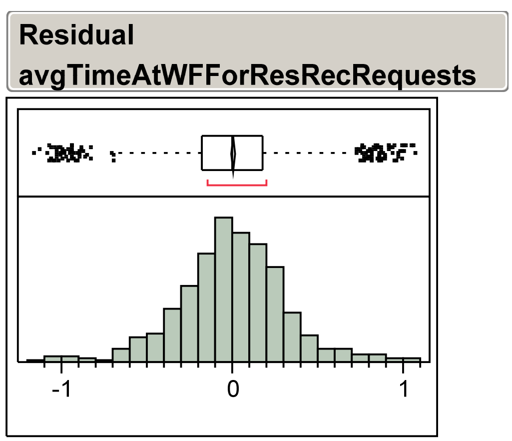


Figure 39. Residuals of Model for avgTimeAtWFForResRecRequests

As seen from Figure 38, the vertical spread of the residuals is not the same. Even though R^2 of the model is fairly high, a model that includes some interactions or quadratic effects may provide a better fit. As seen from Figure 39, the distribution of residuals is almost symmetric and unimodal, which is good.

c. *Regression Model Built by Using Main Effects, Interactions and Quadratic Effects*

After making a stepwise regression analysis by using main effects, interactions and quadratic effects of twenty-seven input factors, a regression model for the avgTimeAtWFForResRecRequests was built. Figure 40 shows the actual by predicted plot of this model. The p-value of this model is less than 0.0001, which means the model is statistically significant. The R^2 value of 0.91 indicates that 91% of the variability in the response variable is explained by the model, which is very good.

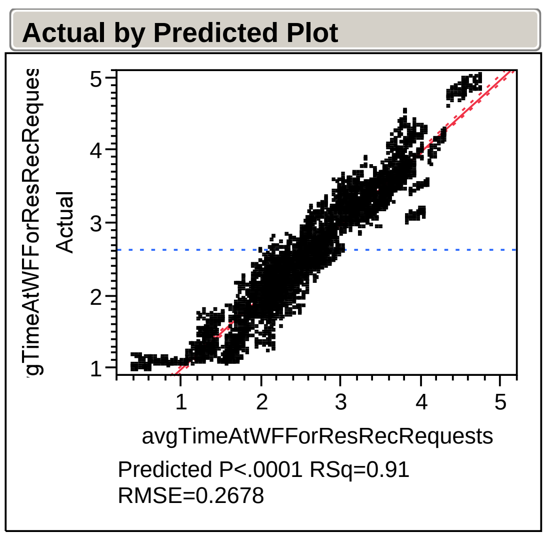


Figure 40. Actual by Predicted Plot of Model for avgTimeAtWFForResRecRequests

Figure 41 shows Summary of Fit (SoF) and Analysis of Variance (AoV) tables of the regression model.

Summary of Fit

RSquare	0.908817
RSquare Adj	0.908506
Root Mean Square Error	0.267847
Mean of Response	2.64015
Observations (or Sum Wgts)	5000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	17	3562.3818	209.552	2920.907
Error	4982	357.4189	0.072	**Prob > F**
C. Total	4999	3919.8007		0.0000*

Figure 41. SoF and AoV Tables of Model for avgTimeAtWFForResRecRequests

As seen from Figure 42, there are seventeen statistically significant terms in the model, sorted by their importance on response.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
modeNumReq	0.2767029	0.001957	141.42	0.0000*
aCDefProb	5.2186091	0.067719	77.06	0.0000*
modeHighPriDueDays	0.3512534	0.004789	73.34	0.0000*
pilotFilErProb	3.9505219	0.065683	60.15	0.0000*
opImgTProb	4.2817056	0.088198	48.55	0.0000*
badWeatConProb	2.9759199	0.067793	43.90	0.0000*
t1CamsDefProb	1.3161107	0.033542	39.24	<.0001*
t3CamsDefProb	1.2499251	0.032901	37.99	<.0001*
(t1CamsDefProb-0.35)*(modeACRepTime-2520)	-0.001598	5.359e-5	-29.82	<.0001*
modeACRepTime	0.0001823	6.192e-6	29.45	<.0001*
(aCDefProb-0.2)*(modeACRepTime-2520)	0.0030971	0.000107	28.86	<.0001*
t5CamsDefProb	0.8118633	0.03312	24.51	<.0001*
t4CamsDefProb	0.9265566	0.046538	19.91	<.0001*
numACs	-0.041932	0.0022	-19.06	<.0001*
(opImgTProb-0.825)*(badWeatConProb-0.2)	-23.32349	1.535017	-15.19	<.0001*
(modeNumReq-12.98)*(aCDefProb-0.2)	-0.253204	0.036634	-6.91	<.0001*
(t3CamsDefProb-0.35)*(t4CamsDefProb-0.35)	1.7470647	0.410275	4.26	<.0001*

Figure 42. Sorted Parameter Estimates of Model for avgTimeAtWFForResRecRequests

A discussion about the sign and importance of main effects was provided in the previous section. As seen from this model, in addition to main effects, there are five interaction terms. Figure 43 shows the interaction profiler.

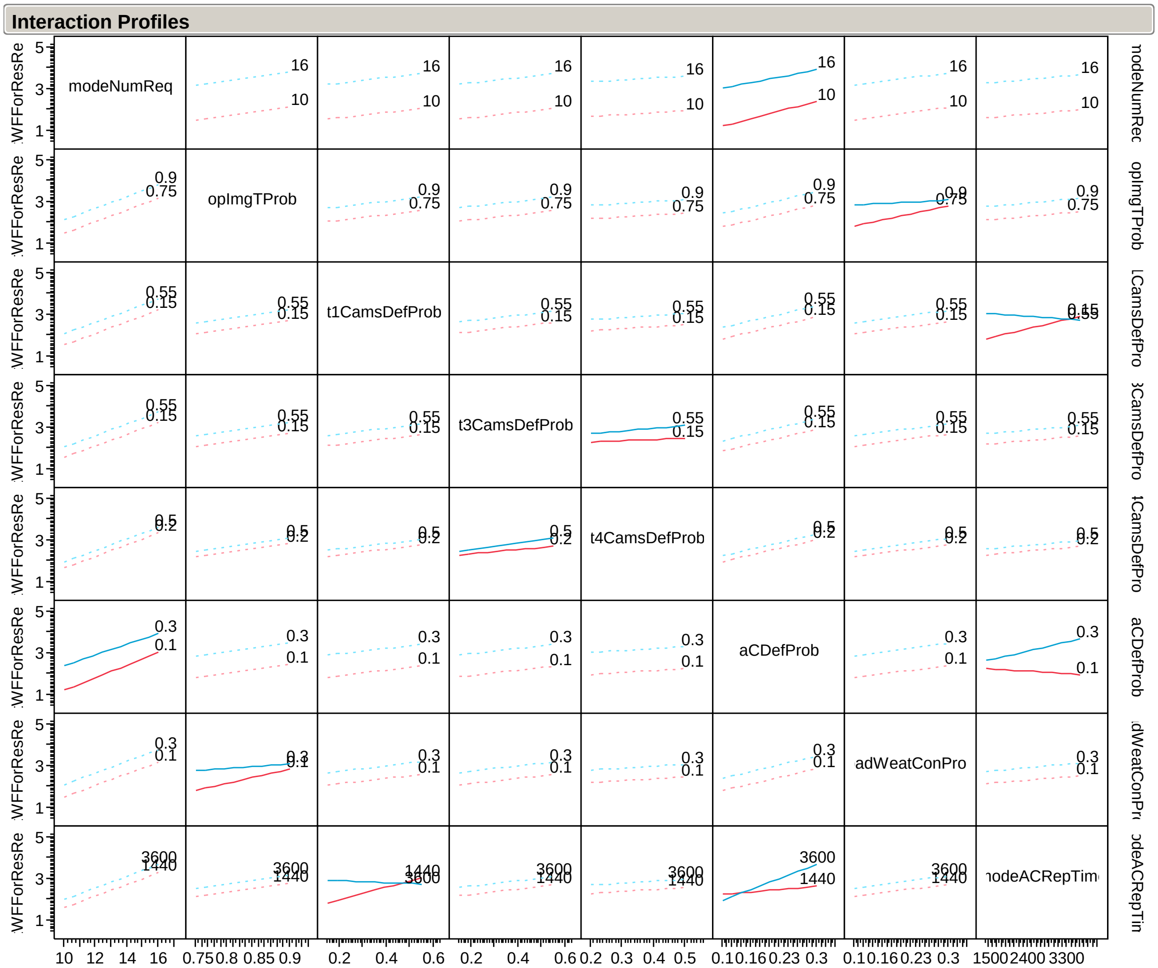


Figure 43. Interaction Profiler of Model for avgTimeAtWFForResRecRequests

The first remarkable interaction is the one between type 1 camera defect probability and mode of aircraft repair time's distribution. For the type 1 camera defect probability of 0.55, an increase in the mode of aircraft repair time decreases the avgTimeAtWFForResRecRequests a little, which is counterintuitive. The reason behind this effect is a decrease in the number of responded reconnaissance requests. However, for the type 1 camera defect probability of 0.15, an increase in the mode of aircraft repair time increases the avgTimeAtWFForResRecRequests a lot, which is intuitive. The reason behind this big increase in the avgTimeAtWFForResRecRequests is the need for more aircraft (because we have more available cameras with this small camera defect probability) to satisfy more reconnaissance requests waiting in the queue.

Another interesting interaction is the one between aircraft defect probability and mode of aircraft repair time's distribution. For the aircraft defect probability of 0.1, an increase in the mode of aircraft repair time changes the avgTimeAtWFForResRecRequests a little. However, for the aircraft defect probability of 0.3, an increase in the mode of aircraft repair time increases the avgTimeAtWFForResRecRequests a lot. We can conclude that we have a redundant number of aircrafts and we see the effect of aircraft repair time when the aircraft defect probability increases to 0.3.

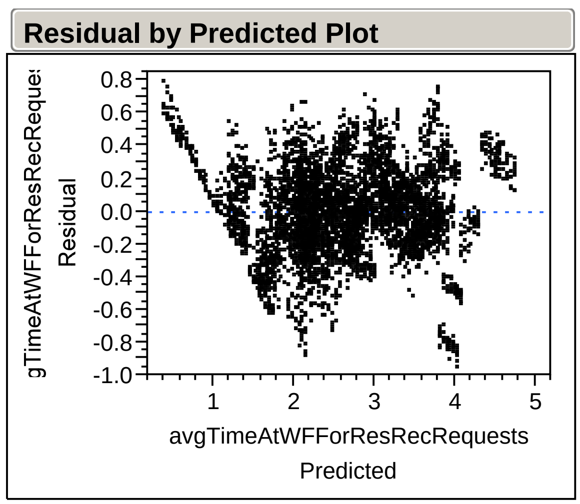


Figure 44. Residual by Predicted Plot of Model for avgTimeAtWFForResRecRequests

As seen from Figure 44, the vertical spread of the residuals is not the same. Even though the R^2 of the model is fairly high, a model that includes more terms may provide a better fit. As seen from Figure 45, the distribution of residuals is almost symmetric and unimodal, which is good.

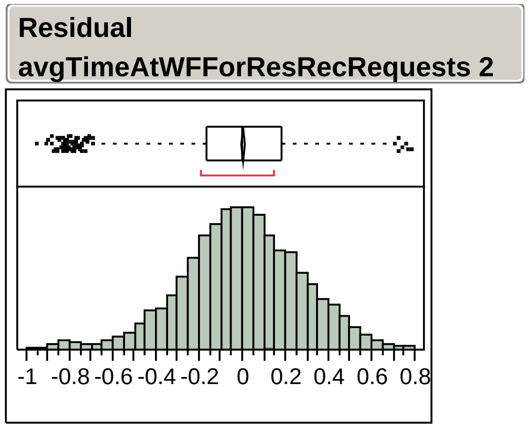


Figure 45. Residuals of Model for avgTimeAtWFForResRecRequests

d. Partition Tree Model

Another model analysts may find useful is the partition tree model. The partition tree is a nonparametric tool "that recursively partitions the data to provide the most explanatory power for a performance of interest" (Kleijnen et al., 2005). For some data sets, regression models and partition trees will have similar explanatory power. For other data sets, one type of model may more clearly capture the relationships between the input factors and the response. One benefit of partition trees is that they can be easier to explain to a decision maker, who may want to focus on a few key inputs that have substantial impacts on the MoE.

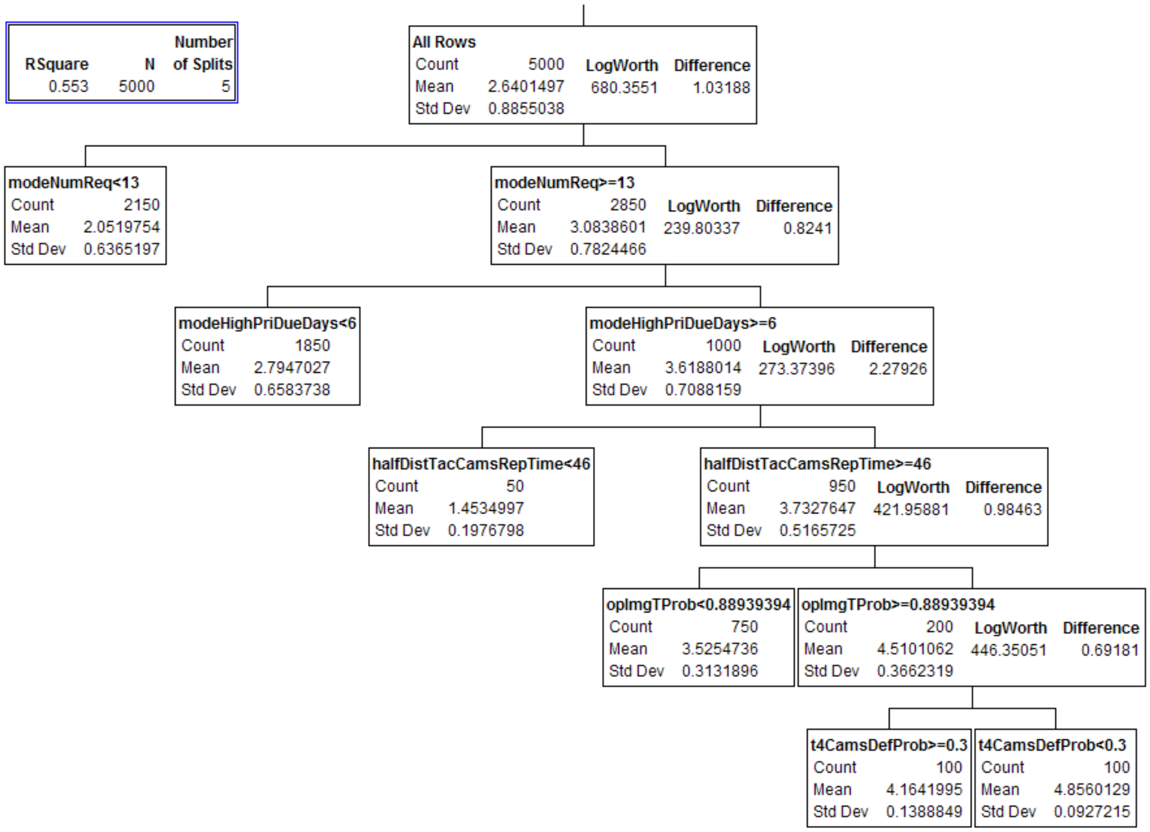


Figure 46. Partition Tree Model for avgTimeAtWFForResRecRequests

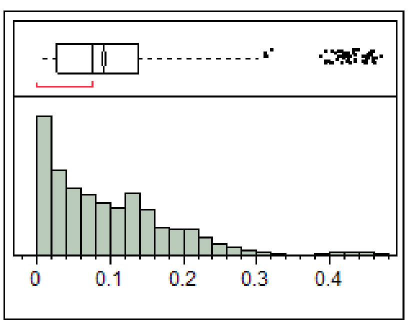
Figure 46 shows a partition tree example with only five splits. The R^2 value of 0.553 indicates that 55% of the variability in the response variable is explained by the model. More splits could be added to this tree if future analysts wish to examine smaller subsets of the data in more detail and to obtain more explanatory power from model. The particular areas of interest in the tree are the leftmost and rightmost areas. In the leftmost area we see that when the mode number of requests arriving to squadron is less than thirteen, the avgTimeAtWFForResRecRequests is low (Mean 2.05 with a SD 0.64), which makes sense. In the rightmost area we see that when the mode number of requests arriving to squadron is greater than or equal to thirteen, the mode number of due days for high priority reconnaissance requests is greater than or equal to six, half distance of triangular distribution for repair time of tactical cameras (all cameras except type 5) is greater than or equal to forty-six, optic image type probability for reconnaissance requests is greater than or equal to 0.89 and type 4 cameras' (used only for night reconnaissance missions) defect probability is less than 0.3, then the avgTimeAtWFForResRecRequests is much higher (Mean 4.86 with a SD 0.09), which also makes sense. Type 4 cameras' defect probability's positive effect on avgTimeAtWFForResRecRequests seems counter-intuitive. But as it decreases, the number of responded reconnaissance requests increases because of an increasing number of successful night missions. Our MoE deals with only responded reconnaissance requests, so avgTimeAtWFForResRecRequests increases, too.

2. Removed Over Arrived Reconnaissance Requests Ratio

a. Basic Statistics

Figure 47 shows the basic statistics for the remOverArrRecRequestsRatio (removed over arrived reconnaissance requests ratio). With the realistic values that the authors used, the mean of removed over arrived reconnaissance requests ratio is 0.092 with a standard deviation of 0.08. Distribution of remOverArrRecRequestsRatio is skewed to the left and not unimodal.

remOverArrRecRequestsRatio



Quantiles

100.0%	maximum	0.47165
99.5%		0.43233
97.5%		0.26511
90.0%		0.20207
75.0%	quartile	0.13886
50.0%	median	0.07591
25.0%	quartile	0.02661
10.0%		0.00269
2.5%		0.00013
0.5%		0.00000
0.0%	minimum	0.00000

Moments

Mean	0.0921045
Std Dev	0.0795681
Std Err Mean	0.0011253
Upper 95% Mean	0.0943105
Lower 95% Mean	0.0898985
N	5000

Figure 47. Distribution of remOverArrRecRequestsRatio

b. Regression Model Built by Using Only Main Effects

After using a stepwise regression analysis with only the main effects of twenty-seven input factors, a regression model for the remOverArrRecRequestsRatio was built. Figure 48 shows the actual by predicted plot of this model. The p-value of this model is less than 0.0001, which means the model is statistically significant. The R^2 value of 0.86 indicates that 86% of the variability in the response variable is explained by the model.

