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A Comparative Analysis of Air-To-Ground Engagement Outcomes in the Joint Warfare System (JWARS) and the JWARS-Joint Semi-Automated Forces Federation

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A COMPARATIVE ANALYSIS OF AIR-TO-GROUND ENGAGEMENT OUTCOMES IN THE JOINT WARFARE SYSTEM (JWARS) AND THE JWARS-JOINT SEMI-AUTOMATED FORCES FEDERATION

by

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ABSTRACT

A COMPARATIVE ANALYSIS OF
AIR-TO-GROUND ENGAGEMENT OUTCOMES
IN THE JOINT WARFARE SYSTEM (JWARS) AND THE
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FEDERATION

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Multi-resolution modeling is the process by which a single model is created by connecting multiple individual models to describe phenomena at different levels of resolution [1]. "When we change resolutions, replacing a detailed model by a more aggregate one, we must ask whether results are 'consistent'" [2].

There are many methods of determining if the results of two simulations are 'consistent'. However, they are very entailed and require a detailed understanding of the individual models including their functionality, algorithms, and inner workings. A straight forward and rapid way of assessing potential inconsistencies is through a statistical comparison of the model outputs.

Three scenarios were executed in OSD JWARS, JWARS as released by the Office of the Secretary of Defense; FED JWARS, the modified version of JWARS utilized in the federation; and the Lynx federation. Using statistical analysis, equivalency of the air-to-ground (A2G) engagement results was tested using the Bonferroni approach to multiple comparisons.

This comparative analysis confirms there is no statistically significant difference in the A2G engagement results of OSD JWARS and FED JWARS. However, the analysis does show there is a statistically significant difference in the A2G engagement results of OSD JWARS and the Lynx federation.

This thesis is dedicated to my family and friends for all their patience, understanding, and love.

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1 INTRODUCTION

1.1 Thesis Statement

The Joint WARfare System (JWARS) as released by the Office of Secretary of Defense (OSD), the modified version of JWARS as utilized in the Lynx federation, and the Lynx federation, where JWARS is federated with the Joint Semi-Automated Forces (JSAF), produce different air-to-ground (A2G) engagement results.

1.2 Problem Statement

Multi-resolution modeling is the process by which a single model is created by connecting multiple individual models to describe phenomena at different levels of resolution [1].[1] One of the individual models "serves as the high resolution of the other" [1]. Multi-resolution modeling has a number of recognized challenges which must be taken into consideration such as: the level of entity resolution, interactions of entities between simulations, differences in the environmental representations, differences in time management, and differences in model algorithms.

"When we change resolutions, replacing a detailed model by a more aggregate one, we must ask whether results are 'consistent'" [2]. There are many methods of determining if the results of two simulations are 'consistent'. However, they are very entailed and require a detailed understanding of the individual models including their functionality, algorithms, and inner workings. For many technicians and users, this is unrealistic due to the limited degree of qualified combat model experts and the specialization of experts. Thus, a straight forward way of assessing potential inconsistencies between the models outputs is needed.

One such method is a statistical comparison of the model outputs. By analyzing the output results, a detailed understanding of the underlying models is not required.

[1] Citation and reference list format for this manuscript are taken from the journal *SIMULATION: Transactions of the Society for Modeling and Simulation International.*

If the output results are found to be statistically different, then further in-depth assessment would be needed to determine the source of the discrepancies. However, if no statistical difference existed, the statistical comparison will minimize, if not eliminate, this need.

1.3 Approach

This research will provide a statistical difference assessment of specific A2G engagements implemented in the Lynx federation. The engagements of interest are Close Air Support (CAS), On Call Strike (OnCallStrike), and Pre-Planned Strike (PrePlanned-Strike). Three scenarios were developed to allow testing and integration of the models and to act as an early experimentation system [3]. In this research, the scenarios will be used to evaluate the A2G engagements mentioned above. Each scenario will be executed in three different simulations:

- The Lynx federation, where JWARS and JSAF are federated; scenarios executed in the Lynx federation are played out in JWARS and select A2G engagements are handed off to JSAF for execution. Once an engagement is completed in JSAF, JSAF hands the engagement results back to JWARS and JWARS continues executing the scenario.

- FED JWARS, where JWARS version 1.5*f* as released by the Office of Secretary of Defense (OSD) has been modified to function in the Lynx federation; scenarios executed in FED JWARS are played out completely in JWARS. This is accomplished by not specifying any missions in the 'Lynx Engagements' pane[2]. Thus, the Lynx federation will run without allowing any A2G engagements to be sent to JSAF and, in turn, only JWARS will execute missions and engagements.

[2]The 'Lynx Engagements' pane is unique to the federation and is used to configure the filters controlling when and which missions are to be sent to JSAF. If a particular mission type is not specified, it will not be sent to JSAF.

- OSD JWARS, where JWARS version 1.5f as released by OSD functions in its stand-alone capacity; each scenario is executed in its entirety in JWARS.

By executing the scenarios in the three different simulations, we will be able to assess the following:

1. Whether the changes made to JWARS, for it to function properly within the Lynx federation, have altered the functionality of JWARS in such a way as to change the output results.

2. Whether the scenario executions in JWARS and the Lynx federation yield similar results to a particular level of confidence.

1.4 Contributions

This thesis demonstrates that mathematical algorithms can be used as tools to assess the differences between models based on their output. Since the application of such algorithms does not require a detailed understanding of the underlying models, this method can be applied by both technicians and users.

This method will minimize the need for additional in-depth assessment of the models with regards to their differences if no statistically significant differences are found between the model outputs.

1.5 Thesis Organization

The remainder of this thesis is organized as follows:

- Section 2: Background. This section surveys research on JWARS, JSAF, and the Lynx federation.

- Section 3: Methodology. This section provides an in depth description of the experiment including study design, metrics, and statistical analysis approach.

- Section 4: Results and Data Analysis. This section presents the results of the statistical analysis.

- Section 5: Conclusions and Future Work. This thesis concludes with a summary of the research results and a description of followon work that could be undertaken to expand upon this effort.

2 BACKGROUND

2.1 JWARS

The Joint Warfare System is a model of joint military operations, which is being developed by the United States Office of the Secretary of Defense for use by the Office of Secretary of Defense, Joint Staff and Joint Task Force Commanders[3], the Military Services, and the Warfighting Commands [4, 5]. The principal goal driving the development of the JWARS program was the necessity for a 'joint' warfare model that could support decisions associated with operation planning and execution, force assessment and modernization studies, system trade analysis, concept and doctrine development, and warfare engagement. At the time of inception, no other model had the capability to provide the level of detail necessary for the type of 'joint' analysis needed.

2.1.1 Simulation Type

Simulations are typically classified based on the level of human involvement required to operate the simulation. The three common simulation types are live, virtual, and constructive.

Live simulations are categorized as simulations involving real people operating real systems. If real equipment or systems are not available, live simulations emulate the functionality and behavior of the real world system as much as possible. Examples of live simulations include lasers transmitting coded signals, codes identifying weapons; signals being detected by sensors, users being alerted of hits. The primary objective of live simulations is to provide the human user with a useful experience [6]. Often times, the 'useful experience' is with regards to training purposed.

[3] Joint Forces Air Component Commander (JFACC), Joint Forces Land Component Commander (JFLCC), Joint Forces Maritime Component Commander (JFMCC), and Joint Forces Special Operations Component Commander (JFSOCC)

Virtual simulations are simulations involving real people operating simulated systems. In virtual simulations, the real systems are recreated with simulators which are operated by human participants. These simulations are designed to immerse the user in a realistic virtual environment. A human-in-the-loop flight simulator and the Virtual Environment Toolkit (VET) are both examples of virtual simulations. As with live simulations, the primary objective of virtual simulations is to provide the human user with a useful experience [6]. Often times, the 'useful experience' is with regards to training purposes.

Constructive simulations involve simulated people operating simulated systems; "real people make inputs into a simulation that carries out those inputs by simulated people operating simulated systems" [6]. Since these simulations do not require a human to execute the simulation, no virtual environment or simulators are needed. The primary objective of a constructive simulation is to obtain useful results [6] either for analysis or training purposes.

JWARS is an example of a constructive simulation; the human user defines the scenario and initialization parameters. Once execution begins, JWARS executes the scenario with the specified initialization parameters by computer generated forces operating the simulation's entities.

2.1.2 Model Resolution

The simulation hierarchy outlines the hierarchy of model resolution, which is characterized by the level of detail and aggregation required by the user. As shown in Figure 1, the simulation hierarchy of combat models is divided into four levels: engineering, engagement, mission/battle, and theater/campaign.

JWARS is a theater/campaign level model; the model is concerned with the series of battles which arise in the geographical theater over a defined period of time rather than what action each entity is performing. At the campaign level, details of little

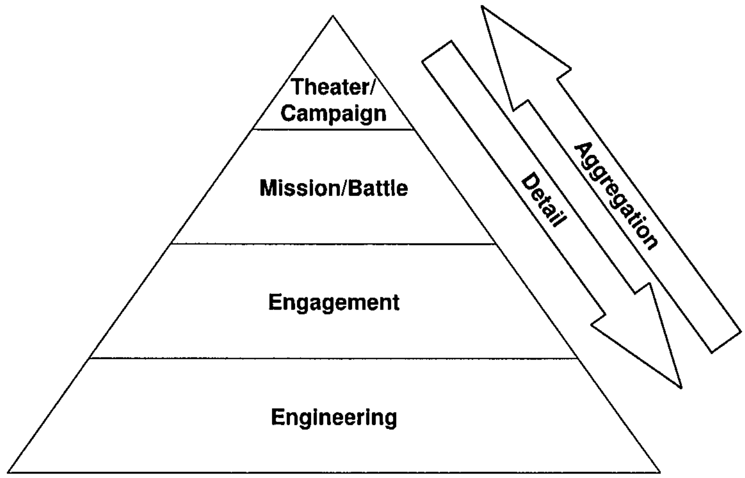

Figure 1. Model Resolution

importance are abstracted away to allow the user to gain a more concise view of what is happening in the larger picture, the theater. Campaign level models generally range from multiple weeks to several months.

2.1.3 Level of Abstraction

> Military simulations are often differentiated based on their inherent level of abstraction. If the primary objects represented in the simulation are collections of doctrinally identifiable military assets (e.g, a tank battalion) then the simulation is referred to as an aggregate-level simulation. If the primary objects represented by the simulation are singular military objects (e.g, a tank or a soldier) the simulation is referred to as an entity-level simulation [7].

JWARS is an aggregate level simulation; simulation objects are grouped together to act as 'entities' within the model. In JWARS, these groups of entities, also known as aggregated-force structures, are called Battle Space Entities (BSEs). BSEs, rather than individual combatants, are given attributes and orders as is the case in an entity-level combat model. A BSE may represent an aggregated-battalion, fighter squadron, or fire-support battery. JWARS is currently supported down to the battalion level. It is possible to create BSEs to represent lower level aggregate-forces such as companies, platoons, and squads. However, the user is left with the responsibility of determining the correct design specifications and implementation for these aggregated forces.

2.1.4 Time-Advance Mechanisms

The JWARS Event Manager utilizes a 'next-event time advance' approach to advancing the simulation clock. "The Event Manager is responsible for efficient management of the 'event queue'" [8]. Each event that is expected to occur is given a time and an associated sequence number. The time specifies when the event is to occur. An event's sequence number specifies the event's priority at execution time. If more than one event occurs at time x, the event with the lowest sequence number will be executed first.