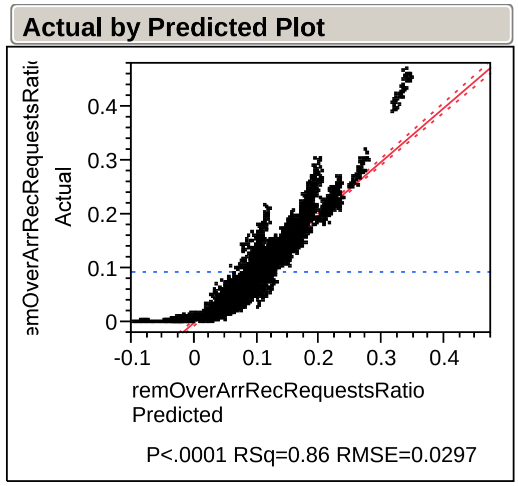


Figure 48. Actual by Predicted Plot of Model for remOverArrRecRequestsRatio

Figure 49 shows the corresponding Summary of Fit (SoF) and Analysis of Variance (AoV) tables for this regression model.

Summary of Fit

RSquare	0.86087
RSquare Adj	0.860367
Root Mean Square Error	0.029733
Mean of Response	0.092105
Observations (or Sum Wgts)	5000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	18	27.245760	1.51365	1712.228
Error	4981	4.403330	0.00088	**Prob > F**
C. Total	4999	31.649090		0.0000*

Figure 49. SoF and AoV Tables of Model for remOverArrRecRequestsRatio

As seen from Figure 50, there are eighteen statistically significant terms, sorted by their importance on response.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
modeNumReq	0.0178149	0.000211	84.30	0.0000*
aCDefProb	0.6073566	0.007211	84.22	0.0000*
pilotFilErProb	0.4211627	0.007211	58.40	0.0000*
badWeatConProb	0.4002211	0.007211	55.50	0.0000*
modeHighPriDueDays	-0.026909	0.000518	-51.98	0.0000*
t1CamsDefProb	0.1481341	0.003606	41.09	<.0001*
t5CamsDefProb	0.1284923	0.003606	35.64	<.0001*
modeACRepTime	2.3718e-5	6.677e-7	35.52	<.0001*
opImgTProb	0.333399	0.009615	34.68	<.0001*
t2CamsDefProb	0.1236451	0.003606	34.29	<.0001*
numACs	-0.004633	0.000244	-18.97	<.0001*
priDueDaysLowOverHighRatio	-0.04944	0.003606	-13.71	<.0001*
t3CamsDefProb	0.040206	0.003606	11.15	<.0001*
t4CamsDefProb	0.0407285	0.004808	8.47	<.0001*
numT5Cams	-0.002157	0.000303	-7.11	<.0001*
halfDistHighPriDueDays	-0.003104	0.000503	-6.18	<.0001*
modeTacCamsRepTime	0.0002171	4.51e-5	4.81	<.0001*
halfDistTacCamsRepTime	0.0003827	8.973e-5	4.26	<.0001*

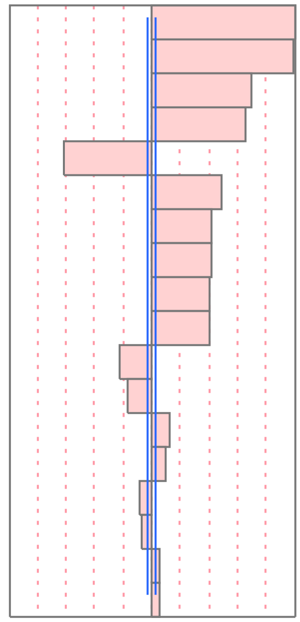


Figure 50. Sorted Parameter Estimates of Model for remOverArrRecRequestsRatio

As seen from Figure 50, coefficients for the mode number of requests, aircraft defect probability, pilot filming error probability, bad weather condition probability, optic image type reconnaissance requests probability, all of the cameras' defect probabilities, mode of aircraft repair time, mode and half dist of tactic cameras repair time are all positive, which makes sense. Coefficients for mode and half distance of high priority due days distribution, number of aircrafts, due days ratio of low over high priority reconnaissance requests and number of type 5 cameras (single strategic camera) are all negative, which also makes sense.

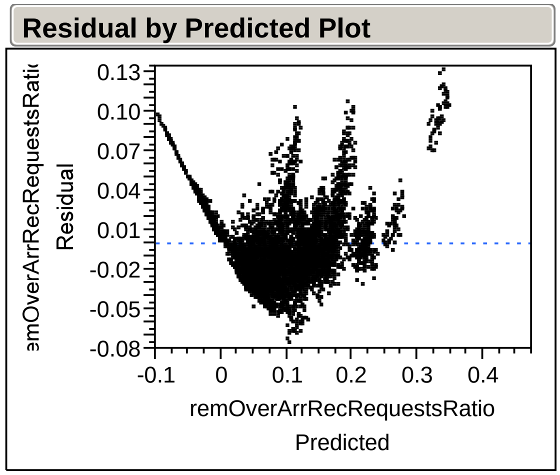


Figure 51. Residual by Predicted Plot of Model for remOverArrRecRequestsRatio

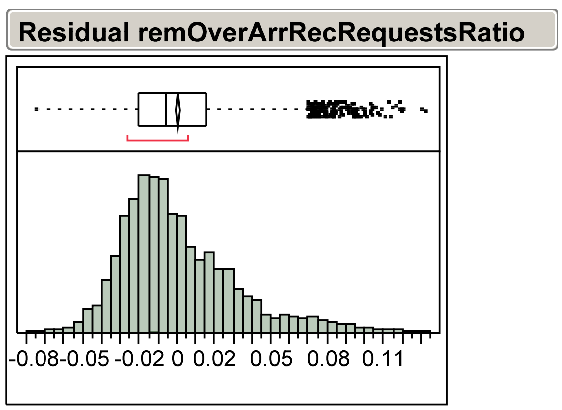


Figure 52. Residuals of Model for remOverArrRecRequestsRatio

As seen from Figure 51, the vertical spread of the residuals is not same, and curvature is evident. Even though the R^2 of the model is fairly high, a model that includes some interactions or quadratic effects may provide a better fit. As seen from Figure 52, the distribution of residuals is unimodal but skewed right.

c. Regression Model Built by Using Main Effects, Interactions and Quadratic Effects

After using a stepwise regression analysis with main effects, interactions and quadratic effects of twenty-seven input factors, a regression model for remOverArrRecRequestsRatio was built. Figure 53 shows the actual by predicted plot of this model. The p-value of this model is less than 0.0001, which means the model is statistically significant. The R^2 value of 0.91 indicates that 91% of the variability in the response variable is explained by the model, which is very good.

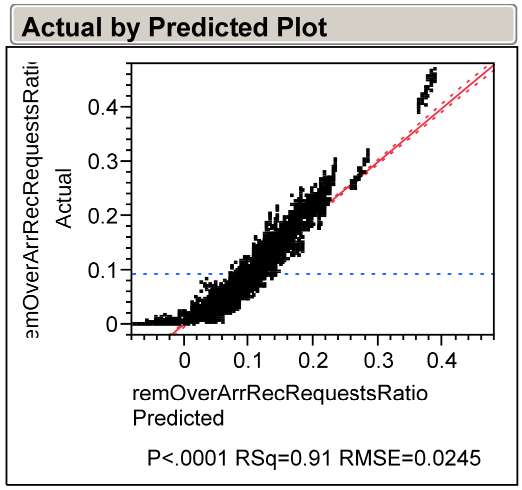


Figure 53. Actual by Predicted Plot of Model for remOverArrRecRequestsRatio

Figure 54 shows the Summary of Fit (SoF) and Analysis of Variance (AoV) tables for this regression model.

Summary of Fit

RSquare	0.905627
RSquare Adj	0.905286
Root Mean Square Error	0.024488
Mean of Response	0.092105
Observations (or Sum Wgts)	5000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	18	28.662282	1.59235	2655.507
Error	4981	2.986808	0.00060	**Prob > F**
C. Total	4999	31.649090		0.0000*

Figure 54. SoF and AoV Tables of Model for remOverArrRecRequestsRatio

As seen from Figure 55, there are eighteen statistically significant terms in the model, sorted by their importance on response.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
aCDefProb	0.6253267	0.006132	101.98	0.0000*
modeNumReq	0.0184024	0.000185	99.67	0.0000*
pilotFilErProb	0.4049123	0.006081	66.58	0.0000*
badWeatConProb	0.3939902	0.006241	63.13	0.0000*
t1CamsDefProb	0.1476793	0.003049	48.44	0.0000*
modeHighPriDueDays	-0.02213	0.000458	-48.31	0.0000*
t5CamsDefProb	0.1439396	0.003025	47.58	0.0000*
modeACRepTime	0.0000212	5.651e-7	37.51	<.0001*
t2CamsDefProb	0.103991	0.003044	34.16	<.0001*
(aCDefProb-0.2)*(modeACRepTime-2520)	0.0003344	0.00001	33.64	<.0001*
opImgTProb	0.2482187	0.00812	30.57	<.0001*
numACs	-0.004633	0.000201	-23.03	<.0001*
(t1CamsDefProb-0.35)*(t1CamsDefProb-0.35)	0.7306969	0.033086	22.08	<.0001*
priDueDaysLowOverHighRatio	-0.067448	0.003126	-21.58	<.0001*
(pilotFilErProb-0.2)*(badWeatConProb-0.2)	1.9372656	0.110585	17.52	<.0001*
t3CamsDefProb	0.0527643	0.0031	17.02	<.0001*
(priDueDaysLowOverHighRatio-1.4)*(t3CamsDefProb-0.35)	-0.412596	0.029216	-14.12	<.0001*
(t2CamsDefProb-0.35)*(modeACRepTime-2520)	-4.852e-5	5.295e-6	-9.16	<.0001*

Figure 55. Sorted Parameter Estimates of Model for remOverArrRecRequestsRatio

A discussion about sign and importance of main effects was provided in the previous section. As seen from this model, in addition to main effects, there are four interaction terms and one quadratic term. Figure 56 shows the interaction profiler.

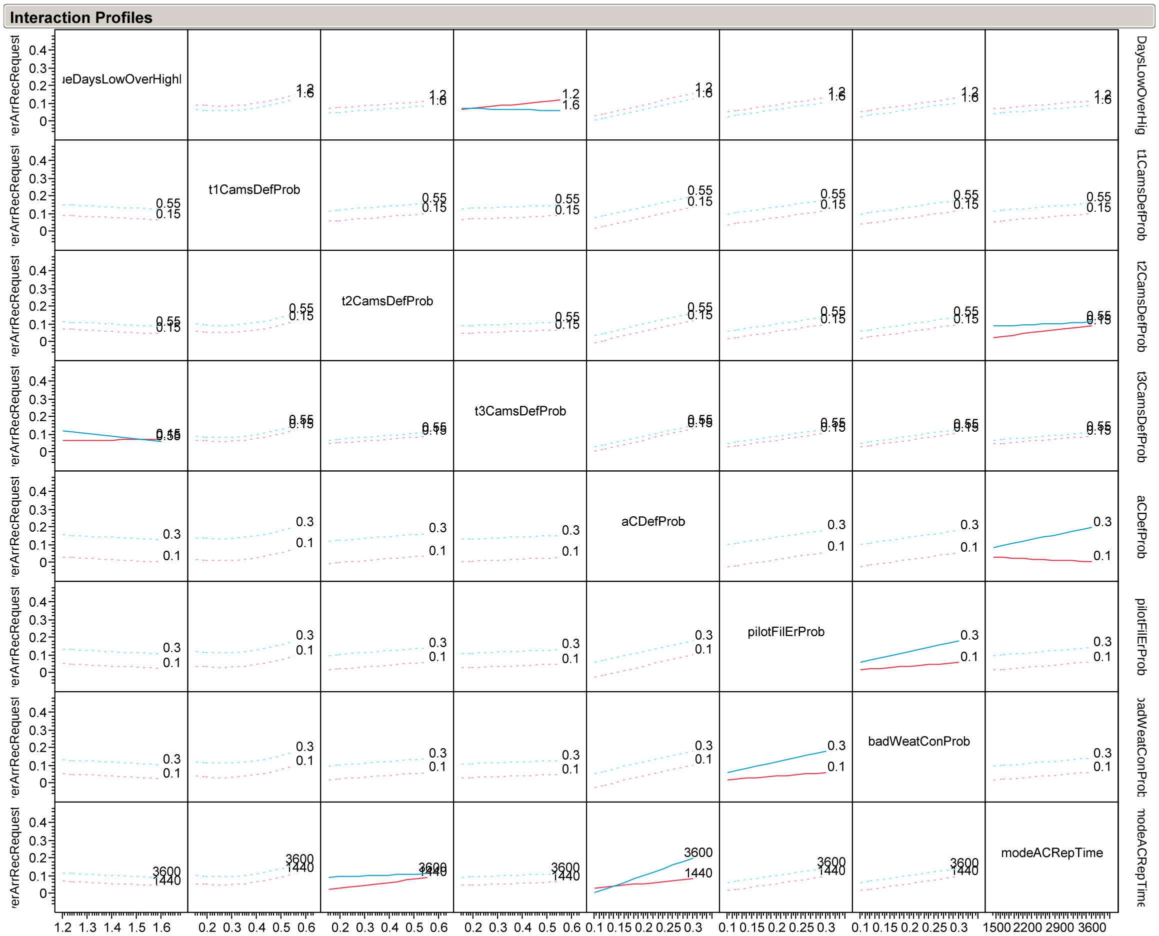


Figure 56. Interaction Profiler of Model for remOverArrRecRequestsRatio

The first remarkable interaction is the one between type 2 camera defect probability and mode of aircraft repair time's distribution. For the type 2 camera defect probability of 0.55, an increase in the mode of aircraft repair time increases the remOverArrRecRequestsRatio a little. However, for the type 2 camera defect probability of 0.15, an increase in the mode of aircraft repair time increases the remOverArrRecRequestsRatio a lot. The reason behind this relatively big increase in the remOverArrRecRequestsRatio is the need for more aircraft (because we have more available cameras with this small camera defect probability) to satisfy more reconnaissance requests waiting in the queue.

Another interesting interaction is the one between aircraft defect probability and mode of aircraft repair time's distribution. For the aircraft defect probability of 0.1, an increase in the mode of aircraft repair time changes the remOverArrRecRequestsRatio a little. However, for the aircraft defect probability of 0.3, an increase in the mode of aircraft repair time increases the remOverArrRecRequestsRatio a lot. We can conclude that we have redundant number of aircrafts and we see the effect of aircraft repair time when the aircraft defect probability increases to 0.3.

Another noteworthy interaction is the one between due days ratio of low over high priority reconnaissance requests and type 3 camera defect probability. For the 1.6 due days ratio of low over high priority reconnaissance requests (low priority reconnaissance requests can wait more in the system before their removal from queue or provided reconnaissance report), an increase in the type 3 camera defect probability (small number of available type 3 cameras) decreases the remOverArrRecRequestsRatio a little, which is counterintuitive. We can conclude that we have redundant number of cameras with the same properties of type 3 camera. However, for the 1.2 due days ratio of low over high priority reconnaissance requests, an increase in the type 3 camera defect probability increases the remOverArrRecRequestsRatio, which is intuitive.

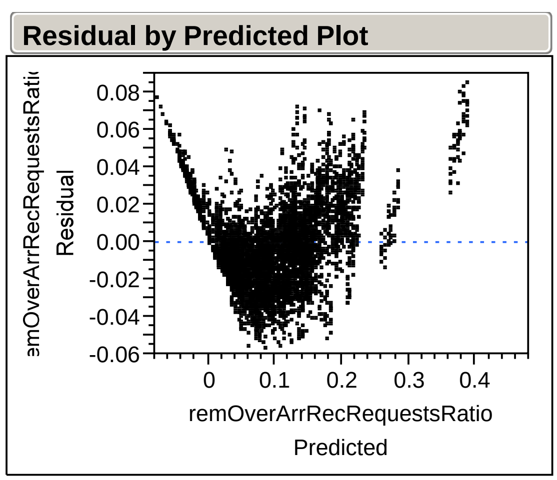


Figure 57. Residual by Predicted Plot of Model for remOverArrRecRequestsRatio

As seen from Figure 57, the vertical spread of the residuals is not same. Even though the R^2 of the model is fairly high and the curvature has been reduced somewhat, a model that includes more terms may provide a better fit. As seen from Figure 58, distribution of residuals is unimodal but skewed right a little.

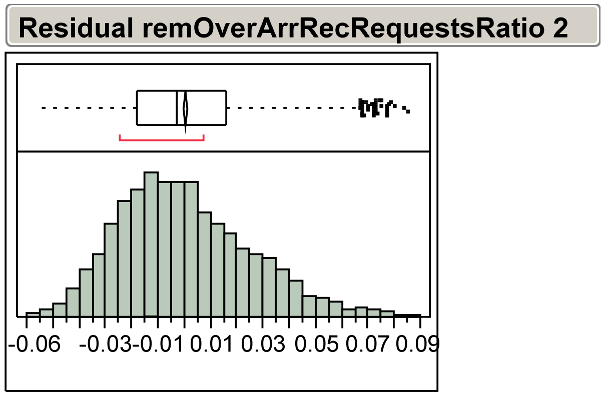


Figure 58. Residuals of Model for remOverArrRecRequestsRatio

d. *Partition Tree Model*

Figure 59 shows a partition tree example with only five splits. The R^2 value of 0.435 indicates that 44% of the variability in the response variable is explained by the model. More splits could be added to this tree if future analysts wish to examine smaller subsets of the data in more detail and to obtain more explanatory power from model. The particular areas of interest in the tree are the leftmost and rightmost areas. In the leftmost area we see that when the mode number of requests arriving to squadron is less than twelve, type 4 cameras' (used only for night reconnaissance missions) defect probability is less than 0.5, bad weather condition probability is less than 0.25, and mode of triangular distribution for repair time of tactical cameras (all cameras except type 5) is greater than or equal to ninety-four, remOverArrRecRequestsRatio is low (Mean 0.008 with a SD 0.009). Except for the mode of triangular distribution for repair time of tactical cameras, all other factors' negative effects on remOverArrRecRequestsRatio make sense. In the rightmost area we see that when the mode number of requests arriving to squadron is greater than or equal to twelve and aircraft defect probability is greater than or equal to 0.3, remOverArrRecRequestsRatio is high (Mean 0.34 with a SD 0.09), which makes sense.