When JWARS initializes, the simulation clock is set to zero and all events on the event queue which occur at time $t = 0$ are executed. "The simulation clock is then advanced to the time of occurrence of the most imminent of the future events, at which point the state of the system is updated to account for the fact that an event has occurred, and" [9] the Event Manager updates the event queue. This process continues until the scenario reaches the terminating event. By utilizing the 'next-event time advance' approach, JWARS is able to "process information and data 500 to 1000 times faster than real-time" [4]. In under two hours, JWARS can simulate a whole-theater, 90-day campaign and do multiple runs simultaneously to capture statistical variations [4].

2.1.5 Interoperability for Distributed Simulation

"HLA provides a standardized framework for the interoperability and integration of simulations" [10]. According to [11], HLA consists of the following components:

- Interface Specification. The interface specification document defines how HLA compliant simulators interact with the Run-Time Infrastructure (RTI). The RTI provides a programming library and an application programming interface (API) compliant to the interface specification.
- Object Model Template (OMT). The OMT specifies what information is communicated between simulations and how it is documented.
- HLA Rules. The Rules define the responsibilities of each simulation in the system of simulations. Each individual simulation and the system of simulations must obey these rules to be compliant to the standard.

"An HLA compliant simulation is referred to as a federate" [11]. Multiple federates, or HLA compliant simulations, connected via a RTI is referred to as a federation [11]. "A collection of related data sent between simulations is referred to as an object" [11]. Objects have attributes which describe the collections of data. "Events sent between simulations are referred to as interactions" [11]. Interactions have parameters which describe the events. JWARS is an HLA compliant simulation. All JWARS output elements (instruments) are HLA interactions and JWARS data elements are the HLA parameters corresponding to each HLA interaction.

It is important to note that though the JWARS Operational Requirements Document (ORD) requires JWARS to be HLA compliant, JWARS version 1.5f, as used in the Lynx federation, has not been certified as HLA compliant. To date, the only version of JWARS that has been certified as HLA compliant by the Defense Modeling and Simulation Office (DMSO) is version 1.4.

2.2 JSAF

Joint Semi-Automated Forces is an entity-level combat model being developed by the U.S. Joint Forces Command Joint Experimentation Directorate, J9, for use by J9, and the U.S. Navy's Maritime Battle Center. JSAF is designed to simulate the physical characteristics and behaviors of vehicles, weapon systems, and sensors operating in the Synthetic Natural Environment (SNE). The synthetic environment is a representation of real world terrain, oceans, and weather conditions that effect the behaviors and capabilities of the synthetic forces. The primary goal of JSAF is to provide a realistic, distributed synthetic environment for training and mission rehearsal [12].

2.2.1 Simulation Type

JSAF's default capacity is as a constructive simulation. However, depending on the intended use of JSAF, JSAF has the ability to function as a live, virtual, and/or constructive simulation. Real-world units composed of military vehicles, manned simulators, and computer generated forces can interact with each other over a network supported by HLA [12].

2.2.2 Model Resolution

JSAF is a mission-level model. Mission-level models are concerned with the interactions among opposing forces and predicting the success or failure of specific missions. "The time frame for a mission level model is on the order of hours to maybe a few days" [13].

2.2.3 Level of Abstraction

JSAF is an entity level simulation; each simulation object is an entity within the model. For instance, tanks, airplanes, ships, and soldiers are all modeled individually as members of larger organizations. Unlike JWARS, the simulation objects in JSAF interact directly with each other.

2.2.4 Time-Advance Mechanisms

JSAF is a scaled, real-time simulation; the progression of time within the simulation is scaled, by some constant factor, to that of wall clock time. The JSAF scheduler utilizes heap-based priority queues to implement a 'fixed-increment time advance' approach to advancing the simulation clock. The scheduler executes functions at the time they are scheduled and no sooner. However, it is possible for the function to be executed later than desired.

Law [9] describes the 'fixed-increment time advance' approach in the following manner:

> The simulation clock is advanced in increments of exactly Δt time units for some appropriate choice of Δt. After each update of the clock, a check is made to determine if any events should have occurred during the previous interval of length Δt. If one or more events were scheduled to have occurred during this interval, these events are considered to occur at the end of the interval and the system state is updated accordingly [9].

2.2.5 Interoperability for Distributed Simulation

"JSAF is an HLA compliant federate that communicates physical battlefield state and events using the RTI. It may employ various Federation Object Models (FOMs) and Simulation Object Models (SOMs) to instantiate objects and convey interactions that are published on the network" [14].

2.3 Lynx Federation

The Lynx federation, also known as the JWARS-JSAF federation, is an HLA federation between two HLA federates, JWARS and JSAF. JWARS provides the campaign level context and JSAF provides the mission level model. The intent of Lynx was to enhance the capability of JWARS by enabling JWARS to hand off missions to JSAF, with JSAF passing back mission outcomes to JWARS. There are three major benefits of federating JWARS and JSAF:

- Since JSAF was designed as a training tool, rather than an analysis tool, JSAF does not yield useful output nor does the output lend itself well to conventional data reduction techniques. Theoretically, in the Lynx federation, all mission engagements can be executed in JSAF, with their outcomes passed back to JWARS and applied to the scenario results. Thus, JWARS can provide JSAF with the analytic capability it lacks.

- Once JWARS hands off a mission to JSAF, JSAF executes the mission in real time. With JSAF running in real time, the federation has the capability to function as a training tool in that human players can manipulate the mission in JSAF and visualize the effects of their decisions over a campaign. In addition, a 3-D visualization tool such as ModStealth can provide a 3-D visual representation of the entity-level mission as it is executed. Thus, the federation has the capacity to operate as a live simulation in a campaign level context.

- JWARS and JSAF are both constructive simulations. As standalone models, JWARS and JSAF have the ability to execute scenarios without human interaction. This is also the case for the Lynx federation. By default, the federation is automated; the hand off of mission initialization parameters and the pass back of mission outcomes and damage assessment is automated so as to eliminate the need for a human in-the-loop. Thus, the Lynx federation has the ability to operate as a constructive simulation as well as a live simulation.

The Lynx federation consists of four federates working in tandem. The federates are JWARS, JSAF, ModStealth, and a management federate as shown in Figure 2. JWARS is the main simulation in the federation. JWARS is responsible for executing all missions and engagements, which are not considered 'critical events.' In the current design of Lynx, a 'critical event' is characterized as an A2G engagement such as a CAS, OnCallStrike, or PrePlannedStrike mission. JSAF executes all missions which are considered 'critical events.' In the federation, ModStealth provides a 3-D representation of entity-level missions as they are executed in JSAF. This is the only federate which is not required for the federation to function as described below. The management federate participates in the federation as a controller and as a passive observer. As a controller, the management federate sends interactions to create the initial instances of objects, enable time management within the federation, and synchronize the federates. In addition, the management federate is used to initiate federation execution once all federates have been synchronized. In its capacity as a passive observer, the management federate is a debugging tool. It monitors the other federates, provides timing and network information, and gathers data such as how many and what interactions have been sent by each federate.

2.3.1 Lynx Functionality

By federating JWARS and JSAF using the HLA RTI, JSAF-based simulation executions can be initialized in realistic operational scenarios. In this federation, JWARS provides the operational setting and the initial starting conditions for execution of A2G engagements in JSAF. During a simulation run, JWARS detects critical A2G engagements for which more detailed analysis is desired. The critical event methodology was selected based on its simplicity and ability to allow the system to run automatically without human interaction. The critical A2G engagements are: Close Air

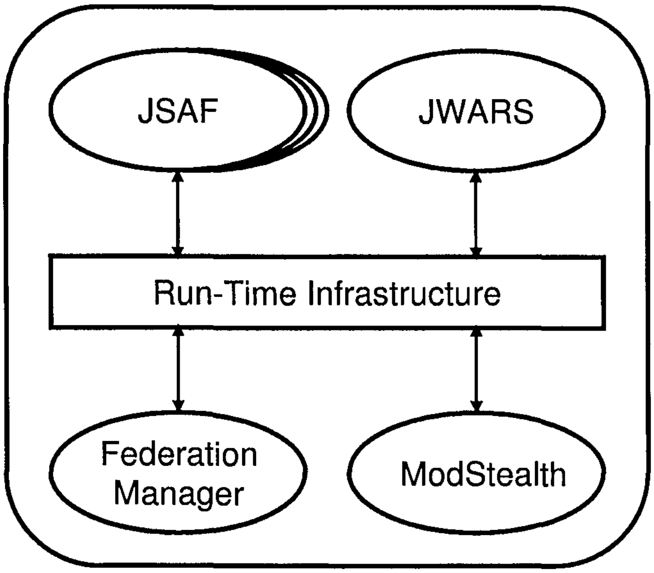

Figure 2. Components of the Lynx Federation

Support (CAS), On Call Strike (OnCallStrike), Offensive Counter Air Strike (OCAStrike), Strategic Attack (StratAttack), and Preplanned Strike. When a critical event is detected, JWARS determines the initialization parameters for the engagement. JWARS then publishes the HLA interaction called AirToGroundEngagementMission with the RTI. The AirToGroundEngagementMission interaction includes "the attacking flight group and its resources, as well as targets and their resources" [15]. Once the interaction has been published, the RTI will reflect the engagement parameters to JSAF. JSAF then uses the initialization parameters to create and execute the mission level scenario. While JSAF is simulating the mission, JWARS adjusts its time management accordingly and continues to execute portions of the scenario which are not affected by the mission being executed in JSAF [3]. Periodically, JSAF will update JWARS with the status of the entities being modeled in JSAF [3]. Inevitably, each A2G engagement, which is executed in JSAF, will entail ground forces being fired upon. When this occurs, JSAF publishes the Fire interaction. If an entity is killed while the mission is being executed in JSAF, JSAF will publish the BSEKill interaction. The BSEKill interaction provides the name of the entity which was destroyed. When the mission is completed, JSAF passes the A2G engagement outcomes and control of the units back to JWARS for continued simulation execution. JSAF accomplishes this by publishing a DamageAssessment interaction followed by a MissionEnded interaction to the RTI. The DamageAssessment interaction is a report of the engagement outcomes. During mission execution, JSAF determines the level of damage taken by each target vehicle based on JSAF's attrition parameters and algorithms. Once the RTI has received the MissionEnded interaction, the RTI sends the DamageAssessment interaction parameters to JWARS for continued simulation execution.

2.3.2 Federation Protocol

Within the federation, scenario data must be passed from JWARS to JSAF and unit status data must be passed from JSAF to JWARS. System operating states control when data are exchanged. The interactions and objects control what data are exchanged. To ensure that the two simulations are synchronized throughout this process, RTI synchronization points are utilized.

2.3.2.1 Operating States During the execution of a scenario, Lynx operates in one of three states: fully aggregated (FA), disaggregated (DA), and paused.

Lynx executes in the fully aggregated state when the entire scenario is running in JWARS. In this state, Lynx runs as fast as possible which is usually hundreds of times faster than real time.

The system arrives in the disaggregated state when one or more A2G missions are executing in JSAF. Since JSAF runs in real time and JWARS runs as fast as possible, JSAF's execution time is the limiting factor of the simulation run-time in the DA state. Thus, in the disaggregated state, JWARS and JSAF move in synchronization with real-time.

The last operating state is the pause state. "The pause state provides the systems the necessary time to create, destroy and update simulation objects when transferring the simulation of those objects between the different resolutions" [3]. Lynx pauses in three situations: when the scenario execution transitions from the fully aggregated state to the disaggregated state, when the scenario execution transitions from the disaggregated state to the fully aggregated state, and when JWARS encounters an A2G engagement while the system is operating in the disaggregated state. As indicated by its state name, time stands still in the pause state.

2.3.2.2 Data Exchange In the Lynx federation, information needs to be passed from JWARS to JSAF and from JSAF to JWARS. Communication between the federates is achieved by enabling interactions and objects to be passed via the RTI from one federate to another. Interactions describe events whereas objects describe simulated entities. For the purpose of this paper, we will only be concerned with the interaction and object classes published to the RTI and then passed to either the JWARS federate or the JSAF federate.

Clearly, the process of publishing and subscribing to interaction and object classes is not as elementary as described below. However, for our purposes, further detail is not needed.

"To send an interaction class, the federate must have published that interaction class" [16]. Likewise, to send an object class, the federate must have published that object class. By publishing an interaction class or an object class, the federate is informing the RTI and the rest of the federation which classes it plans to produce. "It is possible for a federate to publish a subset of the available attributes for a given object class" [16]. However, interactions are 'all or nothing'; that is, either the entire interaction is published or no part of the interaction is published.

To receive an interaction class, the federate must have subscribed to that interaction class. Likewise, to receive an object class, the federate must have subscribed to that object class. By subscribing to an interaction class or an object class, the federate "is expressing an interest in learning about all interaction instances of the class or all object instances of the class" [16]. As with publishing an object class, a federate is able to subscribe to "a subset of the available attributes for a given object class" [16]. However, interactions are 'all or nothing'; that is, either the entire interaction is received or no part of the interaction is received. Once a federate has subscribed to an object or interaction class, the federate is informed by the RTI when a new instance of the object or interaction class has been sent to the RTI.

2.3.2.2.1 Interactions Interaction classes define the events that occur within the simulation. There are five events that are of concern to the federation as a whole: 1) AirToGroundMissionEngagement, 2) Fire, 3) DamageAssessment, 4) BSEKill, and 5) MissionEnded.

The AirToGroundMissionEngagement interaction class is published by JWARS and subscribed to by JSAF; JWARS sends the interaction instance and JSAF receives it. This interaction provides all the initialization parameters that JSAF needs to set up the engagement including "the attacking flight group and its resources, as well as, targets and their resources" [15]. Specifically, the interaction parameters specify the type of A2G mission, the speed of the flight group during the next leg of the mission, the air platform resource executing the mission, the target objective location, potential targets in the area, and the munitions available to the flight group.

Each A2G engagement entails forces being fired upon. When this occurs, JSAF sends a Fire interaction instance and JWARS receives the interaction.

At any time, if an entity is killed while the scenario is being executed in JWARS,

JWARS will send a BSEKill interaction instance to JSAF. If an entity is killed while a mission is being executed in JSAF, JSAF will note in the DamageAssessment interaction instance that there was a catastrophic kill. Once JWARS receives the interaction, JWARS will send a BSEKill interaction instance back to JSAF. The BSEKill interaction simply states the name of the entity which was destroyed.

When the mission is completed, JSAF sends the A2G engagement outcomes back to JWARS via the DamageAssessment interaction. The DamageAssessment interaction is a report of the engagement outcomes. During mission execution, JSAF determines the level of damage taken by each individual target vehicle based on JSAF's attrition parameters and algorithms. The parameters of the DamageAssessment interaction include the force, location, velocity, orientation, and the marking of the firing and target vehicles, the name of the munition in the damage calculation, the type and location of the detonation, the probability of mobility and firepower kill, probability of mobility only kill, probability of no kill, the cause of the damage, the damage state prior to the detonation, the computed damage from the current detonation, and the damage state after the detonation.

The MissionEnded interaction informs JWARS when JSAF has finished executing the A2G mission engagement. The only parameter of the MissionEnded interaction is the name of the flight group that completed the mission. Typically, the MissionEnded interaction is created "when the flight group reaches the final waypoint in its flight plan before the objective location. However, if the distance from this waypoint to the objective is greater than the 'Min Hand Off' in the run definition filter, the hand off occurs when the flight group reaches the 'Min Hand Off' distance" [15].

2.3.2.2.2 Objects Object classes define simulated entities. "Each object class has a name and defines a set of named data called attributes that characterize the class in a certain way. A unique instantiation of an object class that is independent of all other instances of that class is called an object instance" [16]. The object classes which are of interest to this study are: 1) Time, 2) Aggregate, 3) JWARSBSE, and 4) JWARSFCP. Jones [15] describes the objects in the following manner.

To synchronize the environmental conditions, a Time object is sent at the same time as each AirToGroundEngagementMission interaction. When JSAF receives the interaction, it changes its date and time accordingly.

Aggregate objects describe JWARS BSE names, types, locations, etc., but do not include lower-level detail such as resources. When the first mission is passed to JSAF, aggregate objects reflecting virtually every JWARS BSE are also sent.

JWARSBSE objects are created by JSAF to shadow the state of flight groups. It shadows attributes such as position, velocity and resources. JWARSBSE objects provide each aircraft with a unique identifier which is used in connection with JWARS A2G adjudication data collection. JSAF updates properties of these objects on a periodic basis and JWARS in turn updates the actual flight group. When JSAF deletes the JWARSBSE, JWARS assumes control of the flight group again.

JWARSFCP[4] objects are identical in structure and function to JWARSBSE objects except that they shadow target entities rather than flight groups. JWARSFCP objects are unique identifiers which correspond to each resource rather than each aircraft. JWARSFCP objects function in the same manner as JWARSBSE objects; they keep entities in JWARS up to date.

2.3.2.3 Time Management As mentioned previously, JWARS executes missions as fast as possible and JSAF operates in real-time. In the development of the Lynx federation, determining the appropriate time management service for the transition between the two different execution modes was critical to the federation functioning appropriately. Lynx utilizes "RTI synchronization points as the method

[4] "Earlier in the federation development, all targets were Fire Concentration Points (FCPs), although that is no longer the case. We continue to use the FCP name in the Federation Object Model (FOM), but to the JWARS user or developer, this is a misnomer" [15].

of synchronizing the federation. RTI synchronization points enable all federates in a federation to achieve a known state. Each sync point has a name and a tag data field which are used to enable federates to understand the purpose of the sync point" [3]. The name data field specifies the current state of execution; either the federates will 'pause' or 'resume' execution. The tag data field specifies the future operating state, FA, DA, or pause.

Within the Lynx federation, there are four stages of synchronization points:

1. Announce: A federate announces to the RTI that it would like to achieve a syncronization point.

2. Distribute: The RTI distributes the synchronization point announcement to all other federates in the federation.

3. Achieving: Each federate tells the RTI that it has achieved the sync point.

4. Synchronization: Once all federates have achieved the synchronization point, the RTI reports to the federates that the other federates have achieved the synchronization point.

Table 1, by Macannuco [3], illustrates how the protocol components interact to create a multi-resolution federation. In this use case, two critical events occur in JWARS thus forcing multiple engagements to be executed simultaneously in JSAF.

Table 1. Protocol Use Case [3]

Event	Description	State
Start	Federation begins with the entire simulation represented in JWARS	FA
JWARS Detects Critical Event	JWARS issues a synchronization point with name 'Pause' and tag 'FA'	FA
Federation Synchronization	All the federates achieve the synchronization point and JWARS sends AirToGroundMissionEngagement interaction	Pause
Simulation Transfer	JSAF creates the scenario described in the interaction, including JWARSBSE and JWARSFCP object instances	Pause
Simulation Transfer Complete	JSAF issues a synchronization point with name 'Resume' and tag 'DA'	Pause
Federation Synchronization	JSAF and JWARS continue execution in real time	DA
JSAF Updates BSE/ FCP Object Instances	JSAF periodically sends status to JWARS via these object instances	DA
JWARS Detects Critical Event	JWARS issues a synchronization point with name 'Pause' and tag 'DA'	DA
Federation Synchronization	All the federates achieve the synchronization point and JWARS sends AirToGroundMissionEngagement interaction	Pause
Simulation Transfer	JSAF creates the scenario described in the interaction, including JWARSBSE and JWARSFCP objects	Pause
Simulation Transfer Complete	JSAF issues a synchronization point with name 'Resume' and tag 'DA'	Pause
Federation Synchronization	JSAF and JWARS continue execution in real time	DA
Mission Ends	JSAF issues synchronization point with tag 'Pause' and tag 'DA'	DA
Federation Synchronization	All the federates achieve the synchronization point and JSAF sends MissionEnd and DamageAssessment interactions	Pause
Simulation Transfer	JSAF destroys object instances associated with this mission; JWARS resumes control	Pause
Simulation Transfer Complete	JSAF issues a synchronization point with name 'Resume' and tag 'DA'	Pause
Federation Synchronization	JSAF and JWARS continue execution in real time	DA

Table 1. Continued

Event	**Description**	**State**
Mission Ends	JSAF issues synchronization point with tag 'Pause' and tag 'DA'	DA
Federation Synchronization	All the federates achieve the synchronization point and JSAF sends MissionEnd and DamageAssessment interactions	Pause
Simulation Transfer	JSAF destroys object instances associated with this mission; JWARS resumes control	Pause
Simulation Transfer Complete	JSAF issues a synchronization point with name 'Resume' and tag 'FA'	Pause
Federation Synchronization	JWARS continues execution in fast as possible mode	FA

3 METHODOLOGY

This study is intended to statistically assess the output data of the three simulations using the Bonferroni approach to multiple comparisons. Hypothesis testing will be employed to determine if there is a statistical difference among the simulation outputs.

3.1 Limitations

As with all studies, there are limitations which bound what can realistically be studied given the available resources and time constraints. In this study, the limitations are the available scenarios, the A2G engagements modeled, and the data collection tools.

3.1.1 Scenarios

Designing and implementing scenarios for use within JWARS is a time intensive process which requires extensive knowledge of JWARS and subject matter expertise. This process, not including testing and evaluation, has been known to take upwards of eight months for forty trained professionals to complete. For this reason, scenarios were not created specifically for this study.

The three scenarios used in this study were developed specifically for integrating JWARS and JSAF and testing the Lynx federation. For this reason, the scenarios contain A2G engagements which can be passed from JWARS to JSAF when executed within the confines of the Lynx federation.

These scenarios utilize the same initialization parameters and only the initial random number seed is changed between replications. The three scenarios will be executed in the three simulations. For instance, Scenario A will be executed in OSD JWARS, FED JWARS, and the Lynx federation. Scenarios B and C will also be executed in this manner. In this study, the specifics of each scenario are of little importance since each scenario is left unaltered between executions.

3.1.2 A2G Engagements

The Lynx federation is in an early stage of its development and only specific A2G engagements are capable of being passed from JWARS to JSAF for execution. These A2G engagements are CAS, OnCallStrike, and PrePlannedStrike missions from land and naval assets [3]. Only the results from these A2G engagements will be assessed in this study.

In the representative scenarios, a flight group of two fighters attacks truck convoys and enemy armored formations using 2000 lb. bombs and A2G missiles thereby inflicting casualties to personnel and vehicles.

3.1.3 Data Collection

In the three simulations used in this study, JWARS is responsible for data collection. In JWARS, data elements are reported in instruments. "An instrument as a collection of data elements" [17].

Within the JWARS framework, there are only three instruments which pertain to the results of A2G engagements. The instruments are ADJ_A2G_ENG, ADJ_A2G_KVS, and ADJ_A2G_MUNS_EXP. These instruments will be used to determine the metrics for this study.