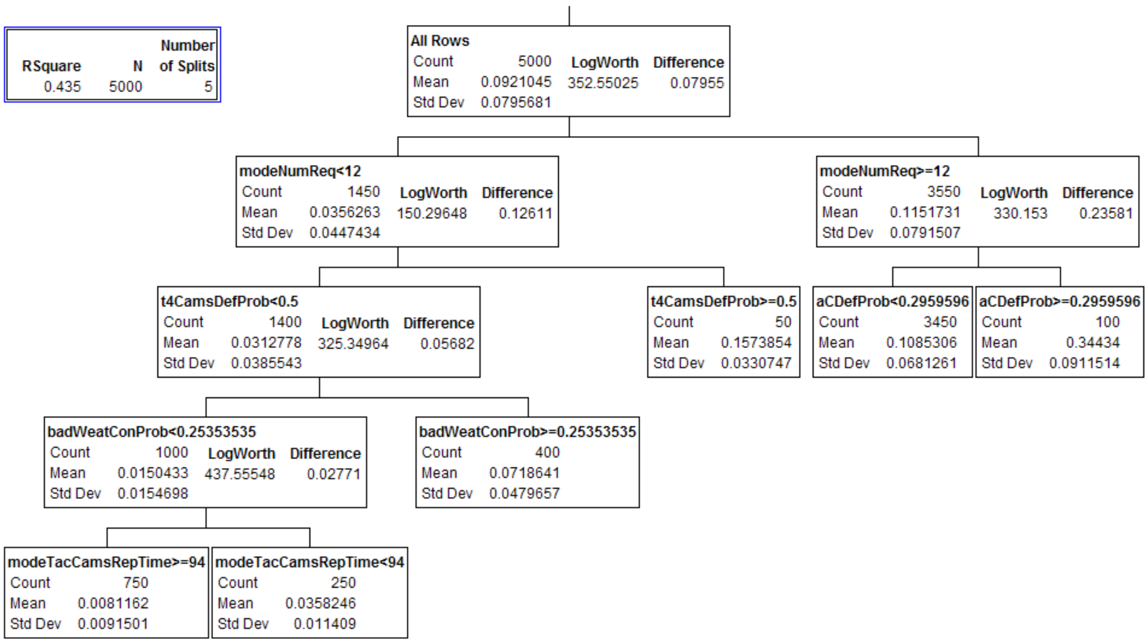


Figure 59. Partition Tree Model for remOverArrRecRequestsRatio

3. Robust Configuration for Reconnaissance Squadron

After using a stepwise regression analysis with main effects, interactions and quadratic effects of eight decision factors regression models for mean and standard deviations of remOverArrRecRequestsRatio and avgTimeAtWFForResRecRequests were built. The remOverArrRecRequestsRatio MoE is more important than the avgTimeAtWFForResRecRequests MoE for the reconnaissance squadron commander. Thus, we will deal with models for remOverArrRecRequestsRatio first. If there will be any conflicting decision factor setting(s), the one(s) used for remOverArrRecRequestsRatio will be recommended. Figure 60 shows the Prediction Profiler for Model of remOverArrRecRequestsRatio's Standard Deviation. Relevant decision factors were set to minimize the standard deviation of remOverArrRecRequestsRatio, and these same values were used to minimize mean of remOverArrRecRequestsRatio, as seen in Figure 61.

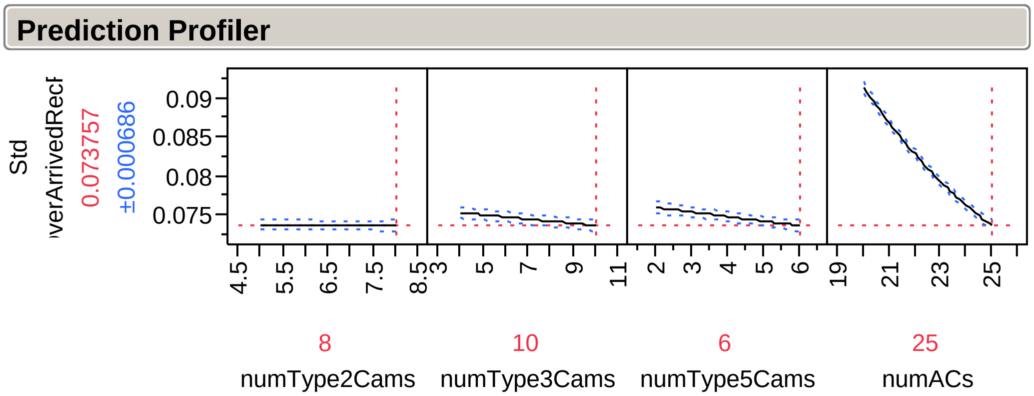


Figure 60. Prediction Profiler for Model of remOverArrRecRequestsRatio’s Standard Deviation

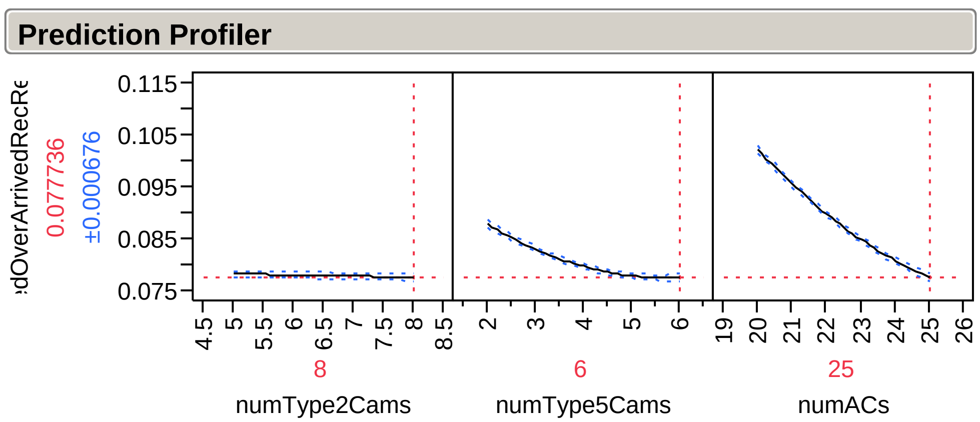


Figure 61. Prediction Profiler for Model of remOverArrRecRequestsRatio’s Mean

Figure 62 shows the Prediction Profiler for Model of avgTimeAtWFForResRecRequests’s Standard Deviation. Relevant decision factors were set to minimize standard deviation of avgTimeAtWFForResRecRequests, and these same values were used to minimize mean of avgTimeAtWFForResRecRequests, as seen in Figure 63.

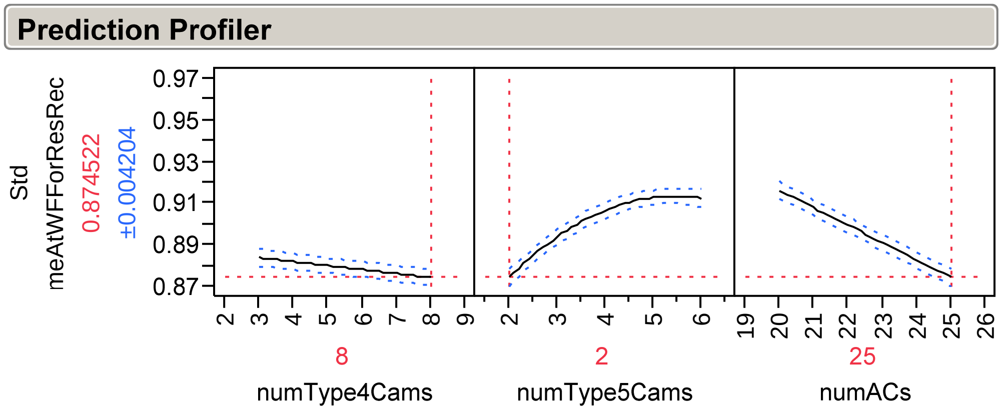


Figure 62. Prediction Profiler for Model of avgTimeAtWFForResRecRequests's Standard Deviation

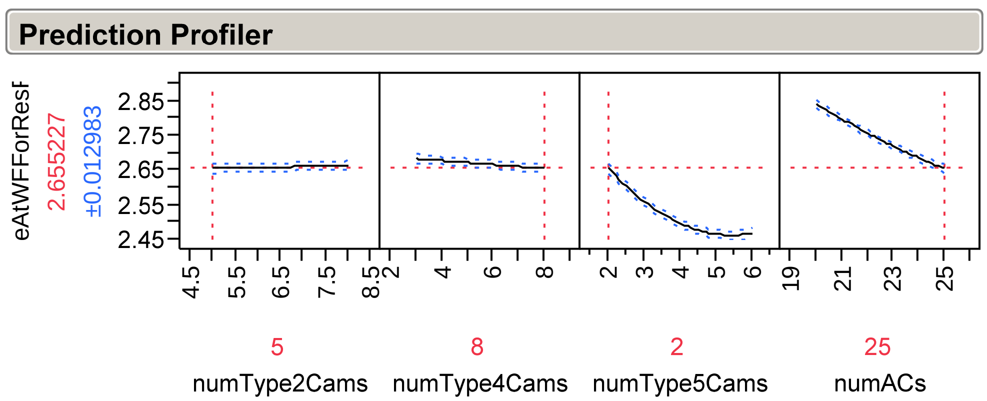


Figure 63. Prediction Profiler for Model of avgTimeAtWFForResRecRequests's Mean

After comparing decision factors' settings for remOverArrRecRequestsRatio and avgTimeAtWFForResRecRequests MoEs, we see that there is only one conflicting decision factor setting, which is numType5Cams. It was set to six to minimize the standard deviation of remOverArrRecRequestsRatio, and this value is recommended. The decision factors not seen in either Prediction Profilers for remOverArrRecRequestsRatio or avgTimeAtWFForResRecRequests are set to the minimum levels used in experiment. Table 4 shows the robust configuration for the reconnaissance squadron in configuration: RF-4 / situation: peace scenario.

Number	Decision Factors	Value
1	numT1Cam	10
2	numT2Cam	8
3	numT3Cam	10
4	numT4Cam	8
5	numT5Cam	6
6	numACs	25
7	numPilots	35
8	numAnalysts	5

Table 4. Robust Configuration for Reconnaissance Squadron in Configuration: RF-4 / Situation: Peace Scenario

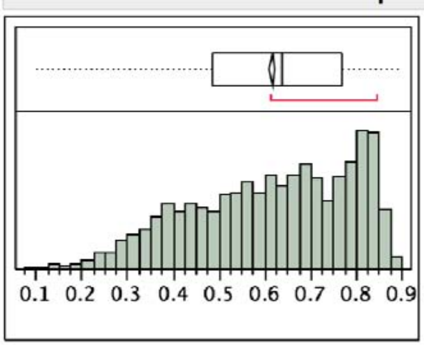
D. OUTPUT ANALYSIS FOR CONFIGURATION: RF-4 / SITUATION: WAR

1. Removed Over Arrived Reconnaissance Requests Ratio

a. Basic Statistics

Figure 64 shows the basic statistics for the remOverArrRecRequestsRatio (removed over arrived reconnaissance requests ratio). With the realistic values the authors used, the mean of removed over arrived reconnaissance requests ratio is 0.61 with a standard deviation of 0.17. The distribution of remOverArrRecRequestsRatio is skewed to the right and is unimodal.

removedOverArrivedRecRequestsRatio



Quantiles

100.0%	maximum	0.89183
99.5%		0.87596
97.5%		0.85563
90.0%		0.8284
75.0%	quartile	0.7702
50.0%	median	0.63517
25.0%	quartile	0.48571
10.0%		0.36881
2.5%		0.27077
0.5%		0.18048
0.0%	minimum	0.09778

Moments

Mean	0.615133
Std Dev	0.1720218
Std Err Mean	0.0024328
Upper 95% Mean	0.6199023
Lower 95% Mean	0.6103638
N	5000

Figure 64. Distribution of remOverArrRecRequestsRatio

b. Regression Model Built by Using Only Main Effects

After using a stepwise regression analysis with only the main effects of twenty-five input factors, a regression model for the remOverArrRecRequestsRatio was built. Figure 65 shows the actual by predicted plot of this model. The p-value of this model is less than 0.0001, which means the model is statistically significant. The R^2 value of 0.37 indicates that 37% of the variability in the response variable is explained by the model.

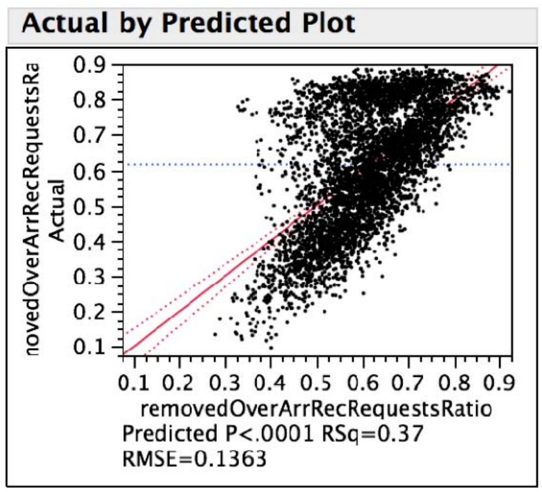


Figure 65. Actual by Predicted Plot of Model for remOverArrRecRequestsRatio

Figure 66 shows the Summary of Fit (SoF) and Analysis of Variance (AoV) tables of the regression model built for remOverArrRecRequestsRatio.

Summary of Fit

RSquare	0.374913
RSquare Adj	0.372654
Root Mean Square Error	0.13625
Mean of Response	0.615133
Observations (or Sum Wgts)	5000

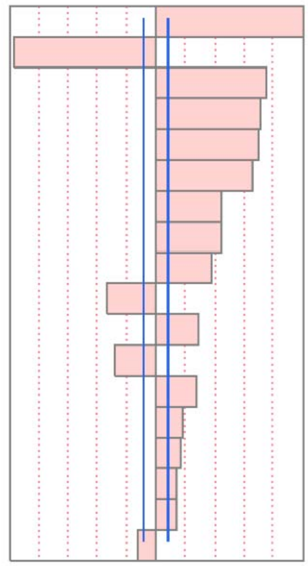
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	18	55.46013	3.08112	165.9719
Error	4981	92.46777	0.01856	**Prob > F**
C. Total	4999	147.92790		0.0000*

Figure 66. SoF and AoV Tables of Model for remOverArrRecRequestsRatio

Figure 67 shows eighteen statistically significant terms, sorted by their importance on response.

Sorted Parameter Estimates



Term	Estimate	Std Error	t Ratio	Prob>|t|
aCDefProb	0.8101601	0.033043	24.52	<.0001*
numACs	-0.026452	0.001119	-23.63	<.0001*
modeNumReq	0.0178984	0.000961	18.62	<.0001*
numT3Cams	0.0170652	0.000973	17.53	<.0001*
modeACRepTime	0.0000524	3.059e-6	17.13	<.0001*
aCInterceptProb	0.7140438	0.04406	16.21	<.0001*
numPilots	0.006542	0.000591	11.07	<.0001*
pilotFilErProb	0.3630568	0.033043	10.99	<.0001*
badWeatConProb	0.3081087	0.033043	9.32	<.0001*
numT1Cams	-0.009159	0.001119	-8.18	<.0001*
numAnalysts	0.0083583	0.001141	7.32	<.0001*
numT2Cams	-0.012129	0.001733	-7.00	<.0001*
t1CamsDefProb	0.1147619	0.016522	6.95	<.0001*
t4CamsDefProb	0.0729393	0.016521	4.41	<.0001*
t2CamsDefProb	0.068144	0.016522	4.12	<.0001*
t3CamsDefProb	0.0585527	0.016521	3.54	0.0004*
t5CamsDefProb	0.0582391	0.016521	3.53	0.0004*
numT5Cams	-0.004086	0.001391	-2.94	0.0033*

Figure 67. Sorted Parameter Estimates of Model for remOverArrRecRequestsRatio

As seen from Figure 67, coefficients for aircraft defect probability, mode number of reconnaissance requests, number of type 3 cameras, mode time of aircraft repair, aircraft interception probability, number of pilots, pilot filming error probability, bad weather condition, number of analysts, type 1,2,3,4 and 5 camera defect probability, are all positive. Most of these make sense, except for the number of type 3 cameras, number of pilots, and number of analysts which seems counter-intuitive. Coefficients for number of aircraft, number of type 1, 2 and 5 cameras, are all negative, which also makes sense.

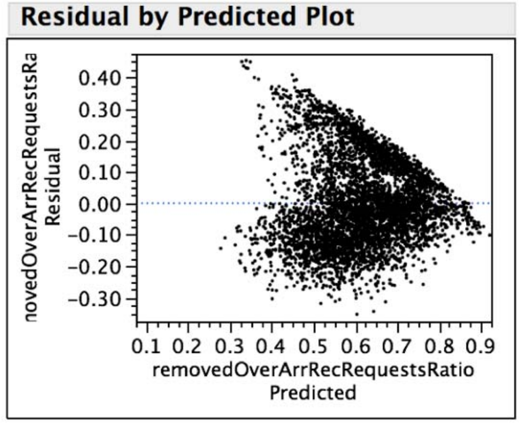


Figure 68. Residual by Predicted Plot of Model for remOverArrRecRequestsRatio

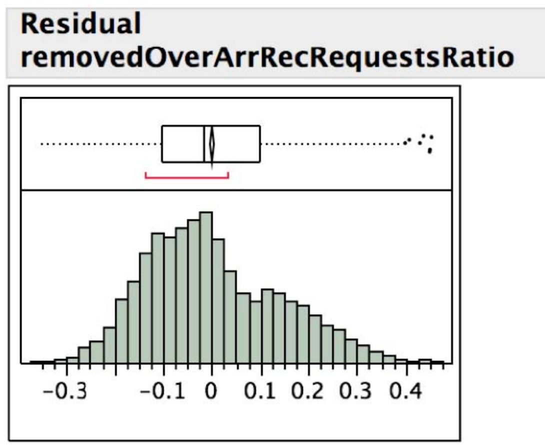


Figure 69. Residuals of Model for remOverArrRecRequestsRatio

As seen from Figure 68, the vertical spread of the residuals is not the same. A model that includes some interactions or quadratic effects may provide a better fit. As seen from Figure 69, distribution of residuals is unimodal but not symmetric.

c. Regression Model Built by Using Main Effects, Interactions and Quadratic Effects

After using a stepwise regression analysis with main effects, interactions and quadratic effects of twenty-five input factors, a regression model for the remOverArrRecRquestsRatio was built. Figure 70 shows the actual by predicted plot of this model. The p-value of this model is less than 0.0001, which means the model is statistically significant. The R^2 value of 0.71 indicates that 71% of the variability in the response variable is explained by the model.