The ADJ_A2G_ENG instrument records a unique air-to-ground "engagement between a flight group and a ground target" [17]. Each record includes a unique A2G engagement ID, the name of the attacking flight group and the ground target attacked, and when the engagement occurred in simulation time.

ADJ_A2G_KVS, also known as the killer-victim-scorecard, records the results of A2G adjudication. Each record includes a unique A2G engagement ID, the name of the attacking flight group and the ground target attacked, the type of munitions used, the number and type of target 'units' destroyed, and the simulation time at which the units were attrited. Each target is composed of multiple target 'units' which identify the specific part of the target which was attrited. For instance, if the target is a mechanized brigade, then the target is composed of target 'units' such as tanks, weapons, and troops. Then, when the mechanized brigade experiences attrition, the target 'unit' destroyed may be a tank, a weapon, or a troop.

ADJ_A2G_MUNS_EXP records the munitions released by a flight group during an A2G engagement. Each record includes a unique A2G engagement ID, the name of the attacking flight group, the name of the air ammunitions released, the quantity of sticks released, and the number of munitions in each stick released in the engagement.

3.2 Metrics

The metrics for this study are as follows:

- Metric 1: Total number of A2G engagements executed.
- Metric 2: Total attrition from A2G engagements.
- Metric 3: Total munitions released during A2G engagements.

These metrics will determine if the same quantitative results are attained by the three simulations during the execution of A2G engagements.

3.3 Data Reduction

Prior to being analyzed, JWARS output data must first be put through a data reduction process in which multiple JWARS instruments are combined and extraneous output data is removed.

The first step in the data reduction process is combining multiple JWARS instruments, with a common instrument parameter, and then abstracting away the parameters of interest. For instance, every JWARS instrument contains a RUN_ID parameter which is a unique identifier of the scenario replication. The RUN_ID is "a character string that begins with 'J,' and is composed by year, month, day, hour, minute, and second. An example is J20020510170941025002" [17]. This string alone does not provide any information about which scenario these data are from. One instrument which contains a RUN_ID parameter is the ADJ_A2G_ENG instrument. The RUN_INFORMATION instrument is an instrument that contains the RUN_ID parameter. In addition, this instrument has a SCENARIO_NAME parameter which is "a user supplied name for the scenario data set that JWARS executed" [17]. By combining the ADJ_A2G_ENG instrument and the RUN_INFORMATION instrument on the RUN_ID parameter, the analyst is able to determine which scenario is referred to by the RUN_ID J20020510170941025002.

The second step is removing extraneous output data obtained from combining multiple JWARS instruments. At face value, the output data for the three simulations appears very similar. However, further investigation reveals the similarities are potentially due to discrepancies between the models. For the three metrics, the extraction of extraneous data was as follows:

- Metric 1: Total number of A2G engagements executed.

  When executed in the Lynx federation, it was observed that scenarios A and B only execute CAS and PreplannedStrike missions in JSAF and Scenario C only executes OnCallStrike and PreplannedStrike missions in JSAF. Thus, for scenarios A and B, CAS and PreplannedStrike missions are of interest and for Scenario C, OnCallStrike and PreplannedStrike missions are of interest. Based on the scenario, these were the only missions included in the calculation of the total number of A2G engagements executed.

- Metric 2: Total attrition from A2G engagements.

  The three simulations discussed in this study send the results of A2G engagements to the respective JWARS instruments. A2G engagements executed in JWARS are issued a unique identifier called an A2G engagement ID. In the Lynx federation, A2G engagements executed in JSAF are not issued an A2G engagement ID. Thus, in the output data, any A2G engagement which lacks an A2G engagement ID was executed by JSAF.

By looking at the Lynx output data, it was observed that in scenario A only units of type FSC_IFV and FSC_TRK_CGO were attrited during JSAF executed missions. In Scenario B, only units of type FSC_IFV, FSC_LAUNCHER_ADA, and FSC_TRK_CGO were attrited during JSAF executed missions. In Scenario C, only units of type FSC_TRK_CGO were attrited when the scenario was executed in JSAF. In these scenarios, the types of units attrited in JSAF executed engagements were not attrited during any other engagement. Thus, in the OSD JWARS and FED JWARS output data, the A2G engagements which attrite these type of units are comparable to the same set of A2G engagements executed in Lynx.

- Metric 3: Total munitions released during A2G engagements.

  It was observed that scenarios A and B only release munitions of type PRO_AGM_FTR and PRO_BOMB_2K during A2G engagements executed in JSAF. In Scenario C, the type of munitions used in the A2G missions executed in JSAF were PRO_BOMB_2K. For the three scenarios, these munitions were not released during any other mission. Thus, it was concluded that any A2G engagements that used these munitions in either version of JWARS would be comparable to the missions in the federation.

3.4 Replications

According to the JWARS user's manual [17], a replication is a single execution of a computer simulation and a set of replications comprises a single run. "The only difference in input among different replications in a run is the starting random number seed; all problem domain and environmental input data are identical" [17].

Though the JWARS' documentation suggests only 10 replications are required to obtain statistically significant results, the number of replications required to estimate the mean value of a metric with a specified error of precision [18] must be determined by employing a mathematical algorithm. The algorithm used to determine the number replications is an iterative process by which the half-width of the confidence interval for the mean of a particular metric is bounded to a specified precision. Bounding the half-width of the confidence interval is a means of bounding the variability of the sample mean, also known as the absolute error, β, of the mean [19]. Suppose $\bar{X}$ is the sample mean of the output data and μ is the population mean, then $|\bar{X} - \mu| = \beta$ where β is the absolute error of the mean. "If we make replications of a simulation until the half-length of the $100(1-\alpha)\%$ confidence interval is less than or equal to β (when $\beta > 0$), then $\bar{X}$ has an absolute error of at most β with a probability of approximately $1 - \alpha$" [9].

"Suppose that we have constructed a confidence interval for μ based on a fixed number of replications R. If we assume that our estimate $S^2(R)$ of the population variance will not change (appreciably) as the number of replications increases, an approximate expression for the total number of replications, $n_a^*(\beta)$, is given by

$$n_a^*(\beta) = min\{r \geq R : t_{\alpha/2,r-1}\sqrt{\frac{S^2(R)}{r}} \leq \beta\} \tag{1}$$

" [9] where r is the number of replications, α is the confidence level, and β is the desired precision level.

3.5 Statistical Analysis Approach

Many statistical tests such as the F-test, the student t-test, Tukey's procedure, and various Bayesian methods and non-parametric tests could be applied in a process such as this. However, for this study, the Bonferroni approach to multiple comparisons was chosen because it is appropriate for data sets with equal variances and for replications using independent or common random numbers. In addition, there is no expectation for the data to be normally or uniformly distributed.

The following sections will discuss how to apply the Bonferroni approach to multiple comparisons and how to use hypothesis testing to determine if there is a statistical difference among results.

3.5.1 Bonferroni Approach to Multiple Comparisons

The Bonferroni approach to multiple comparisons will be used to test the equivalency of the three metrics for the three simulations: OSD JWARS, FED JWARS, and Lynx. To accomplish this, for each metric the following three competing system designs will be analyzed:

1. OSD JWARS vs. FED JWARS
2. OSD JWARS vs. Lynx
3. FED JWARS vs. Lynx

Let j be the competing system designs. Then, $j = 1$ is representative of the metric comparison between OSD JWARS and FED JWARS, $j = 2$ is representative of the metric comparison between OSD JWARS and Lynx, and $j = 3$ is representative of the metric comparison between FED JWARS and Lynx.

3.5.1.1 Test for Equal Variances Since the Bonferroni approach assumes equal variances, it is necessary to determine if the assumption of equal variances is valid. "Levene's test is used to test if k samples have equal variances. Equal variances across samples is called homogeneity of variance. The Levene test can be used to verify that assumption" [20]. The following explanation of the Levene method is taken directly from [20].

The Levene test is defined as:

$$H_0 : \sigma_1 = \sigma_2 = ... = \sigma_k$$

$$H_a : \sigma_i \neq \sigma_j \text{ for at least one pair } (i, j).$$

Given a random variable output Y with sample of size N divided into k subgroups, where N_i is the sample size of the ith subgroup, the Levene test statistic is defined as:

$$W = \frac{(N-k)\sum_{i=1}^{k} N_i(\bar{Z}_{i.} - \bar{Z}_{..})^2}{(k-1)\sum_{i=1}^{k}\sum_{j=1}^{N_i}(Z_{ij} - \bar{Z}_{i.})^2} \tag{2}$$

where $Z_{ij} = |Y_{ij} - \bar{Y}_{i.}|$. $\bar{Z}_{i.}$ are the group means of the Z_{ij} and $\bar{Z}_{..}$ is the overall mean of the Z_{ij}.

The Levene test rejects the hypothesis that the variances are equal if

$$W > F_{(\alpha,k-1,N-k)} \tag{3}$$

where $F_{(\alpha,k-1,N-k)}$ is the upper critical value of the F distribution with $k-1$ and $N-k$ degrees of freedom at a significance level of α.

3.5.1.2 Order the Data The data obtained from the simulations corresponds to the response variables Y_{ri} where r represents the replication and i is the simulation ($r = 1, ..., 40$; $i =$ OSD JWARS, FED JWARS, Lynx). For instance, with regards to the metrics, Y_{ri} may represent the total number of A2G engagements observed during replication r when a particular scenario was executed in simulation i.

An intermediary step of the Bonferroni approach calculates the observed differences for each replication. Thus, it is crucial the data from the competing system designs are comparable for each replication else this approach fails. In this study, this translates to each replication using the same random number seed across the three simulations. Thus, for the data to be comparable, OSD JWARS, FED JWARS, and Lynx must execute the same scenario using the same random number seed. If this is not done, the analysis results will vary since the random numbers are no longer correlated.

3.5.1.3 Overall Error Probability The overall error probability α_E is the probability the C metric comparisons are all true simultaneously. "α_E provides an upper bound on the probability of a false conclusion" [18]. In this study, the C metric comparisons will have the same level of confidence. Then, the confidence level for each metric comparison is α_E/C.

3.5.1.4 Observed Differences The observed differences are calculated by subtracting the variable random data for one simulation from another. The observed difference D_{rj} is the observed difference for a particular metric during replication r in the competing system design j ($r = 1, ..., 40$; $j =$ OSD JWARS vs. FED JWARS, OSD JWARS vs. Lynx, FED JWARS vs. Lynx). Then, for this study, the observed differences are as follows:

$$D_{r1} = D_{r(\text{OSD JWARS vs. FED JWARS})} = Y_{r(\text{OSD JWARS})} - Y_{r(\text{FED JWARS})}$$

$$D_{r2} = D_{r(\text{OSD JWARS vs. Lynx})} = Y_{r(\text{OSD JWARS})} - Y_{r(\text{Lynx})}$$

$$D_{r3} = D_{r(\text{FED JWARS vs. Lynx})} = Y_{r(\text{FED JWARS})} - Y_{r(\text{Lynx})}$$

For instance, for a particular metric, if $r = 2$, then D_{21} equals OSD JWARS' observation for replication 2, $Y_{2\text{OSD JWARS}}$, minus the FED JWARS' observation for replication 2, $Y_{2\text{FED JWARS}}$.

3.5.1.5 Sample Mean Differences The sample mean $\bar{D}_{.j}$ of the observed differences is an estimate of the population mean of the observed differences. The sample mean is calculated by applying Equation 4 to the observed differences.

$$\bar{D}_{.j} = \frac{1}{R}\sum_{r=1}^{R} D_{rj} \tag{4}$$

where j = OSD JWARS vs. FED JWARS, OSD JWARS vs. Lynx, FED JWARS vs. Lynx and $R = 40$.

3.5.1.6 Sample Variance The sample variance of the observed differences $S^2_{D_j}$ is a measure of the spread in the distribution of the observed differences. The sample variance is calculated by applying Equation 5 to the observed differences.

$$S^2_{D_j} = \frac{1}{R-1}\sum_{r=1}^{R}(D_{rj} - \bar{D}_{.j})^2 \tag{5}$$

where j = OSD JWARS vs. FED JWARS, OSD JWARS vs. Lynx, FED JWARS vs. Lynx and $R = 40$.

3.5.1.7 Sample Error The standard error of the observed differences $s.e.(\bar{D}_{.j})$ is the standard deviation of the sampling distribution of the sample mean of the observed differences. The sample error of the observed differences is calculated by applying Equation 6 to the observed differences. This calculation is based on using correlated random numbers since the same random seeds and random-number streams were used.

$$s.e.(\bar{D}_{.j}) = \frac{S^2_{D_j}}{\sqrt{R}} \tag{6}$$

where j = OSD JWARS vs. FED JWARS, OSD JWARS vs. Lynx, FED JWARS vs. Lynx and $R = 40$.

3.5.1.8 Confidence Intervals Based on the Bonferroni Approach to Multiple Comparisons, the confidence intervals for the three metrics are of the form:

$$\bar{D}_{.j} - t_{\alpha_E/2C,R-1} s.e.(\bar{D}_{.j}) \leq \theta_m - \theta_n \leq \bar{D}_{.j} + t_{\alpha_E/2C,R-1} s.e.(\bar{D}_{.j}) \quad (7)$$

where C is the number of metric comparisons, j = OSD JWARS vs. FED JWARS, OSD JWARS vs. Lynx, FED JWARS vs. Lynx, $R = 40$, θ represents the observed sample mean of a particular metric, m and n are the representative simulations, $\bar{D}_{.j}$ is the mean observed difference for the competing system design j between simulations m and n, $t_{\alpha_j/2,R-1} s.e.(\bar{D}_{.j})$ is the half-width of the confidence interval.

3.5.2 Hypothesis Tests

Once the confidence intervals have been constructed using the Bonferroni approach, hypothesis testing provides an interpretation of the confidence intervals. In this study, we want to test the mean difference in the output data obtained when a particular scenario is executed in two different simulations to determine if the results are equal. Let θ represent the observed sample mean of a particular metric and m and n be the representative simulations. Then, the hypothesis tests for this study are of the form:

$$H_0 : \theta_m \neq \theta_n$$

$$H_a : \theta_m = \theta_n$$

where θ_m is the observed sample mean for simulation m and θ_n is the observed sample mean for simulation n. The alternative hypothesis can also be interpreted as $\theta_m - \theta_n = 0$.

By applying the alternative hypothesis to the Bonferroni confidence interval in

Equation 7, we have:

$$\bar{D}_{.j} - t_{\alpha_j/2,R-1} s.e.(\bar{D}_{.j}) \leq \theta_m - \theta_n \leq \bar{D}_{.j} + t_{\alpha_j/2,R-1} s.e.(\bar{D}_{.j})$$

$$\bar{D}_{.j} - t_{\alpha_j/2,R-1} s.e.(\bar{D}_{.j}) \leq \quad 0 \quad \leq \bar{D}_{.j} + t_{\alpha_j/2,R-1} s.e.(\bar{D}_{.j}) \tag{8}$$

This can be interpreted as, if $\theta_m - \theta_n = 0$, then the confidence interval constructed using the Bonferroni approach contains 0. Thus, if the inequality in Equation 8 is a false statement, reject the alternative hypothesis and accept the null hypothesis; there is strong evidence there is a statistically significant difference between simulation m and n for this particular metric. Rejecting the alternative hypothesis is the same as accepting the thesis statement. Otherwise, if the statement is true, accept the alternative hypothesis.

4 RESULTS AND ANALYSIS

This section presents the results for determining the number of replications, the test for equal variances, and the statistical analysis of the competing system designs for each metric using the Bonferroni approach to multiple comparisons.

4.1 Replication Results

JWARS allows the initial random number seed of a particular random number stream to be set to a value between 1 and 50. It is possible to have a random number seed larger than 50 if multiple replications are initialized at the same time. That is, suppose a run is initialized with 20 replications and the first random number seed is 50. Then, replication 1 will use 50 as a random seed, replication 2 will use 51 as a random seed, and so on until the 20 replications are completed. When executed in the Lynx federation, the three scenarios used in this study experienced fatal software errors when the initial random seed was larger than 50. Thus, in this particular study, only 50 initial random seeds could be used. Due to these limitations, 50 replications of each scenario/simulation combination were conducted. However, only 40 of the replications were viable for future statistical analysis due to fatal software errors that occurred in the execution of the Lynx federation.

Given only 40 replications, the best absolute error, β, that can be achieved by each metric/scenario combination is the smallest integer value of β achieved by all three simulations for a particular scenario where β is defined as follows:

$$\beta = t_{\alpha_E/2,R-1}\sqrt{\frac{S^2(R)}{R}} \tag{9}$$

where R is the number of replications completed and $S^2(R)$ is the population variance. Table 2 displays the sample variances for each metric/scenario/simulation combination given $R = 40$.

Table 2. Sample variance.

Scenario:	Scenario A		
	OSD JWARS	FED JWARS	Lynx
Total Number of A2G Engagements Executed	38.1308	37.5359	40.1128
Total Attrition from A2G Engagements	584.0410	658.6154	576.0968
Total Munitions Released during A2G Engagements	80.8814	88.0763	80.8814

Scenario:	Scenario B		
	OSD JWARS	FED JWARS	Lynx
Total Number of A2G Engagements Executed	31.4353	63.7891	80.6436
Total Attrition from A2G Engagements	455.3436	580.4103	464.4487
Total Munitions Released during A2G Engagements	57.6404	82.8590	55.8436

Scenario:	Scenario C		
	OSD JWARS	FED JWARS	Lynx
Total Number of A2G Engagements Executed	1.5769	1.5769	7.1994
Total Attrition from A2G Engagements	3.4301	3.4301	12.2154
Total Munitions Released during A2G Engagements	0	0	19.5641

This study is concerned with the overall confidence levels of 90% and 95%. The corresponding α_E values are $\alpha_E = 0.10$ and $\alpha = 0.05$. A confidence level of 90% yields a critical test statistic of

$$t_{\alpha_E/2,R-1} = t_{0.10/2,39} = t_{0.05,39} = 1.682.$$

A confidence level of 95% yields a critical test statistic of

$$t_{\alpha_E/2,R-1} = t_{0.05/2,39} = t_{0.025,39} = 2.022.$$

Table 3 displays the smallest absolute error, β, based on Equation 9 for a confidence level of 90%. The last column displays the smallest absolute error, β, achieved by all three simulations. Table 4 displays the smallest error error, β, based on Equation 9 for a confidence level of 95%. The last column displays the smallest absolute error, β, achieved by all three simulations.

The best possible absolute error that can be achieved over 40 replications is determined to be the smallest absolute error achieved by the three simulations for each particular metric and scenario. Table 5 displays the smallest absolute error achieved at the 90% and 95% confidence levels.

Table 3. Absolute error, β, given a 90% confidence level, $\alpha_E = 0.10$.

Scenario:	Scenario A			
	OSD JWARS	FED JWARS	Lynx	Smallest β
Total Number of A2G Engagements Executed	2	2	2	2
Total Attrition from A2G Engagements	7	7	7	7
Total Munitions Released during A2G Engagements	3	3	3	3

Scenario:	Scenario B			
	OSD JWARS	FED JWARS	Lynx	Smallest β
Total Number of A2G Engagements Executed	2	3	3	3
Total Attrition from A2G Engagements	6	7	6	7
Total Munitions Released during A2G Engagements	3	3	2	3

Scenario:	Scenario C			
	OSD JWARS	FED JWARS	Lynx	Smallest β
Total Number of A2G Engagements Executed	1	1	1	1
Total Attrition from A2G Engagements	1	1	1	1
Total Munitions Released during A2G Engagements	0	0	2	2

Table 4. Absolute error, β, given a 95% confidence level, $\alpha_E = 0.05$.

Scenario:	Scenario A			
	OSD JWARS	FED JWARS	Lynx	Smallest β
Total Number of A2G Engagements Executed	2	2	3	3
Total Attrition from A2G Engagements	8	9	8	8
Total Munitions Released during A2G Engagements	3	4	3	4

Scenario:	Scenario B			
	OSD JWARS	FED JWARS	Lynx	Smallest β
Total Number of A2G Engagements Executed	2	3	3	3
Total Attrition from A2G Engagements	7	8	7	8
Total Munitions Released during A2G Engagements	3	3	3	3

Scenario:	Scenario C			
	OSD JWARS	FED JWARS	Lynx	Smallest β
Total Number of A2G Engagements Executed	1	1	1	1
Total Attrition from A2G Engagements	1	1	2	2
Total Munitions Released during A2G Engagements	0	0	2	2

Table 5. Best absolute error level.

Scenario:	Scenario A		Scenario B		Scenario C	
Confidence Level:	90%	95%	90%	95%	90%	95%
Total Number of A2G Engagements Executed	2	3	3	3	1	1
Total Attrition from A2G Engagements	7	9	7	8	1	2
Total Munitions Released during A2G Engagements	3	4	3	3	2	2

4.2 Statistical Analysis Results

4.2.1 Test for Equal Variances Results

Levene's test was used to test the random variable data for equal variances. For each metric, there are three subgroups, $k = 3$, which correspond to the simulations (OSD JWARS, FED JWARS, Lynx) which produced the random variable data Y for each metric. Since each scenario was replicated 40 times, the sample size of the ith subgroup is $N_i = 40$ and the overall sample size is

$$\begin{aligned} N &= \sum_{i=1}^{k} N_i \\ &= \sum_{i=1}^{3} N_i \\ &= 40 + 40 + 40 \\ &= 120. \end{aligned}$$

Table 6 presents the Levene test statistics for each scenario/metric combination. A confidence level of 90%, $\alpha = 0.10$, yields a Levene F test statistic of

$$F_{(\alpha,k-1,N-k)} = F_{(0.10,3-1,120-3)} = F_{(0.10,2,117)} = 2.3475$$

A confidence level of 95% yields a Levene F test statistic of

$$F_{(\alpha,k-1,N-k)} = F_{(0.05,3-1,120-3)} = F_{(0.05,2,117)} = 3.074.$$

A simple comparison of the Levene test statistic to the Levene F test statistics concludes $W < F_{(\alpha,k-1,N-k)}$ for each scenario/metric combination at the 90% and 95% confidence levels. The Levene test accepts the null hypothesis. Thus, the assumption of equal variances is satisfied.

4.2.2 Bonferroni Confidence Intervals

Upon completion of the 40 replications conducted in this study, the output data was sorted based on scenario, random seed, simulation, and metric. Sorting the data in this fashion ensures the data is correlated for each pair-wise comparison. The random variable data obtained from the simulations corresponds to the response variables Y_{ri} where r represents the replication and i is the simulation ($r = 1, ..., 40$; $i =$ OSD JWARS, FED JWARS, Lynx). The random variable data, also known as the output data, is presented in Appendix A.1.