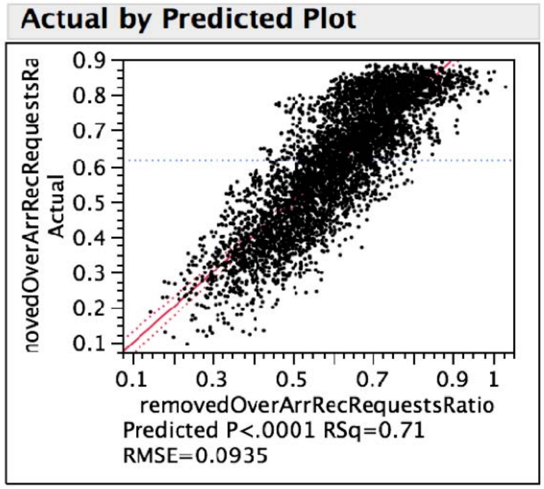


Figure 70. Actual by Predicted Plot of Model for remOverArrRecRequestsRatio

Figure 71 shows the Summary of Fit (SoF) and Analysis of Variance (AoV) tables of the regression model built for remOverArrRecRequestsRatio.

Summary of Fit

RSquare	0.706679
RSquare Adj	0.704789
Root Mean Square Error	0.093465
Mean of Response	0.615133
Observations (or Sum Wgts)	5000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	32	104.53755	3.26680	373.9584
Error	4967	43.39035	0.00874	**Prob > F**
C. Total	4999	147.92790		0.0000*

Figure 71. SoF and AoV Tables of Model for remOverArrRecRequestsRatio

Figure 72 shows thirty-two significant terms in the model, sorted by their importance on the response. A discussion about the sign and importance of main effects was provided in the previous section. As seen from this model, in addition to main effects, there are three quadratic terms and fourteen interaction terms. Figure 73 shows the interaction profiler.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
numACs	-0.060318	0.001035	-58.27	0.0000*
(numT3Cams-7)*(numT3Cams-7)	0.0303606	0.000604	50.28	0.0000*
aCDefProb	0.8103118	0.022667	35.75	<.0001*
numT1Cams	-0.026004	0.000882	-29.48	<.0001*
(numT5Cams-4)*(numT5Cams-4)	-0.025783	0.000941	-27.39	<.0001*
modeNumReq	0.0178894	0.000659	27.13	<.0001*
(numT4Cams-5.56)*(numT4Cams-5.56)	-0.019203	0.000735	-26.14	<.0001*
(numT2Cams-6.38)*(numT3Cams-7)	0.021198	0.000816	25.98	<.0001*
(numT1Cams-12.58)*(numT3Cams-7)	-0.01524	0.000593	-25.68	<.0001*
modeACRepTime	5.2417e-5	2.099e-6	24.98	<.0001*
(numT1Cams-12.58)*(numAnalysts-7.52)	0.0157212	0.000635	24.77	<.0001*
(numT1Cams-12.58)*(numT4Cams-5.56)	-0.016282	0.000684	-23.79	<.0001*
aCInterceptProb	0.7158112	0.030223	23.68	<.0001*
(numT2Cams-6.38)*(numT4Cams-5.56)	0.0207525	0.00092	22.56	<.0001*
(numT1Cams-12.58)*(numT5Cams-4)	-0.018113	0.000834	-21.73	<.0001*
(numT2Cams-6.38)*(numPilots-39.96)	-0.012926	0.000615	-21.01	<.0001*
(numT3Cams-7)*(numT4Cams-5.56)	0.0076772	0.000408	18.82	<.0001*
(numT2Cams-6.38)*(numACs-22.42)	0.0172401	0.000934	18.46	<.0001*
(numT5Cams-4)*(numPilots-39.96)	0.0085447	0.000492	17.38	<.0001*
numAnalysts	0.019773	0.001153	17.15	<.0001*
(numT2Cams-6.38)*(numAnalysts-7.52)	0.0176838	0.001035	17.09	<.0001*
numT2Cams	-0.02719	0.00162	-16.78	<.0001*
pilotFilErProb	0.3633031	0.022667	16.03	<.0001*
numPilots	0.0079505	0.000513	15.50	<.0001*
(numT3Cams-7)*(numPilots-39.96)	-0.003847	0.000258	-14.94	<.0001*
badWeatConProb	0.3082938	0.022667	13.60	<.0001*
numT5Cams	-0.013838	0.001243	-11.13	<.0001*
(numPilots-39.96)*(numAnalysts-7.52)	-0.00346	0.000339	-10.21	<.0001*
t1CamsDefProb	0.1147315	0.011333	10.12	<.0001*
numT4Cams	0.0074224	0.000862	8.61	<.0001*
(numT4Cams-5.56)*(numACs-22.42)	-0.005989	0.000845	-7.08	<.0001*
numT3Cams	0.0033781	0.000789	4.28	<.0001*

Figure 72. Sorted Parameter Estimates of Model for remOverArrRecRequestsRatio

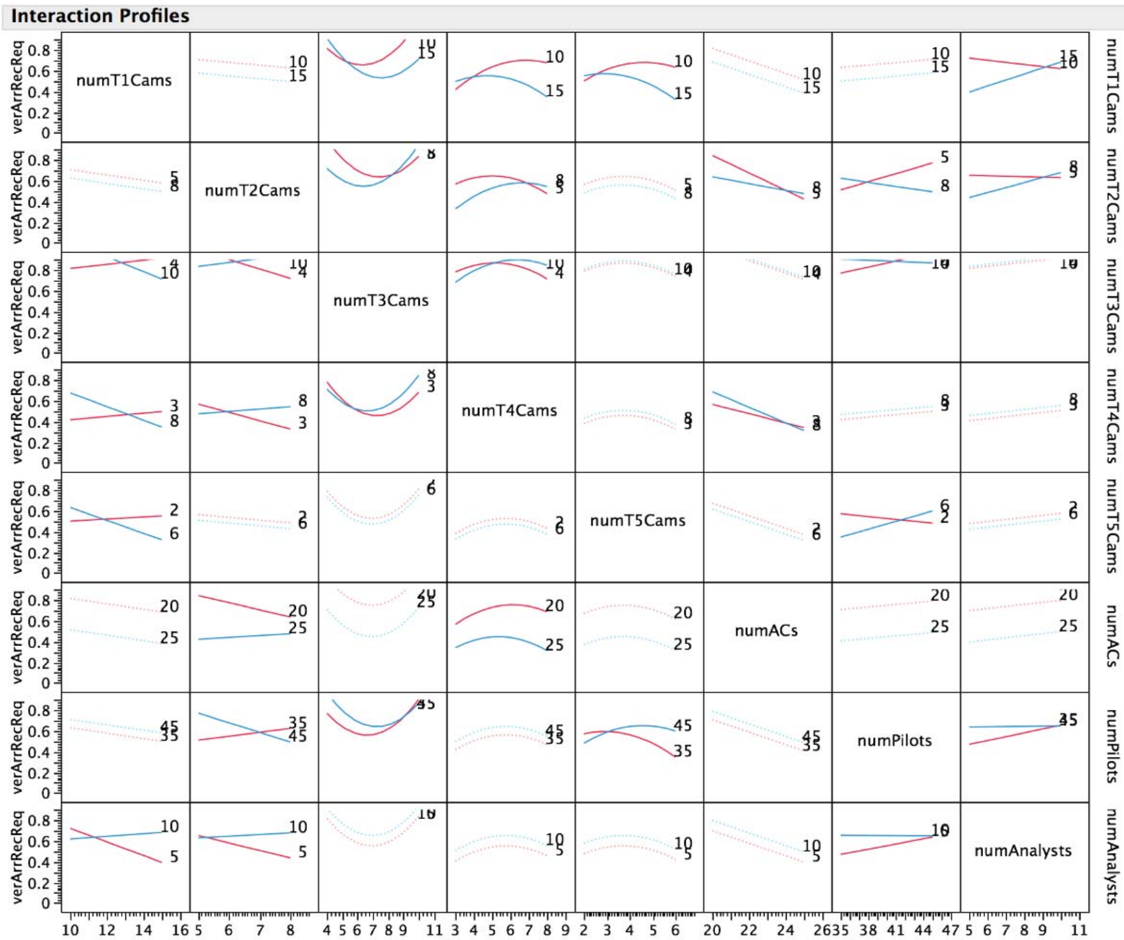


Figure 73. Interaction Profiler of Model for remOverArrRecRequestsRatio

An interesting interaction is the one between the number of type 1 cameras and number of type 5 cameras. For two type 5 cameras, an increase in the number of type 1 cameras increases the remOverArrRecRequestsRatio a little. However, for six type 5 cameras, an increase in type 1 cameras decreases the remOverArrRecRequestsRatio a lot, which is intuitive. The reason behind this is because with the type 1 camera, vertical and optic type requests are planned and with type 5 cameras oblique and optic type requests are planned, increase in those cameras reduces the not responded reconnaissance requests.

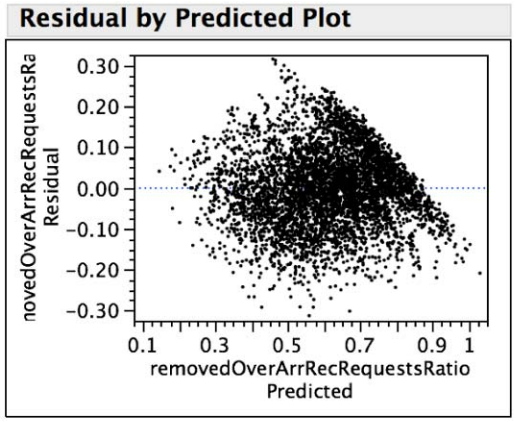


Figure 74. Residual by Predicted Plot of Model for remOverArrRecRequestsRatio

As seen from Figure 75, the vertical spread of the residuals is the same, which is good. As seen from Figure 76, the distribution of residuals is symmetric and unimodal, which is also good.

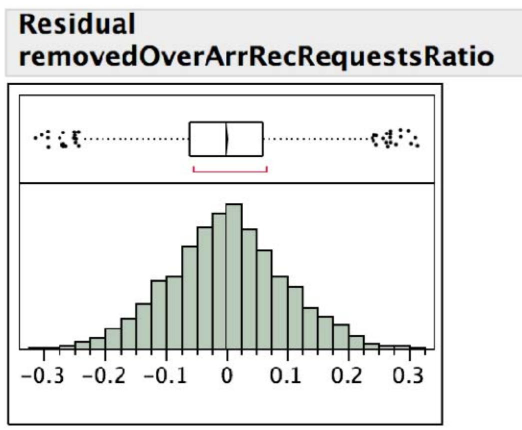


Figure 75. Residuals of Model for remOverArrRecRequestsRatio

2. Robust Design for Reconnaissance Squadron

After using a stepwise regression analysis with main effects, interactions and quadratic effects of eight decision factors, regression models for mean and standard deviations of remOverArrRecRequestsRatio and avgTimeAtWFForResRecRequests were built. We could not find any effective model for remOverArrRecRequestsRatio MoE, so we will only deal with models for avgTimeAtWFForResRecRequests. Figure 76 shows the Prediction Profiler for the model of avgTimeAtWFForResRecRequests's Standard

Deviation. Relevant decision factors were set to minimize standard deviation of avgTimeAtWFForResRecRequests, and these same values were used to minimize mean of avgTimeAtWFForResRecRequests as seen in Figure 77.

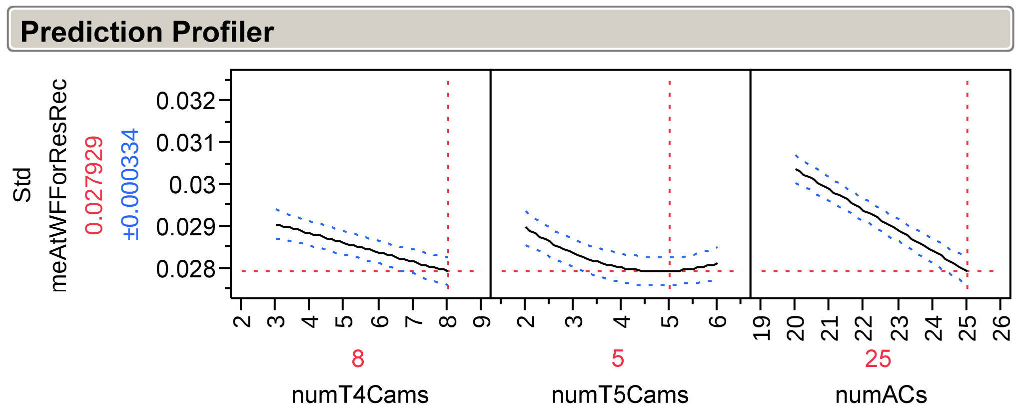


Figure 76. Prediction Profiler for Model of avgTimeAtWFForResRecRequests's Standard Deviation

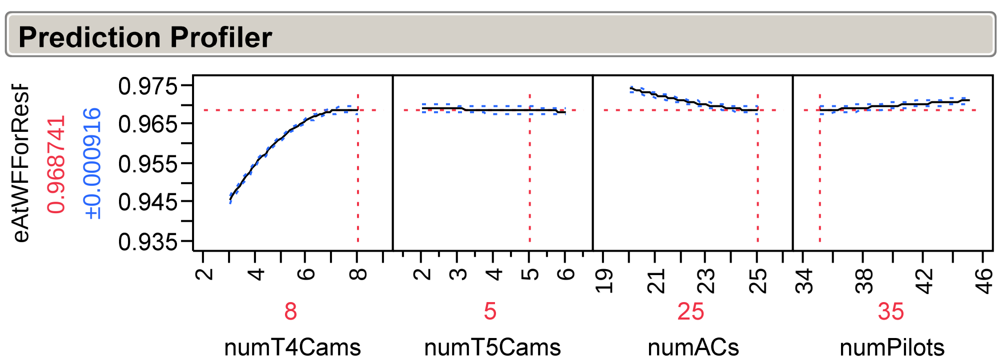


Figure 77. Prediction Profiler for Model of avgTimeAtWFForResRecRequests's Mean

The decision factors not seen in Prediction Profilers for avgTimeAtWFForResRecRequests are set to their minimum levels used in experiment. Table 5 shows the robust configuration for the reconnaissance squadron in configuration: RF-4 / situation: war scenario.

Number	Decision Factors	Value
1	numT1Cam	10
2	numT2Cam	5
3	numT3Cam	4
4	numT4Cam	8
5	numT5Cam	5
6	numACs	25
7	numPilots	35
8	numAnalysts	5

Table 5. Robust Configuration for Reconnaissance Squadron in Configuration: RF-4 / Situation: War Scenario

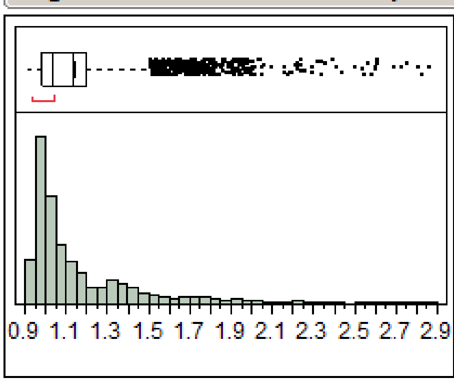
E. OUTPUT ANALYSIS FOR CONFIGURATION: F-16 / SITUATION: PEACE

1. Average Time at Workflow for Responded Reconnaissance Requests

a. Basic Statistics

Figure 78 shows the basic statistics for the average time at workflow for responded reconnaissance requests (avgTimeAtWFForResRecRequests). With the realistic values the authors used, the mean of avgTimeAtWFForResRecRequests is 1.14 days with a standard deviation of 0.25. Distribution of avgTimeAtWFForResRecRequests is unimodal but skewed to the right.

avgTimeAtWFForResRecRequests



Quantiles

100.0%	maximum	2.8613
99.5%		2.2993
97.5%		1.8153
90.0%		1.4485
75.0%	quartile	1.1941
50.0%	median	1.0374
25.0%	quartile	0.9813
10.0%		0.9563
2.5%		0.9356
0.5%		0.9224
0.0%	minimum	0.9125

Moments

Mean	1.1372702
Std Dev	0.2468134
Std Err Mean	0.0034905
Upper 95% Mean	1.1441131
Lower 95% Mean	1.1304274
N	5000

Figure 78. Distribution of avgTimeAtWFForResRecRequests

b. Regression Model Built by Using Only Main Effects

After making stepwise regression analysis by using only the main effects of twenty-three input factors, a regression model for the avgTimeAtWFForResRecRequests was built. Figure 79 shows the actual by predicted plot of this model. The p-value of this model is less than 0.0001, which means the model is statistically significant. The R^2 value of 0.70 indicates that 70% of the variability in the response variable is explained by the model, although the strong curvature indicates a problem with lack-of-fit.

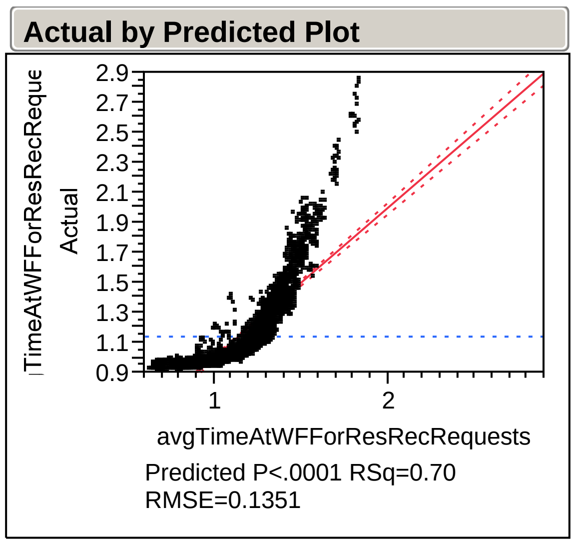


Figure 79. Actual by Predicted Plot of Model for avgTimeAtWFForResRecRequests

Figure 80 shows the Summary of Fit (SoF) and Analysis of Variance (AoV) tables for this regression model.