The confidence intervals for each set of metric comparisons were constructed having an overall confidence level of 90% and 95%. That is, respectively 90 or 95 times out of 100, the results for the comparison between the total number of A2G engage-

Table 6. Levene test statistic, W

Scenario:	Scenario A	Scenario B	Scenario C
Total Number of A2G Engagements Executed	0.0052	0.2384	0.9041
Total Attrition from A2G Engagements	0.0048	0.0459	0.9518
Total Munitions Released during A2G Engagements	0.0011	0.3364	0.2732

ments, the total attrition from A2G engagements, and the total munitions released during A2G engagements will all be true simultaneously. The corresponding overall error probabilities are

$$\alpha_E = 1 - 0.90 = 0.10 \qquad \text{and} \qquad \alpha_E = 1 - 0.95 = 0.05.$$

Three individual confidence intervals, one for each metric, were constructed. Thus, $C = 3$. Since 3 confidence intervals with equal error probability were constructed, the error probability for each interval was then $\alpha_E/C = \alpha_E/3$. An overall confidence level of 90% yields an individual error probability of $\alpha_E/C = 0.10/3 = 0.034$. An overall confidence level of 95% yields an individual error probability of $\alpha_E/C = 0.05/3 = 0.0167$. The critical test statistic for the confidence intervals was $t_{\alpha_E/2C,R-1}$ where $R = 40$ replications and $C = 3$ pair-wise comparisons. An overall confidence level of 90% yields a critical test statistic of

$$t_{\alpha_E/2C,R-1} = t_{0.034/2,39} = t_{0.017,39} = 2.197.$$

An overall confidence level of 95% yields a critical test statistic of

$$t_{\alpha_E/2C,R-1} = t_{0.0167/2,39} = t_{0.00835,39} = 2.501.$$

Table 7 summarizes these calculations. The observed differences were calculated by subtracting the variable random data for one simulation from another. The calculated observed differences can be found found in Appendix A.2.

Using the equations in Section 3, the sample mean of the observed differences $\bar{D}_{.j}$, the sample variance of the observed differences S^2_{Dj}, and the sample error $s.e.(\bar{D}_j) = \frac{S^2_{D_j}}{\sqrt{R}}$ of the observed differences were calculated for each scenario/comparison/metric combination. Table 8 displays these calculations for the three scenarios.

Table 7. Preliminary calculations based on overall confidence level.

	Overall Confidence Level	
	90%	95%
Number of Confidence Intervals, C	3	3
Overall Error Probability, α_E	0.10	0.05
Individual Error Probability, α_E/C	0.034	0.0167
Number of Replications, R	40	40
Critical Test Statistic, $t_{\alpha_E/2C,R-1}$	2.197	2.501

Using the test statistic, the sample mean of the observed differences, and the sample standard error calculated earlier, the confidence intervals were constructed by applying Equation 7. Table 9 displays the 90% and 95% overall confidence intervals for the three metrics comparisons.

The hypothesis tests for this study are of the form:

$$H_0 : \theta_m \neq \theta_n$$

$$H_a : \theta_m = \theta_n$$

where θ_m is the observed sample mean for simulation m and θ_n is the observed sample mean for simulation n. The alternative hypothesis can also be interpreted as $\theta_m - \theta_n = 0$.

In Table 9, the six confidence intervals which compare OSD JWARS and FED JWARS all contain zero. Thus, accept the alternative hypothesis and conclude there is no statistically significant difference between OSD JWARS and FED JWARS when executing Scenario A. This also holds for Scenarios B and C. None of the confidence intervals which compare OSD JWARS and Lynx contain zero. Thus, reject the alternative hypothesis and accept the null hypothesis. There is a statistically significant difference between OSD JWARS and Lynx when executing Scenario A. Likewise, the confidence intervals which compare FED JWARS and Lynx do not contain zero. Thus, reject the alternative hypothesis and conclude there is a statistically significant difference between FED JWARS and Lynx when executing Scenario A.

Table 10 displays the results of the hypothesis test. In terms of the thesis statement, a 'YES' signifies there is a statistically significant difference between the two models for that particular metric. That is, a 'YES' is an affirmation of the thesis statement. A 'NO' signifies there is no statistically significant difference between the two models for that particular metric. That is, a 'NO' is a rejection of the thesis statement. Based on the hypothesis test, there is no statistically significant difference between the results from OSD JWARS and FED JWARS. However, there is a statistically significant difference between the results from OSD JWARS and the Lynx federation, as well as, FED JWARS and the Lynx federation.

Table 8. Descriptive statistics for the observed differences.

Comparison:	OSD JWARS vs. FED JWARS								
Scenario:	Scenario A			Scenario B			Scenario C		
	Sample Mean $\bar{D}_{\cdot j}$	Sample Variance $S^2_{D_j}$	Sample Error $S^2_{D_j}/\sqrt{R}$	Sample Mean $\bar{D}_{\cdot j}$	Sample Variance $S^2_{D_j}$	Sample Error $S^2_{D_j}/\sqrt{R}$	Sample Mean $\bar{D}_{\cdot j}$	Sample Variance $S^2_{D_j}$	Sample Error $S^2_{D_j}/\sqrt{R}$
Total Number of A2G Engagements Executed	0.4	9.6308	0.4907	1.1	79.1692	1.4069	0	0	0
Total Attrition from A2G Engagements	-0.1	180.6564	2.1252	-8.125	96.5224	1.5534	-1.575	4.6609	0.3414
Total Munitions Released during A2G Engagements	0.15	10.3872	0.5096	-9.225	27.5122	0.8293	-1.575	4.6609	0.3414

Comparison:	OSD JWARS vs. Lynx								
Scenario:	Scenario A			Scenario B			Scenario C		
	Sample Mean $\bar{D}_{\cdot j}$	Sample Variance $S^2_{D_j}$	Sample Error $S^2_{D_j}/\sqrt{R}$	Sample Mean $\bar{D}_{\cdot j}$	Sample Variance $S^2_{D_j}$	Sample Error $S^2_{D_j}/\sqrt{R}$	Sample Mean $\bar{D}_{\cdot j}$	Sample Variance $S^2_{D_j}$	Sample Error $S^2_{D_j}/\sqrt{R}$
Total Number of A2G Engagements Executed	-9.85	12.3872	0.5565	-0.2	248.7795	2.4939	0	0	0
Total Attrition from A2G Engagements	-12.425	1.5327	0.1957	-11.95	119.3821	1.7276	-1.725	7.384	0.4297
Total Munitions Released during A2G Engagements	-12	0	0	-11.75	358.0897	2.992	-1.725	7.384	0.4297

Comparison:	FED JWARS vs. Lynx								
Scenario:	Scenario A			Scenario B			Scenario C		
	Sample Mean $\bar{D}_{\cdot j}$	Sample Variance $S^2_{D_j}$	Sample Error $S^2_{D_j}/\sqrt{R}$	Sample Mean $\bar{D}_{\cdot j}$	Sample Variance $S^2_{D_j}$	Sample Error $S^2_{D_j}/\sqrt{R}$	Sample Mean $\bar{D}_{\cdot j}$	Sample Variance $S^2_{D_j}$	Sample Error $S^2_{D_j}/\sqrt{R}$
Total Number of A2G Engagements Executed	-10.25	12.0897	0.5498	-0.475	24.9224	0.7893	0	0	0
Total Attrition from A2G Engagements	-12.325	184.6865	2.1488	-12.675	14.7891	0.6081	14.225	24.384	0.7808
Total Munitions Released during A2G Engagements	-12.15	10.3872	0.5096	-12.2	40.8821	1.011	14.225	24.384	0.7808

Table 9. Bonferroni confidence intervals for the differences in mean value of a particular metric

Comparison:	OSD JWARS vs. FED JWARS											
Scenario:	Scenario A				Scenario B				Scenario C			
Confidence Level:	90%		95%		90%		95%		90%		95%	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Number of A2G Engagements Executed	-0.6780	1.4780	-0.8272	1.6272	-1.9909	4.1909	-2.4185	4.6185	0	0	0	0
Total Attrition from A2G Engagements	-4.7690	4.5690	-5.4151	5.2151	-5.6791	5.2791	-6.4372	6.0372	0	0	0	0
Total Munitions Released During A2G Engagements	-0.9696	1.2696	-1.1245	1.4245	-2.2092	1.2592	-2.4491	1.4991	0	0	0	0

Comparison:	OSD JWARS vs. Lynx											
Scenario:	Scenario A				Scenario B				Scenario C			
Confidence Level:	90%		95%		90%		95%		90%		95%	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Number of A2G Engagements Executed	-11.0726	-8.6274	-11.2418	-8.4582	-11.5378	-4.7122	-12.0101	-4.2399	-2.3250	-0.8250	-2.4287	-0.7213
Total Attrition from A2G Engagements	-12.8551	-11.9949	-12.9146	-11.9354	-15.7455	-8.1545	-16.2707	-7.6293	-2.6689	-0.7811	-2.7996	-0.6504
Total Munitions Released During A2G Engagements	-12	-12	-12	-12	-14.0109	-11.3391	-14.1957	-11.1543	12.5097	15.9403	12.2723	16.1777

Comparison:	FED JWARS vs. Lynx											
Scenario:	Scenario A				Scenario B				Scenario C			
Confidence Level:	90%		95%		90%		95%		90%		95%	
	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Total Number of A2G Engagements Executed	-11.4578	-9.0422	-11.6250	-8.8750	-11.0471	-7.4029	-11.2992	-7.1508	-2.3250	-0.8250	-2.4287	-0.7213
Total Attrition from A2G Engagements	-17.0458	-7.6042	-17.6990	-6.9510	-18.3235	-5.1765	-19.2331	-4.2669	-2.6689	-0.7811	-2.7996	-0.6504
Total Munitions Released During A2G Engagements	-13.2696	-11.0304	-13.4245	-10.8755	-14.4211	-9.9789	-14.7284	-9.6716	12.5097	15.9403	12.2723	16.1777

Table 10. Equivalency of confidence intervals.

Comparison:	OSD JWARS vs. FED JWARS					
Scenario:	Scenario A		Scenario B		Scenario C	
	90%	95%	90%	95%	90%	95%
Total Number of A2G Engagements Executed	NO	NO	NO	NO	NO	NO
Total Attrition from A2G Engagements	NO	NO	NO	NO	NO	NO
Total Munitions Released During A2G Engagements	NO	NO	NO	NO	NO	NO

Comparison:	OSD JWARS vs. Lynx					
Scenario:	Scenario A		Scenario B		Scenario C	
	90%	95%	90%	95%	90%	95%
Total Number of A2G Engagements Executed	YES	YES	YES	YES	YES	YES
Total Attrition from A2G Engagements	YES	YES	YES	YES	YES	YES
Total Munitions Released During A2G Engagements	YES	YES	YES	YES	YES	YES

Comparison:	FED JWARS vs. Lynx					
Scenario:	Scenario A		Scenario B		Scenario C	
	90%	95%	90%	95%	90%	95%
Total Number of A2G Engagements Executed	YES	YES	YES	YES	YES	YES
Total Attrition from A2G Engagements	YES	YES	YES	YES	YES	YES
Total Munitions Released During A2G Engagements	YES	YES	YES	YES	YES	YES

5 CONCLUSION

Designed as a 'proof-of-concept' simulation, the objective of the Lynx federation is to provide a joint theater-level simulation with the ability to execute individual engagements at the entity level. By employing JSAF to execute A2G engagements, the Lynx federation would provide a more precise assessment of A2G engagements. In turn, the results from the Lynx federation should be inline with those from OSD JWARS. That is, the confidence intervals obtained from the Lynx federation should be contained within the range of results obtained from OSD JWARS because, in theory, the federation is providing JWARS with a more refined view of the A2G engagements by handing off engagements to JSAF for execution.