Summary of Fit

RSquare	0.701251
RSquare Adj	0.700412
Root Mean Square Error	0.135092
Mean of Response	1.13727
Observations (or Sum Wgts)	5000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	14	213.54733	15.2534	835.8031
Error	4985	90.97609	0.0182	Prob > F
C. Total	4999	304.52343		0.0000*

Figure 80. SoF and AoV Tables of Model for avgTimeAtWFForResRecRequests

As seen from Figure 81, there are fourteen statistically significant terms in the model, sorted by their importance on response.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
numT2Pods	-0.112805	0.001587	-71.10	0.0000*
t2PodsDefProb	2.9362028	0.065528	44.81	0.0000*
modePodsRepTime	0.00012	3.034e-6	39.56	<.0001*
modeNumReq	0.0341259	0.000911	37.46	<.0001*
verAngTProb	-0.854307	0.032764	-26.07	<.0001*
badWeatConProb	0.8061632	0.032764	24.61	<.0001*
t1PodsDefProb	0.720938	0.065527	11.00	<.0001*
modeHighPriDueDays	0.0240071	0.002334	10.28	<.0001*
opImgTProb	-0.213858	0.032766	-6.53	<.0001*
modeACRepTime	-1.536e-5	3.034e-6	-5.06	<.0001*
numPilots	0.0027387	0.000588	4.66	<.0001*
numT1Pods	-0.0054	0.001265	-4.27	<.0001*
dataLinkDefProb	0.125024	0.032763	3.82	0.0001*
numAnalysts	-0.003696	0.001121	-3.30	0.0010*

Figure 81. Sorted Parameter Estimates of Model for avgTimeAtWFForResRecRequests

As seen from Figure 81, coefficients for Type 2 pods' (cameras) defect probability, mode of pod repair time, mode number of requests, bad weather condition probability, Type 1 pods' defect probability, mode of high priority reconnaissance requests' due days, number of pilots and data link communication defect probability are all positive, which makes sense. The number of pilots' positive effect on avgTimeAtWFForResRecRequests is counter-intuitive. Our explanation is that as the number of pilots increase, reconnaissance requests that have been waiting for long time in the queue are responded to, so their high timeAtWF (time at workflow) will increase the avgTimeAtWFForResRecRequests. Coefficients for the number of Type 2 pods, vertical angle type reconnaissance requests probability, optic image type reconnaissance requests probability, mode of aircraft repair time, number of type 1 pods (only used to satisfy vertical image type reconnaissance requests) and number of analysts are all negative, which also makes sense. The mode of aircraft repair time's negative effect on avgTimeAtWFForResRecRequests is counter-intuitive. As it increases, the number of available aircraft decreases, so reconnaissance requests which have already been waiting for a long time in the queue are not responded to. Therefore, avgTimeAtWFForResRecRequests decreases.

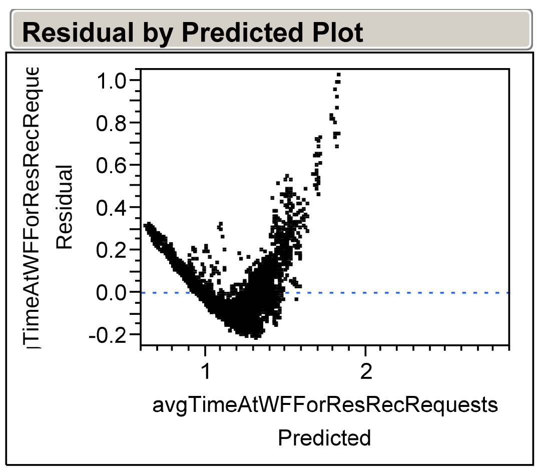


Figure 82. Residual by Predicted Plot of Model for avgTimeAtWFForResRecRequests

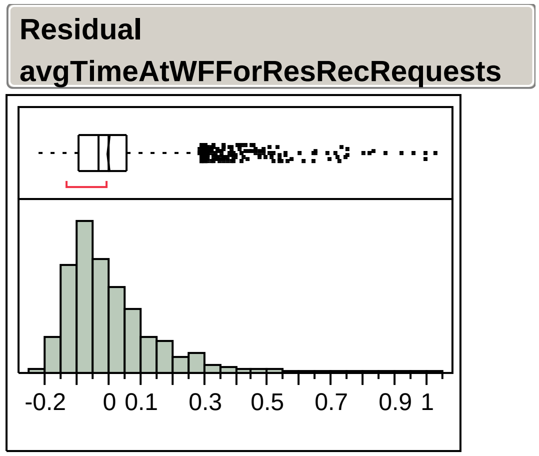


Figure 83. Residuals of Model for avgTimeAtWFForResRecRequests

As seen from Figure 82, the vertical spread of the residuals is not same and there strong curvature is evident. A model that includes some interactions or quadratic effects may provide a better fit. As seen from Figure 83, the distribution of residuals is unimodal but skewed to the right.

c. *Regression Model Built by Using Main Effects, Interactions and Quadratic Effects*

After making a stepwise regression analysis by using main effects, interactions and quadratic effects of twenty-three input factors, a regression model for the avgTimeAtWFForResRecRequests was built. Figure 84 shows the actual by predicted plot of this model. The p-value of this model is less than 0.0001, which means the model is statistically significant. The R^2 value of 0.90 indicates that 90% of the variability in the response variable is explained by the model, which is very good.

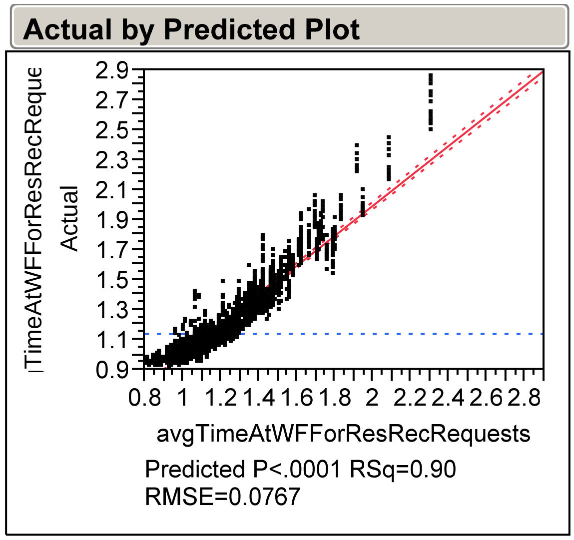


Figure 84. Actual by Predicted Plot of Model for avgTimeAtWFForResRecRequests

Figure 85 shows the Summary of Fit (SoF) and Analysis of Variance (AoV) tables for this regression model.

Summary of Fit

RSquare	0.903697
RSquare Adj	0.903349
Root Mean Square Error	0.076731
Mean of Response	1.13727
Observations (or Sum Wgts)	5000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	18	275.19681	15.2887	2596.722
Error	4981	29.32662	0.0059	**Prob > F**
C. Total	4999	304.52343		0.0000*

Figure 85. SoF and AoV Tables of Model for avgTimeAtWFForResRecRequests

As seen from Figure 86, there are eighteen statistically significant terms in the model, sorted by their importance on response.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
numT2Pods	-0.112805	0.000901	-125.2	0.0000*
t2PodsDefProb	3.1401068	0.038327	81.93	0.0000*
modePodsRepTime	0.0001147	1.74e-6	65.89	0.0000*
modeNumReq	0.0309837	0.000534	58.01	0.0000*
(numT2Pods-4.5)*(t2PodsDefProb-0.1)	-1.517096	0.030907	-49.09	0.0000*
verAngTProb	-0.867674	0.018786	-46.19	0.0000*
badWeatConProb	0.7890755	0.018929	41.69	0.0000*
(numT2Pods-4.5)*(numT2Pods-4.5)	0.0453381	0.001108	40.94	<.0001*
(numT2Pods-4.5)*(modePodsRepTime-2520)	-0.000056	1.431e-6	-39.09	<.0001*
(modePodsRepTime-2520)*(t2PodsDefProb-0.1)	0.0023853	6.172e-5	38.65	<.0001*
(numT2Pods-4.5)*(modeNumReq-12.89)	-0.01553	0.00043	-36.14	<.0001*
(numT2Pods-4.5)*(verAngTProb-0.5)	0.55645	0.015453	36.01	<.0001*
(modePodsRepTime-2520)*(verAngTProb-0.5)	-0.000761	3.143e-5	-24.21	<.0001*
t1PodsDefProb	0.6482204	0.037774	17.16	<.0001*
(modeNumReq-12.89)*(modePodsRepTime-2520)	1.3076e-5	8.527e-7	15.34	<.0001*
modeHighPriDueDays	0.0179997	0.001353	13.30	<.0001*
(verAngTProb-0.5)*(badWeatConProb-0.2)	-3.389556	0.323038	-10.49	<.0001*
(modeHighPriDueDays-5.1)*(t1PodsDefProb-0.1)	0.49652	0.047798	10.39	<.0001*

Figure 86. Sorted Parameter Estimates of Model for avgTimeAtWFForResRecRequests

A discussion about the sign and importance of main effects was provided in the previous section. As seen from this model, in addition to main effects, there are nine interaction terms and one quadratic term. Figure 87 shows the interaction profiler.

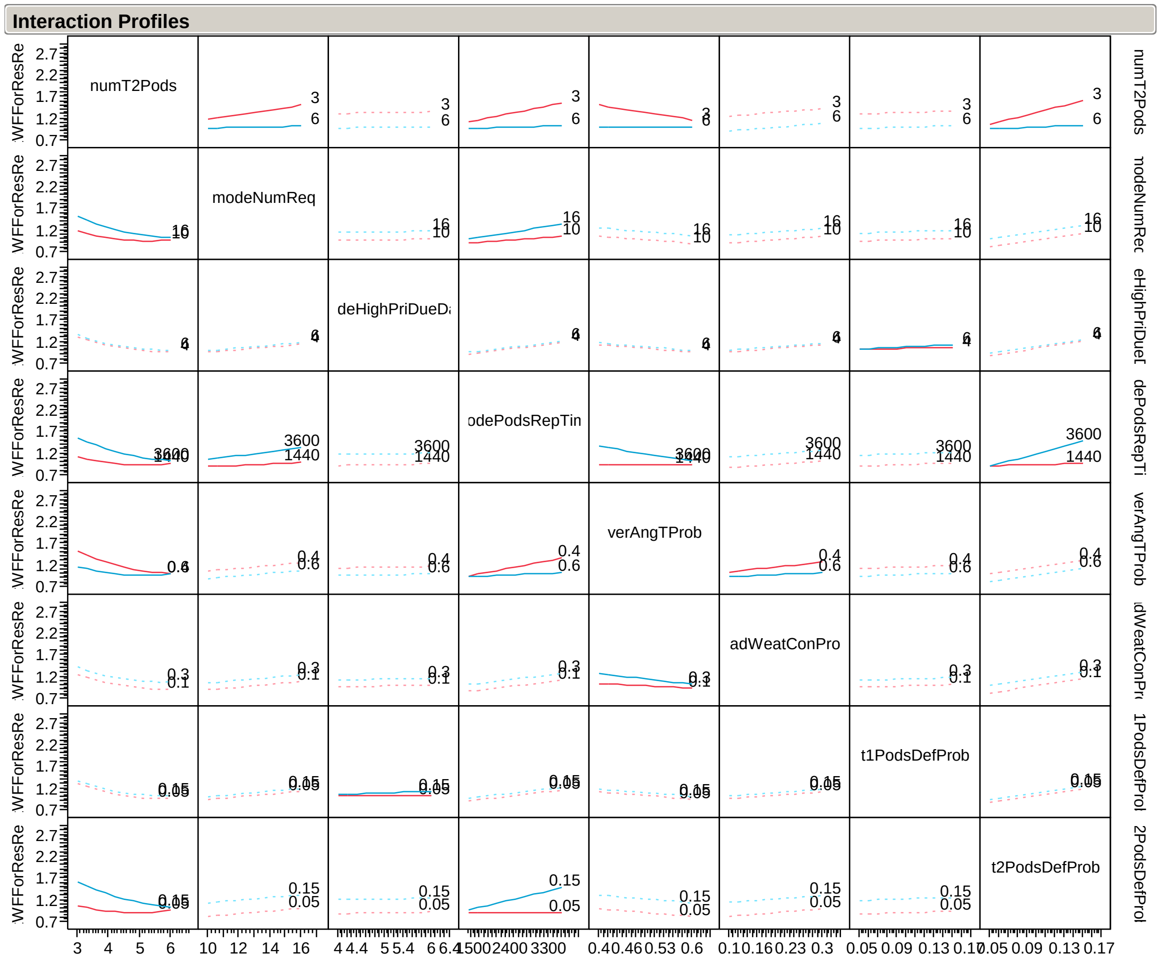


Figure 87. Interaction Profiler of Model for avgTimeAtWFForResRecRequests

One of the remarkable interactions is the one between number of Type 2 pods and Type 2 pods defect probability. For the six Type 2 pods, an increase in the Type 2 pods defect probability increases the avgTimeAtWFForResRecRequests a little. However, for three Type 2 pods, an increase in the Type 2 pods defect probability increases the avgTimeAtWFForResRecRequests a lot. We can conclude that we need more than three (almost six) Type 2 pods to decrease its negative defect probability effect on avgTimeAtWFForResRecRequests.

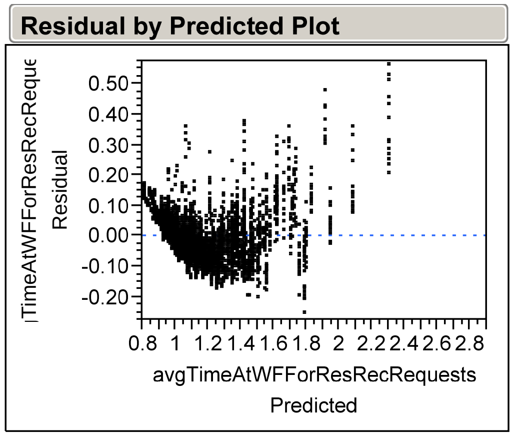


Figure 88. Residual by Predicted Plot of Model for avgTimeAtWFForResRecRequests

As seen from Figure 88, the vertical spread of the residuals is almost the same. As seen from Figure 89, distribution of residuals is almost symmetric and unimodal, which is good.

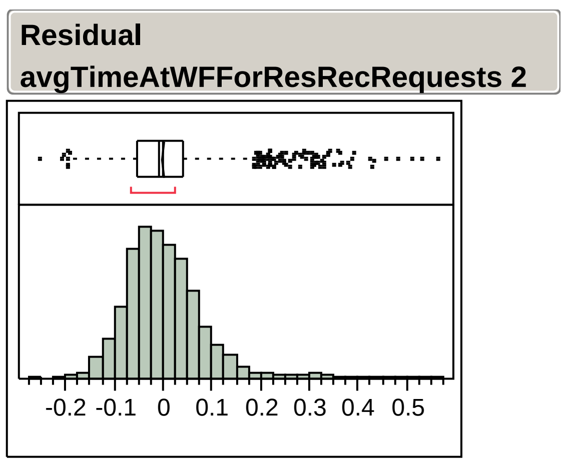


Figure 89. Residuals of Model for avgTimeAtWFForResRecRequests

d. Partition Tree Model

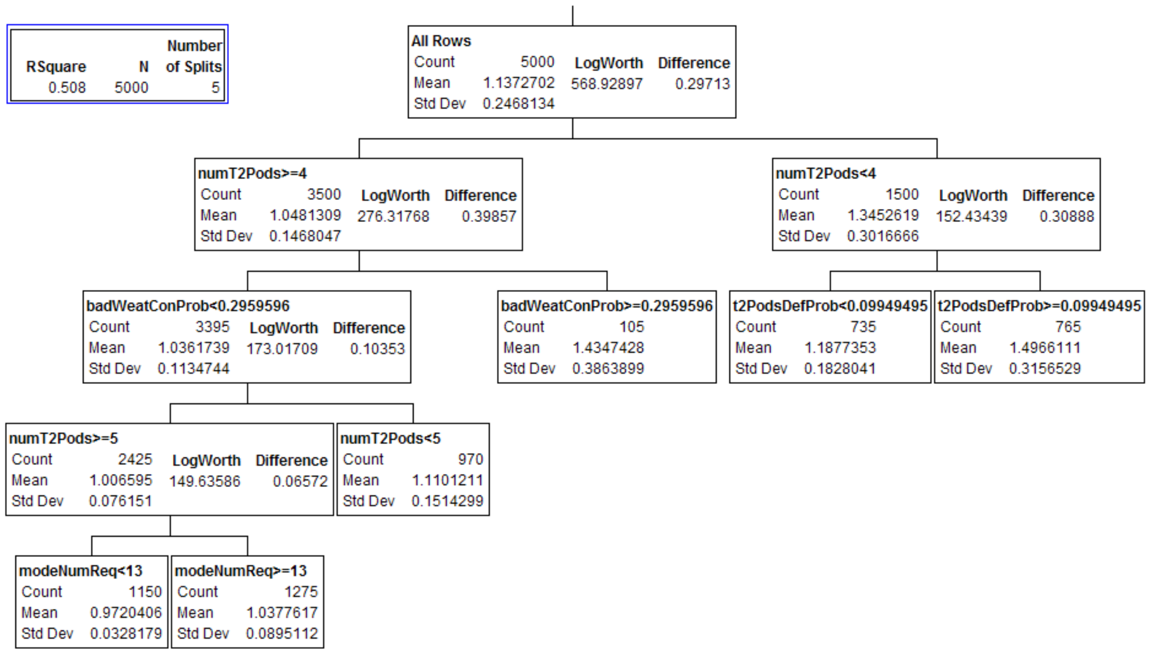


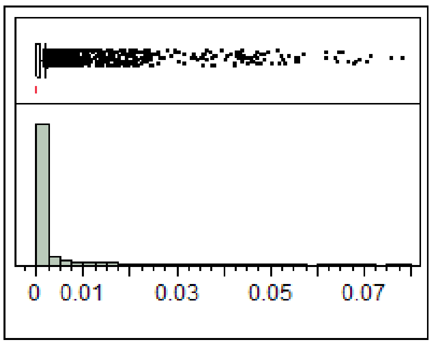
Figure 90. Partition Tree Model for avgTimeAtWFForResRecRequests

Figure 90 shows a partition tree example with only five splits. The R^2 value of 0.508 indicates that 51% of the variability in the response variable is explained by the model. More splits could be added to this tree if future analysts wish to examine smaller subsets of the data in more detail and to obtain more explanatory power from model. The particular areas of interest in the tree are the leftmost and rightmost areas. In the leftmost area we see that when the number of Type 2 pods is greater than or equal to five, bad weather condition probability is less than 0.3 and mode number of requests arriving to squadron is less than thirteen, avgTimeAtWFForResRecRequests is low (Mean 0.97 with a SD 0.03), which makes sense. In the rightmost area we see that when the number of Type 2 pods is less than four and type 2 pods' defect probability is greater than 0.1 avgTimeAtWFForResRecRequests is high (Mean 1.5 with a SD 0.32), which makes sense, too.