There is no statistically significant difference between FED JWARS and OSD JWARS with regards to the A2G engagement metrics discussed in Section 3. Thus, we can conclude that the changes made to OSD JWARS, in order for it to function properly with JSAF in the Lynx federation, have not statistically altered the output data of OSD JWARS in such a way as to have significantly changed the A2G engagement results. If no A2G engagements are to be passed from JWARS to JSAF, as is the case with FED JWARS, there is no apparent benefit associated with executing a scenario in the federation rather than in the OSD version of JWARS due to the increased execution time.

There is a statistically significant difference between the output data from the Lynx federation and OSD JWARS with regards to the A2G engagement results. Since the results obtained from FED JWARS are statistically equivalent to those obtained from OSD JWARS and the major difference between the Lynx federation and FED JWARS is that A2G engagements are passed to JSAF for execution in the Lynx federation, we can conclude that the potential reasons for the differences between OSD JWARS and the Lynx federation are the manner in which A2G engagements are executed and adjudicated. This intuitively supports the statistical results. Follow-on work is needed to determine the specific design issues which contribute to the discrepancies in output data. Had no statistical difference been found between the models, this method would eliminate the necessity for an in-depth analysis to pinpoint the differences between the simulations.

This comparative analysis confirms the thesis statement that OSD JWARS and the Lynx federation produce statistically different A2G engagement results. Further investigation is required to determine the source of these discrepancies. Lynx is not a refinement of the JWARS simulation. Lynx is significantly different than OSD JWARS.

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A Data Tables

A.1 Random Variable Data

The tables in this section displays the random variable data obtained from executing each scenario in each simulation. Column 1 is the replication number. The remaining columns contain the actual random variable data obtained from the simulations where Y_{ri} is random variable data collected for a particular metric during replication r in simulation i ($r = 1, ..., 40$; $i =$ OSD JWARS, FED JWARS, Lynx).

In Table 11, Y_{ri} is the random variable data for the total number of A2G engagements executed during replication r in simulation comparison i.

In Table 12, Y_{ri} is the random variable data for the total attrition from A2G engagements executed during replication r in simulation comparison i.

In Table 13, Y_{ri} is the random variable data for the total munitions released during A2G engagements executed during replication r in simulation comparison i.

Table 11. Random variable data: Total number of A2G engagements executed.

Replication, r	Scenario A OSD JWARS Y_{r1}	Scenario A FED JWARS Y_{r2}	Scenario A Lynx Y_{r3}	Scenario B OSD JWARS Y_{r1}	Scenario B FED JWARS Y_{r2}	Scenario B Lynx Y_{r3}	Scenario C OSD JWARS Y_{r1}	Scenario C FED JWARS Y_{r2}	Scenario C Lynx Y_{r3}
1	40	40	51	43	42	52	7	7	17
2	32	32	44	45	41	55	8	8	16
3	47	43	59	43	43	53	6	6	7
4	44	44	54	39	48	48	7	7	8
5	45	40	54	49	47	63	5	5	6
6	36	36	47	42	42	55	7	7	8
7	34	30	46	38	38	46	6	6	7
8	43	43	52	45	51	56	7	7	8
9	41	39	53	42	46	53	6	6	7
10	39	38	48	45	43	61	7	7	8
11	45	46	53	50	50	60	8	8	9
12	36	38	45	50	49	57	6	6	7
13	39	38	50	46	47	50	6	6	7
14	32	31	42	37	35	47	7	7	8
15	41	41	54	56	45	65	7	7	8
16	40	42	50	42	45	52	8	8	9
17	35	34	47	38	40	47	8	8	9
18	42	43	53	46	43	55	6	6	7
19	42	42	53	45	47	54	7	7	16
20	35	33	44	35	31	46	8	8	9
21	42	41	49	42	45	50	6	6	7
22	44	35	54	47	46	55	7	7	8
23	42	43	51	46	39	56	7	7	8
24	38	42	49	40	44	54	7	7	8
25	41	39	52	42	39	49	7	7	8
26	40	43	49	46	38	53	6	6	7
27	43	43	53	43	48	50	8	8	9
28	44	44	54	42	46	47	7	7	8
29	41	41	51	43	49	51	6	6	7
30	26	33	37	41	37	54	8	8	9
31	25	26	38	32	33	43	6	6	7
32	25	25	32	31	32	41	6	6	7
33	29	29	40	37	35	43	7	7	8
34	35	35	46	42	41	53	6	6	7
35	41	41	50	42	45	50	8	8	9
36	52	58	63	53	54	60	1	1	1
37	41	42	52	45	44	54	8	8	9
38	48	46	60	50	57	59	8	8	9
39	41	41	51	43	44	61	6	6	7
40	48	38	38	58	8	8	8	8	9

Table 12. Random variable data: Total attrition from A2G engagements.

	Scenario A			Scenario B			Scenario C		
Replication, r	OSD JWARS Y_{r1}	FED JWARS Y_{r2}	Lynx Y_{r3}	OSD JWARS Y_{r1}	FED JWARS Y_{r2}	Lynx Y_{r3}	OSD JWARS Y_{r1}	FED JWARS Y_{r2}	Lynx Y_{r3}
1	149	153	161	166	157	171	9	9	22
2	140	141	153	161	156	172	10	10	19
3	173	165	185	171	160	183	8	8	9
4	161	177	173	146	177	152	8	8	9
5	190	183	202	193	188	207	6	6	7
6	159	155	173	172	165	200	7	7	8
7	132	123	146	145	137	155	8	8	9
8	145	139	158	152	184	164	10	10	11
9	162	158	175	171	182	179	6	6	7
10	146	149	157	175	175	208	10	10	11
11	164	173	177	164	172	175	10	10	11
12	149	149	160	174	171	184	7	7	8
13	180	176	191	201	218	203	8	8	9
14	133	130	145	147	155	161	9	9	10
15	166	163	181	211	164	222	9	9	10
16	155	158	166	155	151	165	9	9	10
17	145	129	158	151	140	149	11	11	12
18	191	179	204	173	170	182	8	8	9
19	177	181	188	203	198	193	9	9	20
20	123	129	136	130	113	143	10	10	11
21	159	160	170	156	180	166	8	8	9
22	194	162	207	185	186	198	8	8	9
23	177	175	187	182	158	193	10	10	11
24	159	158	171	152	169	174	8	8	9
25	155	152	168	154	148	165	9	9	10
26	136	147	147	165	132	171	7	7	8
27	161	159	173	153	164	164	10	10	11
28	163	164	175	167	171	161	8	8	9
29	134	149	146	142	158	154	7	7	8
30	101	135	114	150	131	163	11	11	12
31	100	98	115	115	114	126	7	7	8
32	112	106	123	132	131	144	8	8	9
33	121	125	133	145	137	154	9	9	10
34	132	127	146	149	152	160	7	7	8
35	147	144	159	147	160	158	11	11	12
36	198	247	210	190	202	197	2	2	2
37	183	159	194	165	165	176	11	11	12
38	173	173	188	186	206	195	12	12	13
39	177	189	191	185	190	212	7	7	8
40	154	141	167	131	133	191	11	11	12

Table 13. Random variable data: Total munitions released during A2G engagements.

	Scenario A			Scenario B			Scenario C		
Replication, r	OSD JWARS Y_{r1}	FED JWARS Y_{r2}	Lynx Y_{r3}	OSD JWARS Y_{r1}	FED JWARS Y_{r2}	Lynx Y_{r3}	OSD JWARS Y_{r1}	FED JWARS Y_{r2}	Lynx Y_{r3}
1	62	62	74	61	61	74	30	30	28
2	45	45	57	60	55	72	30	30	28
3	65	60	77	60	60	72	30	30	13
4	60	60	72	55	70	67	30	30	14
5	60	55	72	60	60	72	30	30	15
6	50	50	62	55	55	67	30	30	15
7	52	47	64	52	52	64	30	30	13
8	62	62	74	62	71	74	30	30	13
9	62	62	74	61	66	73	30	30	16
10	60	60	72	55	55	81	30	30	14
11	70	70	82	70	70	82	30	30	18
12	50	55	62	70	70	82	30	30	13
13	50	50	62	60	60	67	30	30	15
14	52	52	64	52	52	64	30	30	15
15	60	60	72	70	60	82	30	30	14
16	60	60	72	60	60	72	30	30	16
17	52	52	64	52	52	64	30	30	14
18	60	60	72	60	60	72	30	30	15
19	60	60	72	55	55	67	30	30	33
20	52	47	64	47	42	59	30	30	14
21	62	62	74	62	62	74	30	30	14
22	60	50	72	60	60	72	30	30	15
23	60	60	72	60	50	72	30	30	14
24	62	62	74	57	62	73	30	30	13
25	62	62	74	62	57	74	30	30	11
26	62	62	74	62	52	74	30	30	14
27	60	60	72	60	65	72	30	30	13
28	62	62	74	62	67	68	30	30	13
29	62	62	74	61	66	73	30	30	12
30	37	47	49	52	47	64	30	30	16
31	37	37	49	42	42	54	30	30	16
32	37	37	49	42	42	54	30	30	14
33	42	42	54	47	47	59	30	30	14
34	52	52	64	57	57	69	30	30	14
35	62	62	74	57	62	69	30	30	14
36	80	89	92	80	80	92			
37	60	60	72	60	60	72	30	30	15
38	70	70	82	69	79	76	30	30	12
39	60	60	72	55	60	77	30	30	16
40	52	52	64	47	47	73	30	30	15

A.2 Observed Differences

The tables in this section displays the observed differences calculated based on the three simulations being compared. Column 1 is the replication number. The remaining columns contain the calculated values where D_{rj} is the observed difference for a particular metric during replication r in simulation comparison j ($r = 1, ..., 40$; $j =$ OSD JWARS vs. FED JWARS, OSD JWARS vs. Lynx, FED JWARS vs. Lynx).

In Table 14, D_{rj} is the observed difference in the total number of A2G engagements executed during replication r in simulation comparison j.

In Table 15, D_{rj} is the observed difference in the total attrition from A2G engagements executed during replication r in simulation comparison j.

In Table 16, D_{rj} is the observed difference in the total munitions released during A2G engagements executed during replication r in simulation comparison j.

Table 14. Observed differences: Total number of A2G engagements executed.