2. Removed Over Arrived Reconnaissance Requests Ratio

Figure 91 shows the basic statistics for the remOverArrRecRequestsRatio (removed over arrived reconnaissance requests ratio). With the realistic values the authors used, the mean of remOverArrRecRequestsRatio is 0.002 with a standard deviation of 0.007. The distribution of remOverArrRecRequestsRatio is skewed to the right and is unimodal. The maximum remOverArrRecRequestsRatio is 0.08, which is fairly small, so no model was created for remOverArrRecRequestsRatio.

removedOverArrivedRecRequestsRatio



Quantiles

100.0%	maximum	0.07837
99.5%		0.05183
97.5%		0.02099
90.0%		0.00432
75.0%	quartile	0.00070
50.0%	median	0.00000
25.0%	quartile	0.00000
10.0%		0.00000
2.5%		0.00000
0.5%		0.00000
0.0%	minimum	0.00000

Moments

Mean	0.0020508
Std Dev	0.0069939
Std Err Mean	0.0000989
Upper 95% Mean	0.0022447
Lower 95% Mean	0.0018569
N	5000

Figure 91. Distribution of remOverArrRecRequestsRatio

3. Robust Configuration for Reconnaissance Squadron

After using a stepwise regression analysis with main effects, interactions and quadratic effects of five decision factors, regression models for mean and standard deviations of remOverArrRecRequestsRatio and avgTimeAtWFForResRecRequests were built. The remOverArrRecRequestsRatio MoE is more important than avgTimeAtWFForResRecRequests MoE for the reconnaissance squadron commander. Therefore we will deal with models for remOverArrRecRequestsRatio first. If there will be any conflicting decision factor setting(s), the one(s) used for remOverArrRecRequestsRatio will be recommended. Figure 92 shows the Prediction Profiler for the model of remOverArrRecRequestsRatio’s standard deviation. Relevant decision factors were set to minimize the standard deviation of remOverArrRecRequestsRatio, and these same values were used to minimize the mean of remOverArrRecRequestsRatio, as seen in Figure 93.

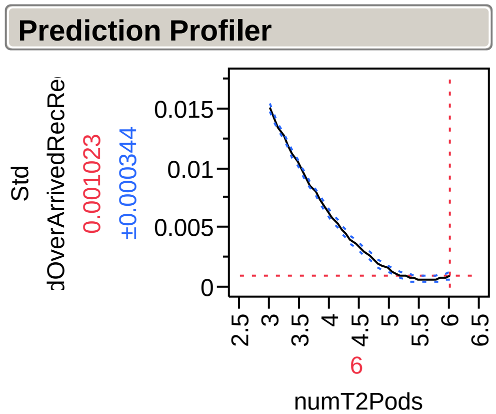


Figure 92. Prediction Profiler for Model of remOverArrRecRequestsRatio's Standard Deviation

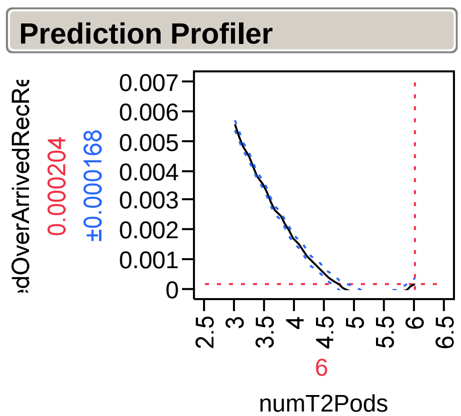


Figure 93. Prediction Profiler for Model of remOverArrRecRequestsRatio's Mean

Figure 94 shows the prediction profiler for the Model of avgTimeAtWFForResRecRequests's standard deviation. Relevant decision factors were set to minimize standard deviation of avgTimeAtWFForResRecRequests, and these same values were used to minimize mean of avgTimeAtWFForResRecRequests, as seen in Figure 95.

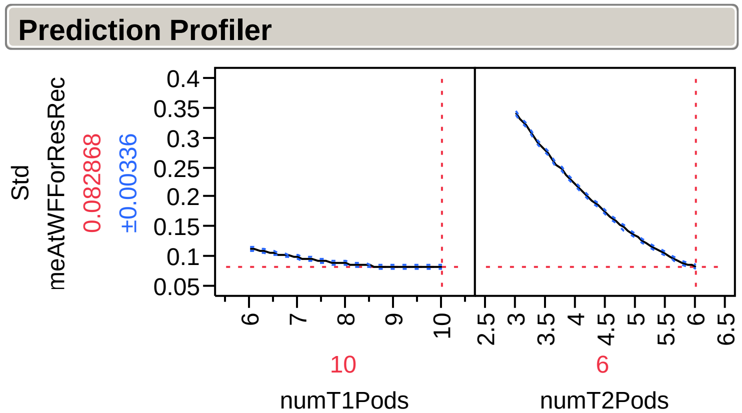


Figure 94. Prediction Profiler for Model of avgTimeAtWFForResRecRequests's Standard Deviation

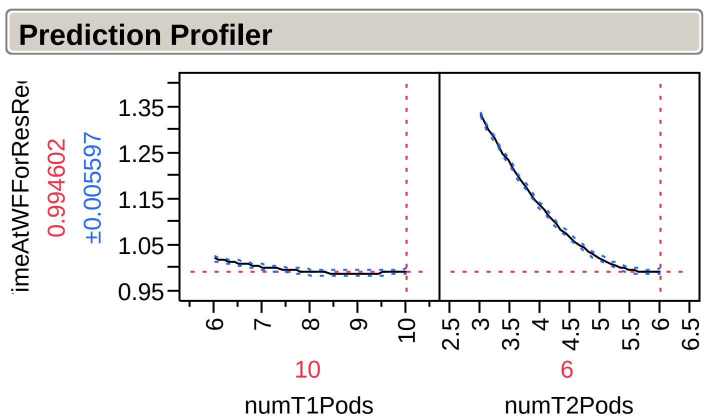


Figure 95. Prediction Profiler for Model of avgTimeAtWFForResRecRequests's Mean

After comparing decision factors' settings for remOverArrRecRequestsRatio and avgTimeAtWFForResRecRequests MoEs, we see that there is no conflicting decision factor. The decision factors not seen in either Prediction Profilers for remOverArrRecRequestsRatio or avgTimeAtWFForResRecRequests are set to their minimum levels used in experiment. Table 6 shows the robust configuration for the reconnaissance squadron in configuration: F-16 / situation: peace scenario.

Number	Decision Factors	Value
1	numT1Pods	10
2	numT2Pods	6
3	numACs	20
4	numPilots	35
5	numAnalysts	5

Table 6. Robust Configuration for Reconnaissance Squadron in Configuration: F-16 / Situation: Peace Scenario

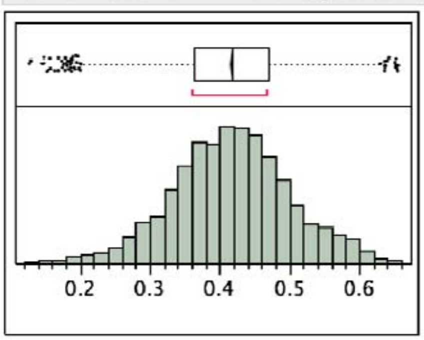
F. OUTPUT ANALYSIS FOR CONFIGURATION: F-16 / SITUATION: WAR

1. Removed Over Arrived Reconnaissance Requests Ratio

a. Basic Statistics

Figure 96 shows the basic statistics for the remOverArrRecRequestsRatio (removed over arrived reconnaissance requests ratio). With the realistic values the authors used, the mean of remOverArrRecRequestsRatio is 0.41 with a standard deviation of 0.08. Distribution of remOverArrRecRequestsRatio is unimodal and symmetric. Maximum remOverArrRecRequestsRatio is 0.65, which is big.

removedOverArrRecRequestsRatio



Quantiles

100.0%	maximum	0.65579
99.5%		0.61735
97.5%		0.58427
90.0%		0.52365
75.0%	quartile	0.46945
50.0%	median	0.41615
25.0%	quartile	0.36255
10.0%		0.31239
2.5%		0.24981
0.5%		0.18659
0.0%	minimum	0.12827

Moments

Mean	0.4161831
Std Dev	0.0828509
Std Err Mean	0.0011717
Upper 95% Mean	0.4184801
Lower 95% Mean	0.413886
N	5000

Figure 96. Distribution of remOverArrRecRequestsRatio

b. Regression Model Built by Using Only Main Effects

After using a stepwise regression analysis with only the main effects of twenty-one input factors, a regression model for the remOverArrRecRequestsRatio was built. Figure 97 shows the actual by predicted plot of this model. The p-value of this model is less than 0.0001, which means the model is statistically significant. The R^2 value of 0.80 indicates that 80% of the variability in the response variable is explained by the model.

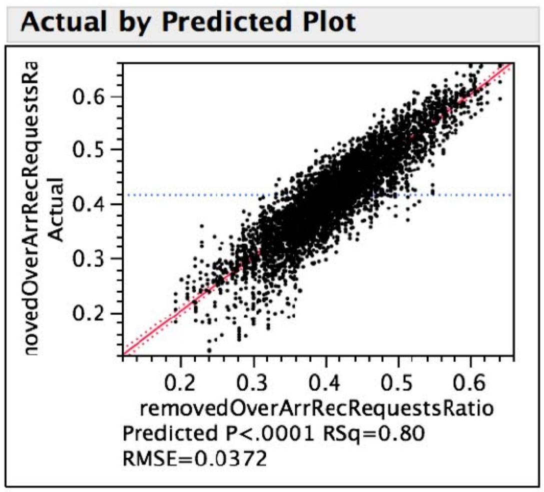


Figure 97. Actual by Predicted of Model for remOverArrRecRequestsRatio

Figure 98 shows the Summary of Fit (SoF) and Analysis of Variance (AoV) tables for the regression model built for remOverArrRecRequestsRatio.

Summary of Fit

RSquare	0.799341
RSquare Adj	0.798818
Root Mean Square Error	0.037161
Mean of Response	0.416183
Observations (or Sum Wgts)	5000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	13	27.428997	2.10992	1527.854
Error	4986	6.885524	0.00138	**Prob > F**
C. Total	4999	34.314521		0.0000*

Figure 98. SoF and AoV Tables of Model for remOverArrRecRequestsRatio

Figure 99 shows thirteen statistically significant terms, sorted by their importance on response. Mode time of pods repair, mode number of reconnaissance requests, probability of aircraft interception, probability of both type 1 and 2 pods defects, probability of bad weather condition, mode time of aircraft repair and half distance of time for pods repair have a positive effect on remOverArrRecRequestsRatio.

On the other hand, the number of type 2 pods, number of type 1 pods, probability of vertical angle type, half distance aircraft repair time and probability of data link defect have a negative effect on remOverArrRecRequestsRatio. The half distance aircraft repair time and probability of data link defects negative effects seem counter-intuitive, although these have much smaller impacts than the other terms with negative effects.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
modePodsRepTime	5.8651e-5	8.346e-7	70.28	0.0000*
modeNumReq	0.0160183	0.000251	63.92	0.0000*
numT2Pods	-0.025662	0.000436	-58.80	0.0000*
aCInterProb	0.9975895	0.020032	49.80	0.0000*
t1PodsDefProb	0.8170746	0.018026	45.33	0.0000*
t2PodsDefProb	0.5162471	0.018025	28.64	<.0001*
numT1Pods	-0.009163	0.000348	-26.33	<.0001*
verAngTProb	-0.231675	0.009013	-25.70	<.0001*
badWeatConProb	0.2255787	0.009013	25.03	<.0001*
halfDistACRepTime	-2.948e-5	4.507e-6	-6.54	<.0001*
modeACRepTime	4.8893e-6	8.348e-7	5.86	<.0001*
halfDistPodsRepTime	2.0848e-5	4.506e-6	4.63	<.0001*
dataLinkDefProb	-0.037634	0.009013	-4.18	<.0001*

Figure 99. Sorted Parameter Estimates of Model for remOverArrRecRequestsRatio

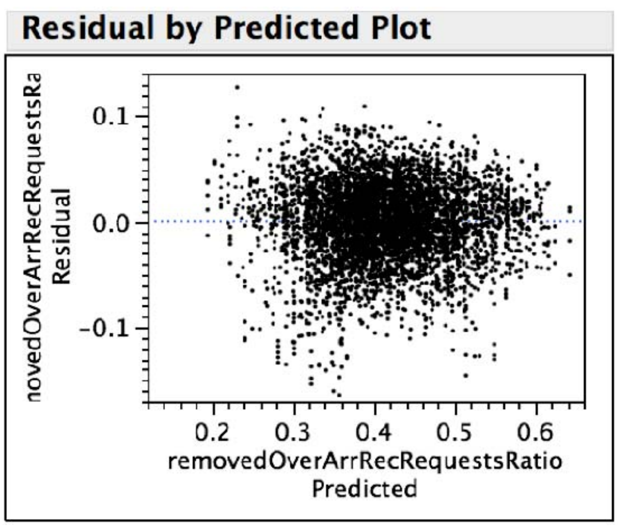


Figure 100. Residual by Predicted Plot of Model for remOverArrRecRequestsRatio

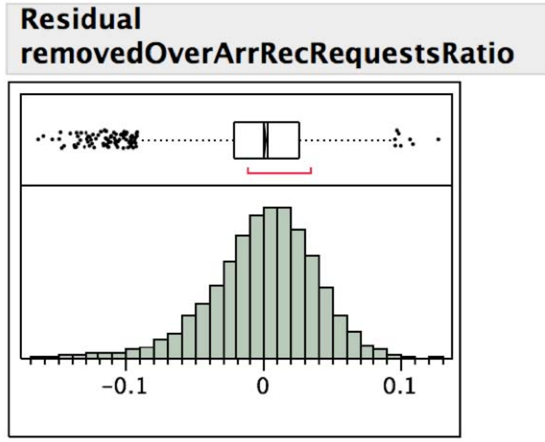


Figure 101. Residuals of Model for remOverArrRecRequestsRatio

As seen from Figure 100, the vertical spread of the residuals is almost the same. A model that includes some interactions or quadratic effects may provide a better fit. As seen from Figure 101, the distribution of residuals is bimodal but not symmetric.

c. Regression Model Built by Using Main Effects, Interactions and Quadratic Effects

After using a stepwise regression analysis with main effects, interactions and quadratic effects of twenty-one input factors, a regression model for the remOverArrRecRquestsRatio was built. Figure 102 shows the actual by predicted plot of this model. The p-value of this model is less than 0.0001, which means the model is statistically significant. The R^2 value of 0.90 indicates that 90% of the variability in the response variable is explained by the model.

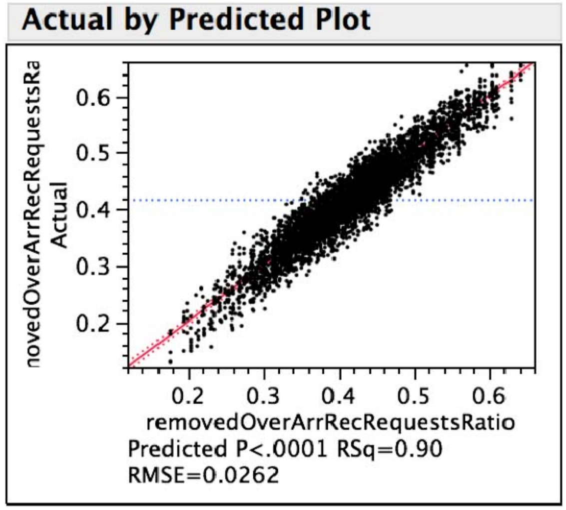


Figure 102. Actual by Predicted Plot of Model for remOverArrRecRequestsRatio

Figure 103 shows Summary of Fit (SoF) and Analysis of Variance (AoV) tables of regression model built for remOverArrRecRequestsRatio.

Summary of Fit

RSquare	0.900394
RSquare Adj	0.899953
Root Mean Square Error	0.026206
Mean of Response	0.416183
Observations (or Sum Wgts)	5000

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	22	30.896580	1.40439	2044.988
Error	4977	3.417941	0.00069	**Prob > F**
C. Total	4999	34.314521		0.0000*

Figure 103. SoF and AoV Tables of Model for remOverArrRecRequestsRatio

Figure 104 shows twenty-two statistically significant terms, sorted by their importance on response. Figure 105 shows interactions between the significant terms.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
modePodsRepTime	5.5515e-5	6.191e-7	89.68	0.0000*
modeNumReq	0.0157178	0.000182	86.60	0.0000*
numT2Pods	-0.025662	0.000308	-83.38	0.0000*
t1PodsDefProb	0.9863369	0.014166	69.63	0.0000*
aCInterProb	0.9538715	0.014634	65.18	0.0000*
(aCInterProb-0.075)*(aCInterProb-0.075)	-33.28651	0.657934	-50.59	0.0000*
badWeatConProb	0.302247	0.006564	46.05	0.0000*
verAngTProb	-0.271771	0.006514	-41.72	0.0000*
t2PodsDefProb	0.5375632	0.013069	41.13	<.0001*
numT1Pods	-0.009163	0.000245	-37.33	<.0001*
(modeNumReq-12.89)*(aCInterProb-0.075)	-0.160204	0.006861	-23.35	<.0001*
(numT1Pods-8)*(aCInterProb-0.075)	0.2173503	0.009353	23.24	<.0001*
(numT2Pods-4.5)*(aCInterProb-0.075)	0.2195525	0.011729	18.72	<.0001*
(numT2Pods-4.5)*(verAngTProb-0.5)	0.0840791	0.005278	15.93	<.0001*
(numT1Pods-8)*(verAngTProb-0.5)	-0.065634	0.004209	-15.59	<.0001*
(modeNumReq-12.89)*(modeNumReq-12.89)	-0.001528	0.000111	-13.76	<.0001*
(t1PodsDefProb-0.1)*(aCInterProb-0.075)	6.9444003	0.53184	13.06	<.0001*
(modePodsRepTime-2520)*(aCInterProb-0.075)	0.0002805	2.354e-5	11.91	<.0001*
(modePodsRepTime-2520)*(t2PodsDefProb-0.1)	0.0002095	1.983e-5	10.57	<.0001*
(numT1Pods-8)*(t2PodsDefProb-0.1)	-0.082234	0.008418	-9.77	<.0001*
(modeNumReq-12.89)*(modePodsRepTime-2520)	2.9428e-6	3.184e-7	9.24	<.0001*
upRepReqProb	0.0161007	0.006573	2.45	0.0143*

Figure 104. Sorted Parameter Estimates of Model for remOverArrRecRequestsRatio

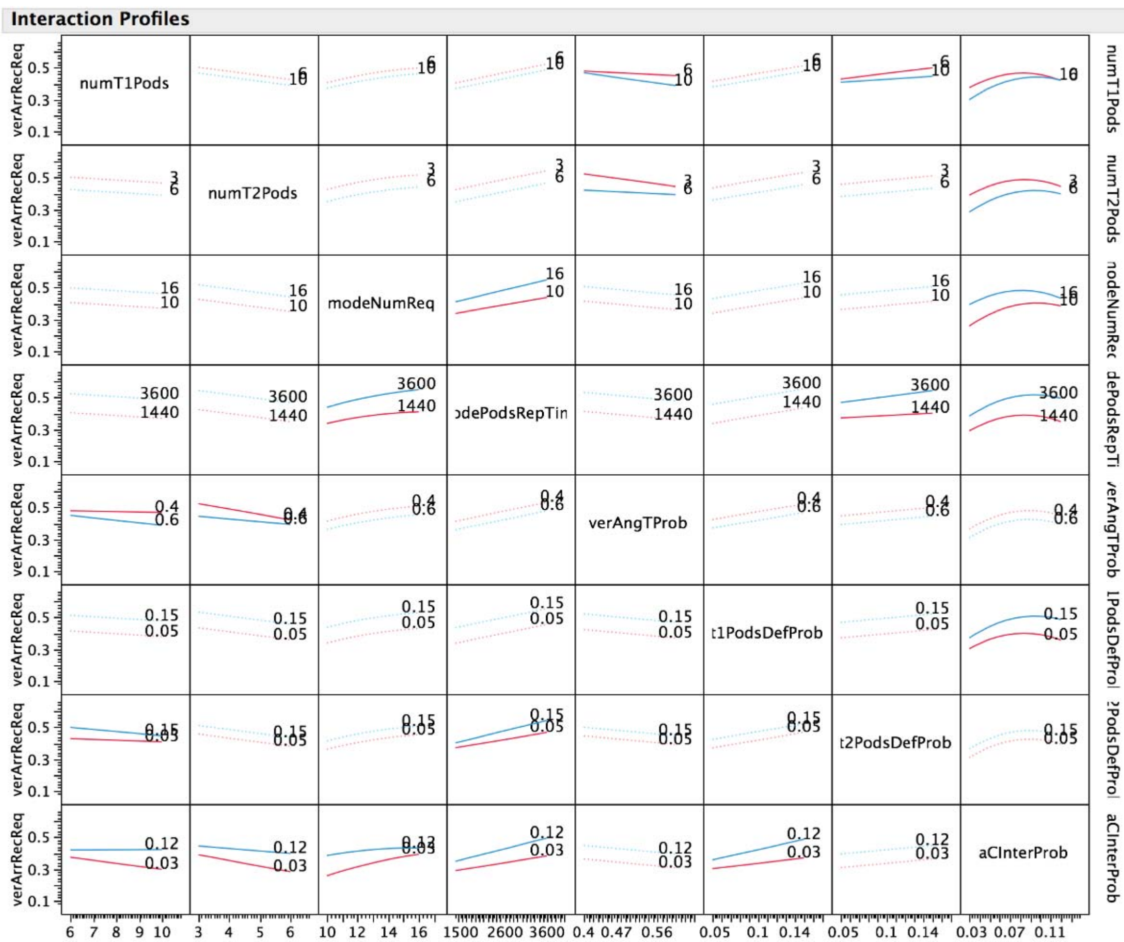


Figure 105. Interaction Profiler of Model for remOverArrRecRequestsRatio

The first remarkable interaction is the one between the number of type 1 pods and vertical angle image type probability. For the six Type 1 pods (type 1 pods takes vertical imagery only), an increase in the vertical angle image type probability decreases the remOverArrRecRequestsRatio a little. However, for ten Type 1 pods, an increase in the vertical angle image type probability decreases the remOverArrRecRequestsRatio a lot. We can conclude that we need more than six Type 1 pods to increase its negative effect on remOverArrRecRequestsRatio.

Another interesting interaction is the one between the number of type 1 pods and aircraft interception probability. For the 0.12 interception probability, an increase in the number of type 1 pods does not change the remOverArrRecRequestsRatio. However, for the 0.03 interception probability, an increase in the number of type 1 pods decreases the remOverArrRecRequestsRatio a lot. We can conclude that we need more aircraft to satisfy reconnaissance requests when the aircraft interception probability is high. For a low aircraft interception probability, we can see the negative effect of the number of type 1 pods.

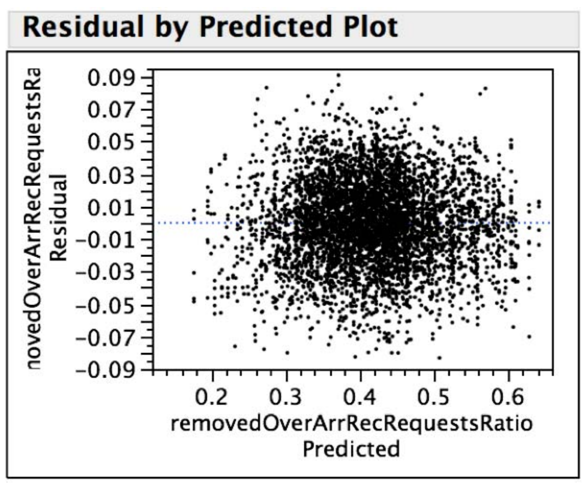


Figure 106. Residual by Predicted Plot of Model for remOverArrRecRequestsRatio

As seen from Figure 106, the vertical spread of the residuals is the same, which is good. As seen from Figure 107, the distribution of residuals is symmetric and unimodal, which is also good.

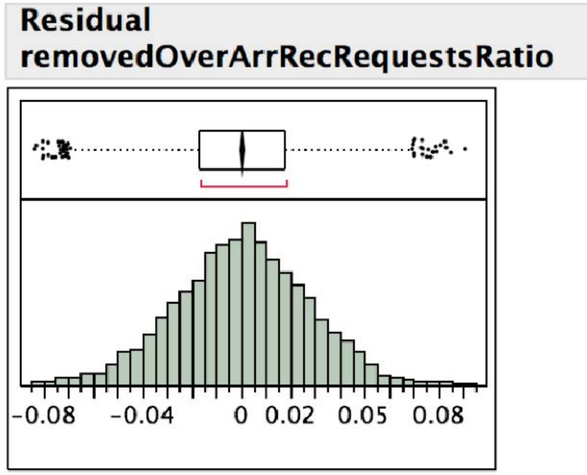


Figure 107. Residual of Model for remOverArrRecRequestsRatio

d. Partition Tree Model

Figure 108 shows a partition tree example with only six splits. The R^2 value of 0.542 indicates that 54% of the variability in the response variable is explained by the model. More splits could be added to this tree if future analysts wish to examine smaller subsets of the data in more detail and to obtain more explanatory power from model. The particular areas of interest in the tree are the leftmost and rightmost areas. In the leftmost area we see that when mode time for pods repair is less than 3,250, the number of type 2 pods is greater than or equal to five, and aircraft interception probability is greater than or equal to 0.05, and mode number of requests is less than fourteen, remOverArrRecRequestsRatio is at minimum (Mean 0.36 with a SD 0.05). In the rightmost area we see that when the mode time for pods repair is greater than or equal to 3,250, and type 1 pod defect probability is greater than or equal to 0.09, remOverArrRecRequestsRatio is at maximum (Mean 0.54 with a SD 0.04).

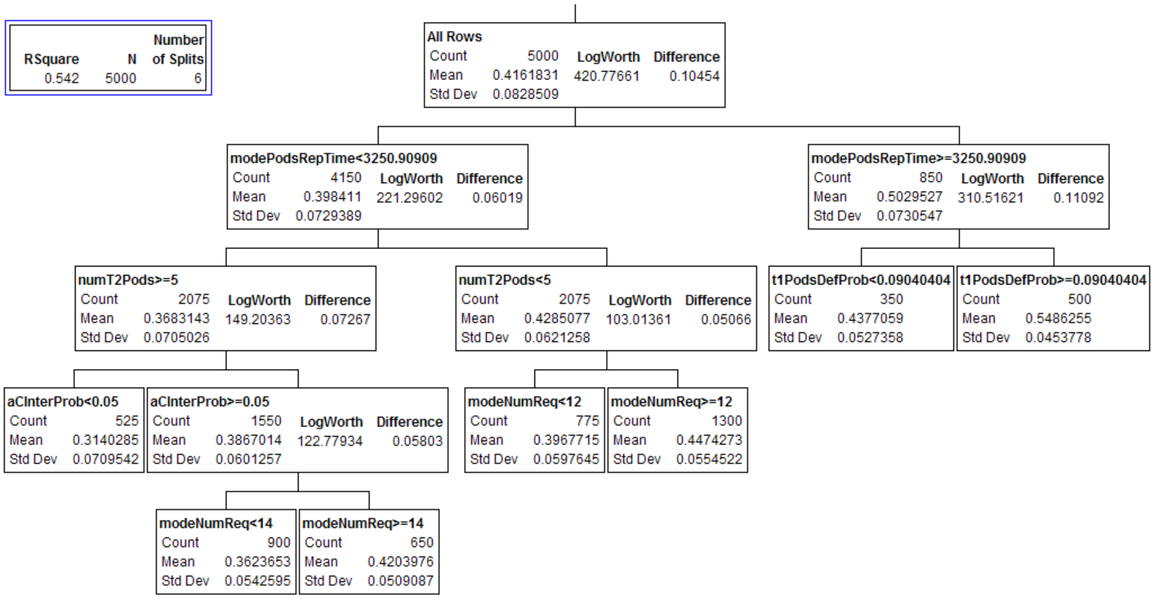


Figure 108. Partition Tree Model for remOverArrRecRequestsRatio

2. Robust Configuration for Reconnaissance Squadron

After using a stepwise regression analysis with main effects, interactions and quadratic effects of five decision factors, regression models for mean and standard deviations of remOverArrRecRequestsRatio and avgTimeAtWFForResRecRequests were built. The remOverArrRecRequestsRatio MoE is more important than avgTimeAtWFForResRecRequests MoE for the reconnaissance squadron commander. Therefore we will deal with models for remOverArrRecRequestsRatio first. If there will be any conflicting decision factor setting(s), the one(s) used for remOverArrRecRequestsRatio will be recommended. Figure 109 shows the prediction profiler for the model of remOverArrRecRequestsRatio's standard deviation. Relevant decision factors were set to minimize the standard deviation of remOverArrRecRequestsRatio, and these same values were used to minimize mean of remOverArrRecRequestsRatio, as seen in Figure 110.

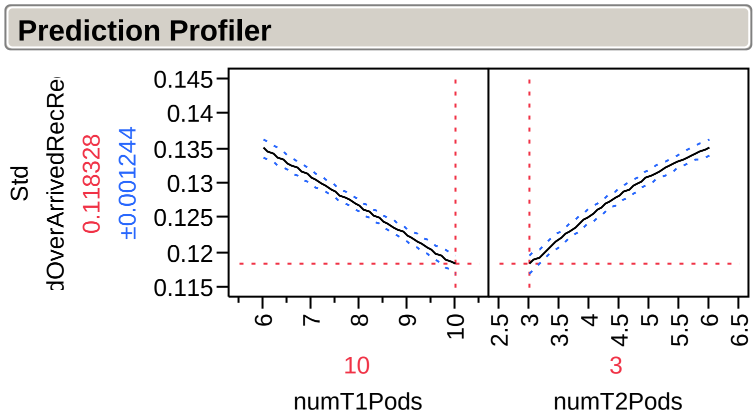


Figure 109. Prediction Profiler for Model of remOverArrRecRequestsRatio's Standard Deviation

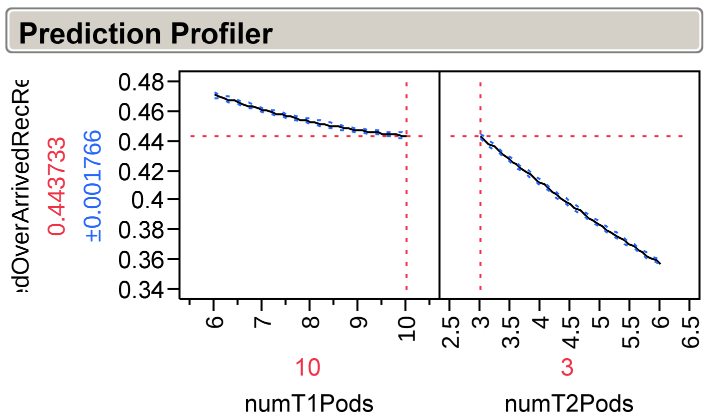


Figure 110. Prediction Profiler for Model of remOverArrRecRequestsRatio's Mean

Figure 111 shows the prediction profiler for the model of avgTimeAtWFForResRecRequests's standard deviation. Relevant decision factors were set to minimize standard deviation of avgTimeAtWFForResRecRequests, and these same values were used to minimize mean of avgTimeAtWFForResRecRequests, as seen in Figure 112.

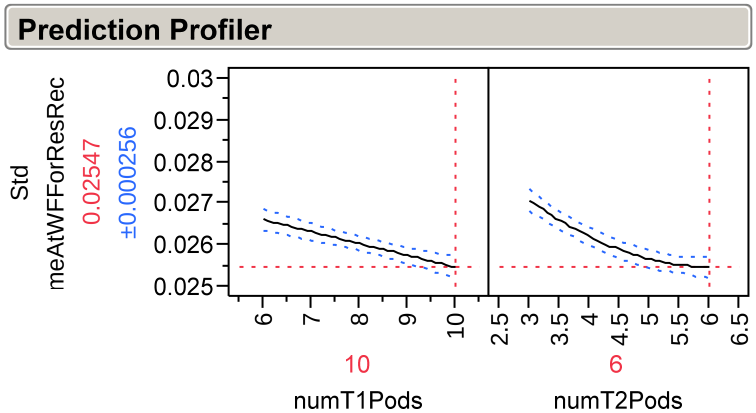


Figure 111. Prediction Profiler for Model of avgTimeAtWFForResRecRequests's Standard Deviation

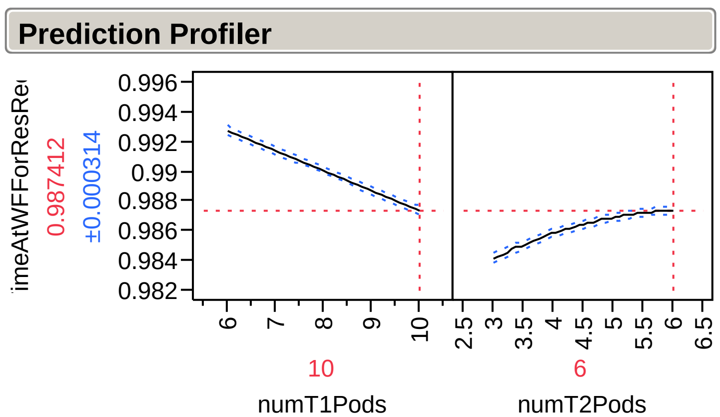


Figure 112. Prediction Profiler for Model of avgTimeAtWFForResRecRequests's Mean

After comparing decision factors' settings for remOverArrRecRequestsRatio and avgTimeAtWFForResRecRequests MoEs, we see that there is only one conflicting decision factor setting, which is the numType2Pods. It was set to three to minimize the standard deviation of remOverArrRecRequestsRatio, and this value is recommended. The decision factors not seen in prediction profilers for either remOverArrRecRequestsRatio or avgTimeAtWFForResRecRequests are set to their minimum levels used in experiment. Table 7 shows the robust configuration for the reconnaissance squadron in configuration: F-16 / situation: war scenario.

Number	Decision Factors	Value
1	numT1Pods	10
2	numT2Pods	3
3	numACs	20
4	numPilots	35
5	numAnalysts	5

Table 7. Robust Configuration for Reconnaissance Squadron in Configuration: F-16 / Situation: War Scenario

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VI. RECONNAISSANCE SQUADRON WORKFLOW SIMULATION GUI FOR QUICK ANALYSIS

There is one Graphical User Interface (GUI) for each scenario. In this thesis there were in total four scenarios, thus four GUIs. The GUIs are for facilitating quick analysis by the user. The user can enter the most updated information for input factors of each scenario. Figure 113 shows Peace Situation Configuration RF-4 GUI, which consists of Inputs and Statistics panes. The input pane contains four tabs: Sim Params, Params(1), Params(2), and Probabilities. The Sim Params tab includes replication and duration input parameters, while the Params(1), Params(2) and Probabilities tabs includes model-specific input parameters, such as the number of aircraft, number of pilots, probability of aircraft defect, etc. Figure 114 shows War Situation Configuration RF-4 GUI. In contrast to the Peace Situation Configuration RF-4 GUI, it includes the probability of aircraft interception input and excludes input parameters for priority due dates.