	Scenario A			Scenario B			Scenario C		
Replication, r	OSD JWARS vs. FED JWARS (D_{r1})	OSD JWARS vs. Lynx (D_{r2})	FED JWARS vs. Lynx (D_{r3})	OSD JWARS vs. FED JWARS (D_{r1})	OSD JWARS vs. Lynx (D_{r2})	FED JWARS vs. Lynx (D_{r3})	OSD JWARS vs. FED JWARS (D_{r1})	OSD JWARS vs. Lynx (D_{r2})	FED JWARS vs. Lynx (D_{r3})
1	0	-11	-11	1	-9	-10	0	-10	-10
2	0	-12	-12	4	-10	-14	0	-8	-8
3	4	-12	-16	0	-10	-10	0	-1	-1
4	0	-10	-10	-9	-9	0	0	-1	-1
5	5	-9	-14	2	-14	-16	0	-1	-1
6	0	-11	-11	0	-13	-13	0	-1	-1
7	4	-12	-16	0	-8	-8	0	-1	-1
8	0	-9	-9	-6	-11	-5	0	-1	-1
9	2	-12	-14	-4	-11	-7	0	-1	-1
10	1	-9	-10	2	-16	-18	0	-1	-1
11	-1	-8	-7	0	-10	-10	0	-1	-1
12	-2	-9	-7	1	-7	-8	0	-1	-1
13	1	-11	-12	-1	-4	-3	0	-1	-1
14	1	-10	-11	2	-10	-12	0	-1	-1
15	0	-13	-13	11	-9	-20	0	-1	-1
16	-2	-10	-8	-3	-10	-7	0	-1	-1
17	1	-12	-13	-2	-9	-7	0	-1	-1
18	-1	-11	-10	3	-9	-12	0	-1	-1
19	0	-11	-11	-2	-9	-7	0	-9	-9
20	2	-9	-11	4	-11	-15	0	-1	-1
21	1	-7	-8	-3	-8	-5	0	-1	-1
22	9	-10	-19	1	-8	-9	0	-1	-1
23	-1	-9	-8	7	-10	-17	0	-1	-1
24	-4	-11	-7	-4	-14	-10	0	-1	-1
25	2	-11	-13	3	-7	-10	0	-1	-1
26	-3	-9	-6	8	-7	-15	0	-1	-1
27	0	-10	-10	-5	-7	-2	0	-1	-1
28	0	-10	-10	-4	-5	-1	0	-1	-1
29	0	-10	-10	-6	-8	-2	0	-1	-1
30	-7	-11	-4	4	-13	-17	0	-1	-1

Table 14. Continued

Replication, r	Scenario A: OSD JWARS vs. FED JWARS (D_{r1})	Scenario A: OSD JWARS vs. Lynx (D_{r2})	Scenario A: FED JWARS vs. Lynx (D_{r3})	Scenario B: OSD JWARS vs. FED JWARS (D_{r1})	Scenario B: OSD JWARS vs. Lynx (D_{r2})	Scenario B: FED JWARS vs. Lynx (D_{r3})	Scenario C: OSD JWARS vs. FED JWARS (D_{r1})	Scenario C: OSD JWARS vs. Lynx (D_{r2})	Scenario C: FED JWARS vs. Lynx (D_{r3})
31	-1	-13	-12	-1	-11	-10	0	-1	-1
32	0	-7	-7	-1	-10	-9	0	-1	-1
33	0	-11	-11	2	-6	-8	0	-1	-1
34	0	-11	-11	1	-11	-12	0	-1	-1
35	0	-9	-9	-3	-8	-5	0	-1	-1
36	-6	-11	-5	-1	-7	-6	0	0	0
37	-1	-11	-10	1	-9	-10	0	-1	-1
38	2	-12	-14	-7	-9	-2	0	-1	-1
39	0	-10	-10	-1	-18	-17	0	-1	-1
40	10	10	0	50	50	0	0	-1	-1

Table 15. Observed differences: Total attrition from A2G engagements executed.

	Scenario A			Scenario B			Scenario C		
Replication, r	OSD JWARS vs. FED JWARS (D_{r1})	OSD JWARS vs. Lynx (D_{r2})	FED JWARS vs. Lynx (D_{r3})	OSD JWARS vs. FED JWARS (D_{r1})	OSD JWARS vs. Lynx (D_{r2})	FED JWARS vs. Lynx (D_{r3})	OSD JWARS vs. FED JWARS (D_{r1})	OSD JWARS vs. Lynx (D_{r2})	FED JWARS vs. Lynx (D_{r3})
1	-4	-12	-8	9	-5	-14	0	-13	-13
2	-1	-13	-12	5	-11	-16	0	-9	-9
3	8	-12	-20	11	-12	-23	0	-1	-1
4	-16	-12	4	-31	-6	25	0	-1	-1
5	7	-12	-19	5	-14	-19	0	-1	-1
6	4	-14	-18	7	-28	-35	0	-1	-1
7	9	-14	-23	8	-10	-18	0	-1	-1
8	6	-13	-19	-32	-12	20	0	-1	-1
9	4	-13	-17	-11	-8	3	0	-1	-1
10	-3	-11	-8	0	-33	-33	0	-1	-1
11	-9	-13	-4	-8	-11	-3	0	-1	-1
12	0	-11	-11	3	-10	-13	0	-1	-1
13	4	-11	-15	-17	-2	15	0	-1	-1
14	3	-12	-15	-8	-14	-6	0	-1	-1
15	3	-15	-18	47	-11	-58	0	-1	-1
16	-3	-11	-8	4	-10	-14	0	-1	-1
17	16	-13	-29	11	2	-9	0	-1	-1
18	12	-13	-25	3	-9	-12	0	-1	-1
19	-4	-11	-7	5	10	5	0	-11	-11
20	-6	-13	-7	17	-13	-30	0	-1	-1
21	-1	-11	-10	-24	-10	14	0	-1	-1
22	32	-13	-45	-1	-13	-12	0	-1	-1
23	2	-10	-12	24	-11	-35	0	-1	-1
24	1	-12	-13	-17	-22	-5	0	-1	-1
25	3	-13	-16	6	-11	-17	0	-1	-1
26	-11	-11	0	33	-6	-39	0	-1	-1
27	2	-12	-14	-11	-11	0	0	-1	-1
28	-1	-12	-11	-4	6	10	0	-1	-1
29	-15	-12	3	-16	-12	4	0	-1	-1
30	-34	-13	21	19	-13	-32	0	-1	-1

Table 15. Continued

	Scenario A			Scenario B			Scenario C		
Replication, r	**OSD JWARS vs. FED JWARS** (D_{r1})	**OSD JWARS vs. Lynx** (D_{r2})	**FED JWARS vs. Lynx** (D_{r3})	**OSD JWARS vs. FED JWARS** (D_{r1})	**OSD JWARS vs. Lynx** (D_{r2})	**FED JWARS vs. Lynx** (D_{r3})	**OSD JWARS vs. FED JWARS** (D_{r1})	**OSD JWARS vs. Lynx** (D_{r2})	**FED JWARS vs. Lynx** (D_{r3})
31	2	-15	-17	1	-11	-12	0	-1	-1
32	6	-11	-17	1	-12	-13	0	-1	-1
33	-4	-12	-8	8	-9	-17	0	-1	-1
34	5	-14	-19	-3	-11	-8	0	-1	-1
35	3	-12	-15	-13	-11	2	0	-1	-1
36	-49	-12	37	-12	-7	5	0	0	0
37	24	-11	-35	0	-11	-11	0	-1	-1
38	0	-15	-15	-20	-9	11	0	-1	-1
39	-12	-14	-2	-5	-27	-22	0	-1	-1
40	13	-13	-26	-2	-60	-58	0	-1	-1

Table 16. Observed differences: Total munitions released during A2G engagements.

Replication, r	Scenario A: OSD JWARS vs. FED JWARS (D_{r1})	Scenario A: OSD JWARS vs. Lynx (D_{r2})	Scenario A: FED JWARS vs. Lynx (D_{r3})	Scenario B: OSD JWARS vs. FED JWARS (D_{r1})	Scenario B: OSD JWARS vs. Lynx (D_{r2})	Scenario B: FED JWARS vs. Lynx (D_{r3})	Scenario C: OSD JWARS vs. FED JWARS (D_{r1})	Scenario C: OSD JWARS vs. Lynx (D_{r2})	Scenario C: FED JWARS vs. Lynx (D_{r3})
1	0	-12	-12	0	-13	-13	0	2	2
2	0	-12	-12	5	-12	-17	0	2	2
3	5	-12	-17	0	-12	-12	0	17	17
4	0	-12	-12	-15	-12	3	0	16	16
5	5	-12	-17	0	-12	-12	0	15	15
6	0	-12	-12	0	-12	-12	0	15	15
7	5	-12	-17	0	-12	-12	0	17	17
8	0	-12	-12	-9	-12	-3	0	17	17
9	0	-12	-12	-5	-12	-7	0	14	14
10	0	-12	-12	0	-26	-26	0	16	16
11	0	-12	-12	0	-12	-12	0	12	12
12	-5	-12	-7	0	-12	-12	0	17	17
13	0	-12	-12	0	-7	-7	0	15	15
14	0	-12	-12	0	-12	-12	0	15	15
15	0	-12	-12	10	-12	-22	0	16	16
16	0	-12	-12	0	-12	-12	0	14	14
17	0	-12	-12	0	-12	-12	0	16	16
18	0	-12	-12	0	-12	-12	0	15	15
19	0	-12	-12	0	-12	-12	0	-3	-3
20	5	-12	-17	5	-12	-17	0	16	16
21	0	-12	-12	0	-12	-12	0	16	16
22	10	-12	-22	0	-12	-12	0	15	15
23	0	-12	-12	10	-12	-22	0	16	16
24	0	-12	-12	-5	-16	-11	0	17	17
25	0	-12	-12	5	-12	-17	0	19	19
26	0	-12	-12	10	-12	-22	0	16	16
27	0	-12	-12	-5	-12	-7	0	17	17
28	0	-12	-12	-5	-6	-1	0	17	17
29	0	-12	-12	-5	-12	-7	0	18	18
30	-10	-12	-2	5	-12	-17	0	14	14

Table 16. Continued

	Scenario A			Scenario B			Scenario C		
Replication, r	OSD JWARS vs. FED JWARS (D_{r1})	OSD JWARS vs. Lynx (D_{r2})	FED JWARS vs. Lynx (D_{r3})	OSD JWARS vs. FED JWARS (D_{r1})	OSD JWARS vs. Lynx (D_{r2})	FED JWARS vs. Lynx (D_{r3})	OSD JWARS vs. FED JWARS (D_{r1})	OSD JWARS vs. Lynx (D_{r2})	FED JWARS vs. Lynx (D_{r3})
31	0	-12	-12	0	-12	-12	0	14	14
32	0	-12	-12	0	-12	-12	0	16	16
33	0	-12	-12	0	-12	-12	0	16	16
34	0	-12	-12	0	-12	-12	0	16	16
35	0	-12	-12	-5	-12	-7	0	16	16
36	-9	-12	-3	0	-12	-12	0	0	0
37	0	-12	-12	0	-12	-12	0	15	15
38	0	-12	-12	-10	-7	3	0	18	18
39	0	-12	-12	-5	-22	-17	0	14	14
40	0	-12	-12	0	-26	-26	0	15	15

B Acronyms and Abbreviations

3-D	3 Dimensional
A2G	Air-to-Ground
API	Application Programming Interface
BSE	Battle Space Entity
CAS	Close Air Support
DA	Disaggregated
DMSO	Defense Modeling and Simulation Office
FA	Fully Aggregated
FCP	Fire Concentration Points
FED JWARS	Lynx federation with no A2G engagements executed in JSAF
FOM	Federation Object Model
HLA	High Level Architecture
JFACC	Joint Forces Air Component Commander
JFLCC	Joint Forces Land Component Commander
JFMCC	Joint Forces Maritime Component Commander
JFSOCC	Joint Forces Special Operations Component Commander
JSAF	Joint Semi-Automated Forces
JWARS	Joint WARfare System
OMT	Object Model Template
OnCallStrike	On Call Strike
ORD	Operational Requirements Document
OSD	Office of Secretary of Defense
PreplannedStrike	Preplanned Strike
RTI	Run-Time Infrastructure
SNE	Synthetic Natural Environment

SOM	Simulation Object Model
VET	Virtual Environment Toolkit

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