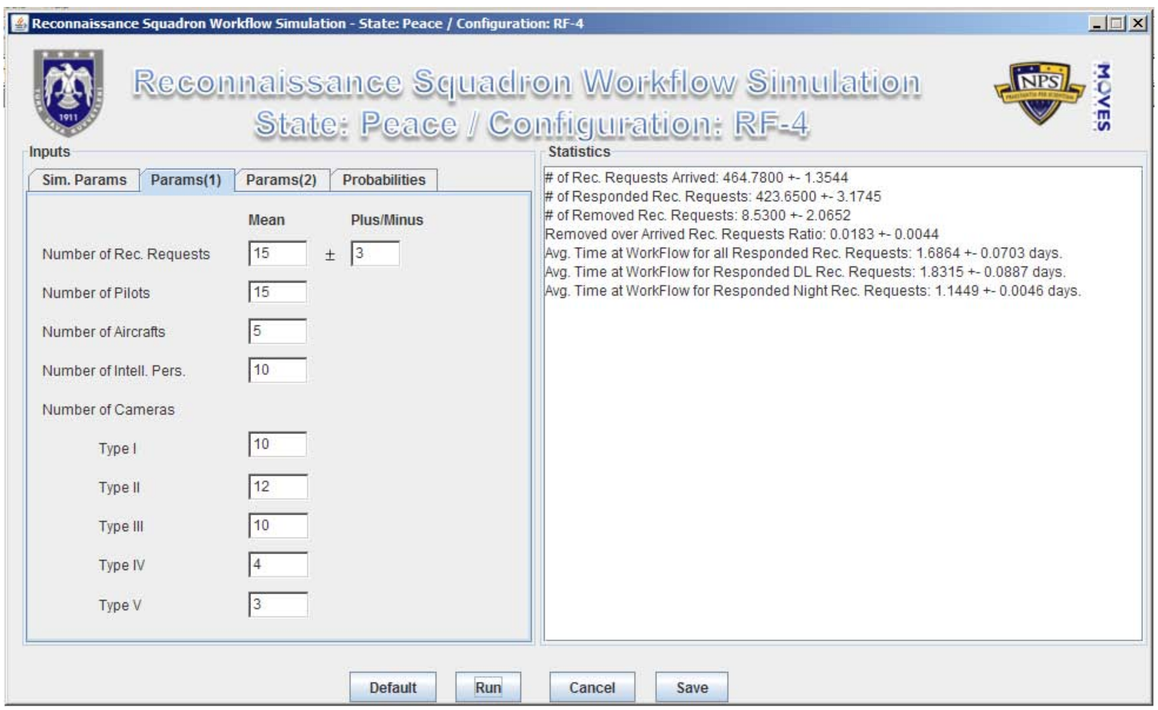

Figure 113. Conf.: RF-4 / Sit.: Peace Quick Analysis GUI

The statistics pane is used for simulation results. After the simulation run, the number of reconnaissance requests, number of responded requests, number of removed requests, and average time at workflow for both day and night requests, etc., are presented with a 95% confidence interval (CI). For war situations, the statistics pane also gives the average time that the RF-4 reconnaissance squadron was operational.

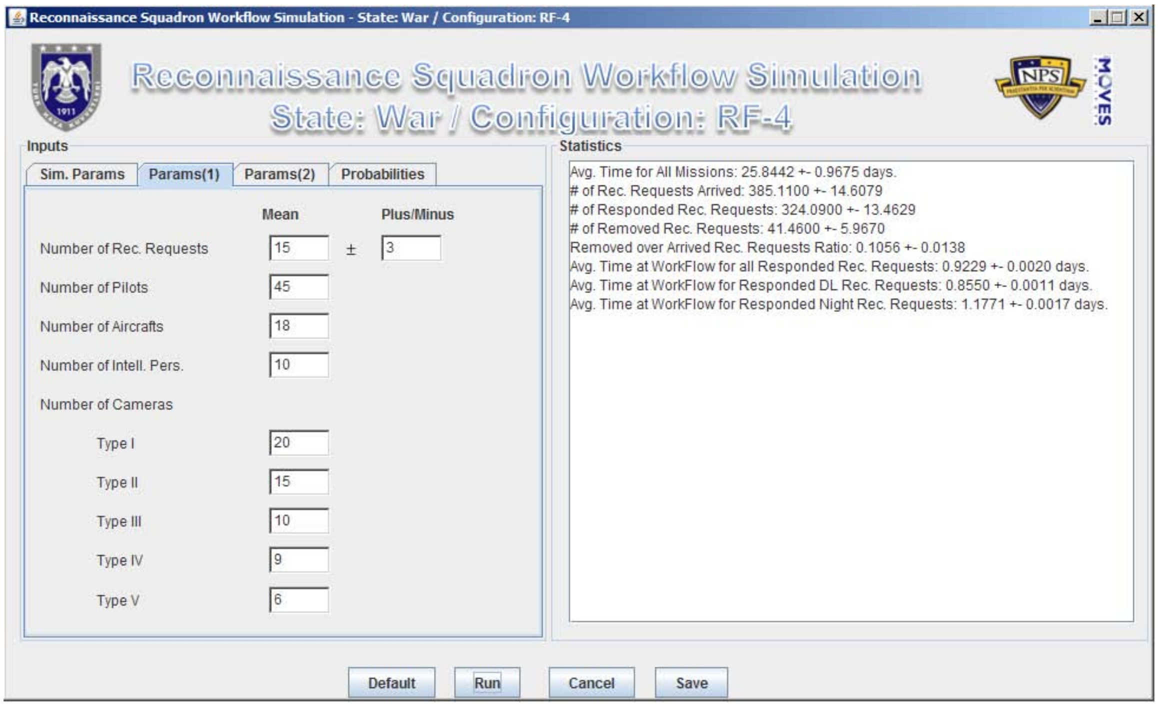

Figure 114. Conf.: RF-4 / Sit.: War Quick Analysis GUI

Figure 115 shows the Peace Situation Configuration F-16 GUI, with model specific input parameters such as data link defect probability, night mission probability, requiring update reconnaissance mission probability, etc.

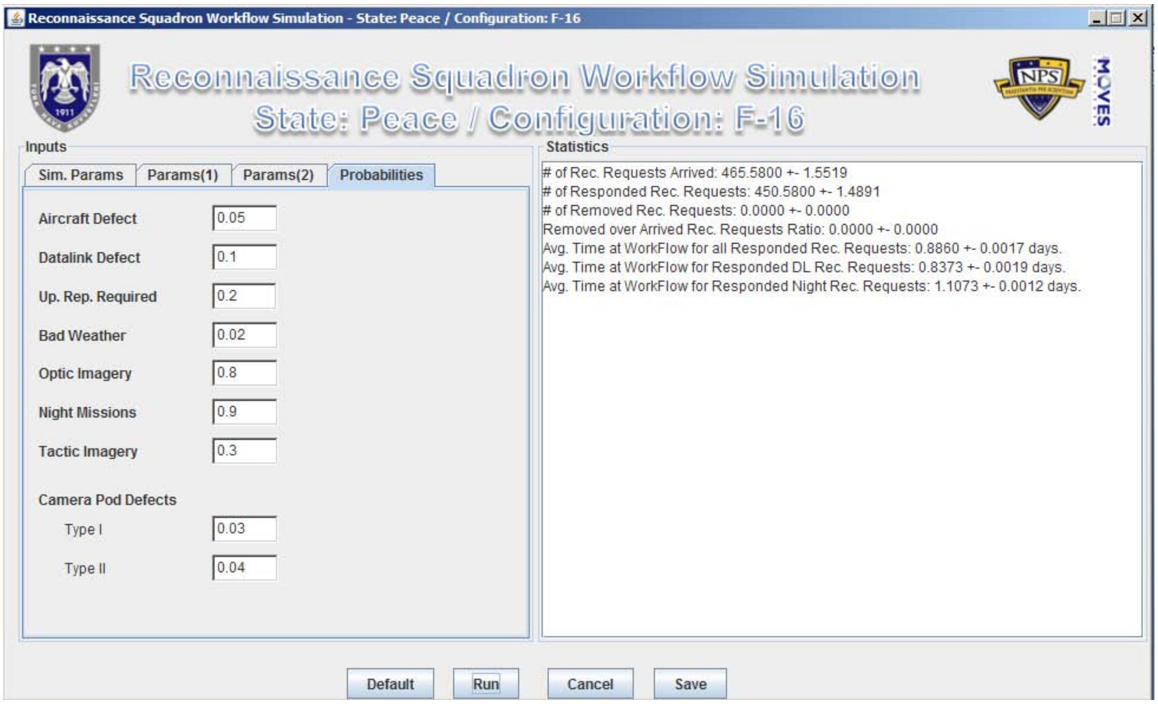

Figure 115. Conf.: F-16 / Sit.: Peace Quick Analysis GUI

Figure 116 depicts the War Situation Configuration F-16 GUI for quick analysis. This GUI is different than the Peace Situation Configuration F-16 GUI depicted in Figure 115 because it includes the probability of aircraft interception input, and excludes priority due dates input parameters specific to the peace scenario (recall that all wartime requests are due within one day).

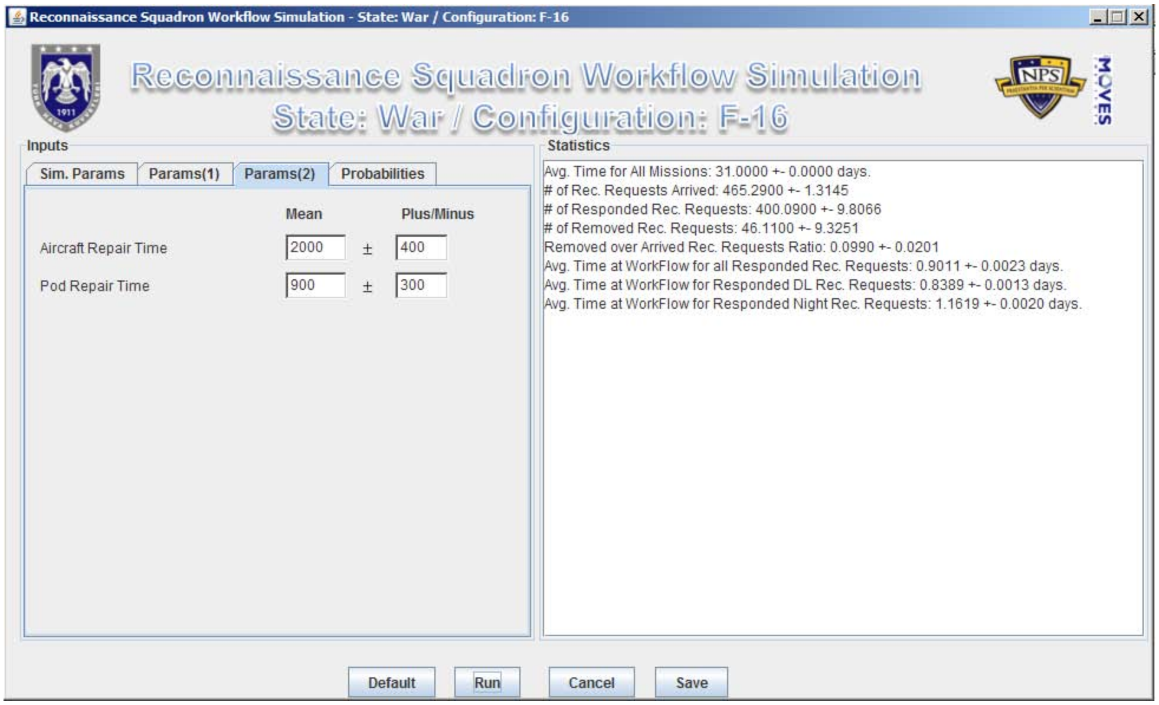

Figure 116. Conf.: F-16 / Sit.: War Quick Analysis GUI

There are four buttons at the bottom of the GUI. The default button sets default values defined in the simulation for input parameters; this way, users are not required to change every input parameter. The run button starts the simulation. It also checks the parameters for correct input types. Moreover, when run is clicked, a message box appears which says the simulation is running. The message pane closes automatically once the results of the simulation are written in the statistics pane. The cancel button closes the GUI, while the save button saves the results of the simulation in a user-defined name and location.

VII. CONCLUSIONS AND FUTURE WORK

A. CONCLUSIONS

A simplified reconnaissance cycle includes the arrival of reconnaissance requests, planning of reconnaissance flights, flying the mission and exploitation of the films or images, and then dissemination of the intelligence reports. The reconnaissance cycle was modeled for four different scenarios (peace and war as situations, and RF-4 and F-16 as configurations). There are two points of view about reconnaissance squadron workflow. The first one is the reconnaissance requesters' view. They want to know the estimated time it would take for a request to be answered based on the resources and other factors before the actual request was made. The second one is the reconnaissance squadron commanders' perspective. They want to respond to as many reconnaissance requests as possible. For that reason, they want to know and revise the ideal numbers of personnel and equipment. For the purpose of answering these questions, satisfying these requests, and having a better understanding about reconnaissance cycle, we modeled and analyzed Reconnaissance Squadron Workflow for four different scenarios.

For the development of models, we used a basic modeling process and discrete event simulation techniques. Simkit was used as the simulation tool. Input and distributional parameters are based on realistic notional data (because of their classified nature) that are used to generate the levels of each input factor. Two designs (one for decision and one for noise factors) were generated for each model by using the "Generating and Improving Orthogonal Designs by Using Mixed Integer Programming tool." (see also Vieira et al., 2010) These two designs were crossed to generate designs for each scenario. We experimented all of the four models by using these designs. Generated output data was imported to the statistical analysis software, JMP, for analysis. Effective regression models were generated to estimate and analyze each MoE. The factors that have the most significant effects on the MoEs were identified in relevant sections. We found a robust configuration (set of decision factor settings) for each scenario, in order to identify ideal numbers of personnel and equipment.

In Chapter V, we provided detailed explanations of how the factors affect the MoEs. When all regression models are considered, we see that there is no common rule to determine which factors (either decision or noise) are the key determinants of each MoE. But we noticed that the ratio of the total number of noise factors to the total number of decision factors in each model is high. Some of these noise factors could be controllable, including aircraft, camera and pod defect probabilities and their repair times. Some precautionary measures should be taken to reduce these defect probabilities and repair times.

Specifically, in the RF-4 configuration models, pilot filming error is a significant factor, which shows that training of the pilots is also important and cannot be ignored.

When the F-16 models are considered, we see that data link defect probability is a significant factor. This suggests that data link capability is an important factor in providing reconnaissance requests quickly, and special precautions should be taken to keep this capability working.

We also developed four GUIs—one for each model (scenario)—to facilitate quick analysis. Future users can run each simulation extremely fast with correct and valid inputs. When the simulation ends, some of the average values for state variables such as number of arrived requests, responded requests, un-responded requests, average time at workflow for responded requests, etc., are presented in 95% CI intervals; these can be used for defense resource planning, resource management, and decision making.

There is optimization involved in flight planning for reconnaissance missions. When a flight needs to be planned, simulation assigns the resources that will be available at the earliest time.

B. FUTURE WORK

In the developed models, reconnaissance requests have fixed target assignments and are assumed to arrive to the squadron in bulk. Our model assumes that reconnaissance requests arrive to the squadron the day before the actual mission takes place. However, in real world situations, there are also emerging targets to be filmed, such as mobile units. So, in addition to the bulk arriving reconnaissance requests, dynamic arrival of reconnaissance requests can be implemented. Also, flight leg planning integrated with air refueling can be implemented to represent flight legs more realistically.

2D or 3D visualization can be added to overall simulation in compliance with DES. Real time statistics can be generated while the simulation is running. With these additions, future users can get a better understanding about the workload and workflow of the reconnaissance squadron.

Pilots and image analysts' sick days or daily leaves can be implemented in each model. These factors might change the regression models and/or increase the number of pilots and image analysts in the recommended robust configurations.

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APPENDIX. INPUT FACTOR PARAMETERS FOR DIFFERENT SCENARIOS

A. RF-4 CONFIGURATION / PEACE SITUATION SCENARIO

numT1Cams	numT2Cams	numT3Cams	numT4Cams	
10	5	4	3	
15	8	10	8	
				8 Decision Factors
numT5Cams	numACs	numPilots	numAnalysts	
2	20	35	5	
6	25	45	10	
modeNumReq	halfDistNumReq	modeHighPriDueDays	halfDistHighPriDueDays	
10	2	4	1	
16	6	6	3	
priDueDays LowOverHighRatio	opImgTProb	t1CamsDefProb	t2CamsDefProb	
1.2	0.75	0.15	0.15	
1.6	0.9	0.55	0.55	
				19 Noise Factors
t3CamsDefProb	t4CamsDefProb	t5CamsDefProb	aCDefProb	
0.15	0.2	0.15	0.1	
0.55	0.5	0.55	0.3	
pilotFilErProb	badWeatConProb	modeACRepTime	halfDistACRepTime	
0.1	0.1	1440	500	
0.3	0.3	3600	900	
modeTacCams RepTime	halfDistTacCams RepTime	camsRepTime StraOverTacRatio		
90	45	1.4		
120	60	1.8		

B. RF-4 CONFIGURATION / WAR SITUATION SCENARIO

num1Cams	numT2Cams	numT3Cams	numT4Cams	
10	5	4	3	
15	8	10	8	
				8 Decision Factors
numT5Cams	numACs	numPilots	numAnalysts	
2	20	35	5	
6	25	45	10	
modeNumReq	halfDistNumReq	aCInterceptProb	optImgTProb	
10	2	0.05	0.75	
16	6	0.2	0.9	
t1CamsDefProb	t2CamsDefProb	t3CamsDefProb	t4CamsDefProb	
0.15	0.15	0.15	0.2	
0.55	0.55	0.55	0.6	
				17 Noise Factors
t5CamsDefProb	aCDefProb	pilotFilErProb	badWeatConProb	
0.15	0.1	0.1	0.1	
0.55	0.3	0.3	0.3	
modeACRepTime	halfDistACRepTime	modeTacCams RepTime	halfDistTacCams RepTime	
1440	500	90	45	
3600	900	120	60	
camsRepTime StraOverTacRatio				
1.4				
1.8				

C. F-16 CONFIGURATION / PEACE SITUATION SCENARIO

numT1Pods	numT2Pods	numACs	numPilots	
6	3	20	35	
10	6	25	45	
				5 Decision Factors
numAnalysts				
5				
10				
modeNumReq	halfDistNumReq	modeHighPriDueDays	halfDistHighPriDueDays	
10	2	4	1	
16	6	6	3	
priDueDays LowOverHighRatio	modeACRepTime	halfDistACRepTime	modePods RepTime	
1.2	1440	500	1440	
1.6	3600	900	3600	
halfDistPods RepTime	opImgTProb	verAngTProb	nightFlightProb	18 Noise Factors
500	0.4	0.4	0.8	
900	0.6	0.6	0.9	
badWeatConProb	dataLinkDefProb	t1PodsDefProb	t2PodsDefProb	
0.1	0.1	0.05	0.05	
0.3	0.3	0.15	0.15	
aCDefProb	upRepReqProb			
0.05	0.1			
0.15	0.3			

D. F-16 CONFIGURATION / WAR SITUATION SCENARIO

numT1Pods	numT2Pods	numACs	numPilots	
6	3	20	35	
10	6	25	45	
				5 Decision Factors
numAnalysts				
5				
10				
modeNumReq	halfDistNumReq	modeACRepTime	halfDistACRepTime	
10	2	1440	500	
16	6	3600	900	
modePods RepTime	halfDistPods RepTime	opImgTProb	verAngTProb	
1440	500	0.4	0.4	
3600	900	0.6	0.6	
				16 Noise Factors
nightFlightProb	badWeatConProb	dataLinkDefProb	t1PodsDefProb	
0.8	0.1	0.1	0.05	
0.9	0.3	0.3	0.15	
t2PodsDefProb	aCDefProb	aCInterProb	upRepReqProb	
0.05	0.05	0.03	0.1	
0.15	0.15	0.12	0.3	

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