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Airlift operations modeling using Discrete Event Simulation (DES)

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THESIS

AIRLIFT OPERATION MODELING USING DISCRETE EVENT SIMULATION (DES)

by

Yew Chong Foong

December 2009

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The goal for this thesis is to develop a stochastic model using Discrete Event Simulation (DES) that can be employed to analyze the devised force structure's airlift operation performance at the operational/tactical level to augment the analysis work performed under that project. The intent is to provide a more complete solution for any stakeholders who want to take the project further to the next level.

The resulting model demonstrates the ability to measure the airlift operation performance and provide insights into operation workflow efficiency. The experiments conducted support the earlier findings on the devised Phase Zero force's ability to meet the most stringent mission requirements but suggested a different maximum airlift capability.

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AIRLIFT OPERATION MODELING
USING DISCRETE EVENT SIMULATION (DES)

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LIST OF ACRONYMS AND ABBREVIATIONS

A_O	Operational Availability
AOR	Areas of Responsibility
APOD	Aerial Port of Debarkation
APOE	Aerial Port of Embarkation
DES	Discrete Event Simulation
ea	Each
HLL	High Level Language
hr	Hour
int	Integer
JRE	Java Runtime Environment
JVM	Java Virtual Machine
lbs	Pounds
LAM	Load Allocation Mode
LRM	Landing Spot Reassignment Mode
LEGO	Listener Event Graph Objects
min	Minute
MOE	Measure of Effectiveness
MOP	Measure of Performance
MTBF	Mean-time-between-Failure
MTTR	Mean-time-to-Repair
N/A	Not Applicable
NPS	Naval Postgraduate School
OPNAV N8F	Warfare Integration/Senior National Representative
SBEL	Sea Based Logistics
SEA-15	Systems Engineering and Analysis Cohort 15
STOM	Ship-To-Objective Maneuver
UAV	Unmanned Aerial Vehicle
U.S.	United States
VETREP	Vertical Replenishment
WFI	Water-for-Injection

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I. INTRODUCTION

A. PROBLEM STATEMENT

The recently completed integrated project by the Systems Engineering and Analysis Cohort 15 (herein referred to as Project SEA-15) [1] in June 2009 has recommended an alternative force structure for operating in a maritime environment during the initial phase of military operations known as Phase Zero. The Phase Zero operation is comprised of three primary missions: anti-smuggling, civil support, and information sharing. The force's airlift capability was also found to be a critical factor in the accomplishment of the civil support mission. Two variants to the force structure were proposed; one based on current platforms only, and the other with the inclusion of future platforms that are deployable by 2020, using total procurement and operating costs of $1.5B (FY08 constant dollars) per annum.

As part of the solution, the force structure required for airlift operation support was determined by using a mix of mathematical and linear optimization modeling to ensure that all critical requirements defined for the mission scenarios could be satisfied at the lowest cost. The modeling was done using high-level and static performance parameters that did not take into consideration the tactical operation factors in a dynamic operating environment. While the abstraction may be adequate to support front-end strategic level planning, it does not have the resolution to support a proper performance analysis for the recommended force structure at the operation/tactical level. For example, the optimization model has assumed unlimited landing spots and a logistics crew that can support the concurrent loading of airlift platforms using a fixed loading time. The missing details are particularly important in this case, as the airlift operations are meant to support disaster relief missions characterized by short notice, high-load demands with a compressed delivery schedule, where the task force's real-time throughput performance matters.

It is, therefore, necessary to provide a higher resolution model to augment the analysis work that has already been performed under the Project SEA-15 so that a more complete solution can be made available to any stakeholders who want to take the project to the next level.

B. OBJECTIVES AND SCOPE

The main goal for the thesis work is to develop a dynamic model using the Discrete Event Simulation (DES) that can be used to analyze the airlift operation performance of the naval force structure recommended by Project SEA-15 at the operational/tactical level. A data-driven model will be developed to mimic the airlift operation process with the key factors abstracted as user-definable parameters to facilitate the analysis work in different settings.

With the appropriate input data, the model output can be used to validate the performance of recommended force structures under different scenario requirements and support sensitivity analysis to identify key areas that may limit or improve the force structure capabilities and effectiveness in a different operating environment. The model will help stakeholders answer the following questions:

- Is the proposed force structure optimized or feasible as per the high-level static analysis suggested it might be?
- What are the operating profiles for the proposed force structure, e.g., the duration to complete a mission, the number and the sequence of the sorties flown, etc.?
- What are the lower level performance measures for the proposed force structures and how well are they being met under the different mission demands, including operational availability, utilization rate, etc.?
- How will the proposed force structure capabilities and effectiveness be affected by the operation and logistics support constraints? For example,

what is the number of concurrent sorties that can be supported and the turnaround time between sorties under the possible constraints of limited landing/loading spots and logistics crew support?

- What are the force structure's capabilities and limitations beyond the current designed mission envelope?
- Can the proposed force structure be modified to achieve better mission effectiveness without impacting the other Phase Zero operation support? If so, what are the possible alternative structures and associated strengths/ weaknesses?

C. PROJECT SEA-15 OVERVIEW [1]

1. Background

Project SEA-15 was conducted under NPS' System Engineering Analysis curriculum as a capstone project for the students to combine their learning, and as a team, solve a real world problem. Thirty-three students from the United States (U.S.), Israel and Singapore participated in the project over a six-month period. The tasking given to this cohort came from the Warfare Integration/Senior National Representative (OPNAV N8F), which was to devise a maritime force for Phase Zero mission deployable by year 2020. Specifically:

> *Design a system of systems to employ a regional Maritime Theater Security Force to conduct all maritime missions associated with Phase Zero operations. Consider current fleet structure and funded programs as the baseline system of systems to execute security and shaping missions in developing these concept of operations, then develop alternative fleet architectures for platforms, manning, command and control, communication, logistics and operational procedures to evaluate against the current program. A complete redesign of a naval force capable of executing phase 0 operations, employable by 2020, and using total procurement and operating costs of $1.5B (FY08 constant dollars) per annum, should be one of the alternatives.*

2. General Work

The first thing that the team did was to develop a mission statement for the required maritime force. After much research on the various definitions for the term *Phase Zero*, and their relevance to the world's current landscape, the team has decided on the following:

> *A Phase Zero force will work closely with multinational, interagency and other partners to maintain or enhance stability, prevent or mitigate crises and set the conditions for access and responsive crisis intervention.*

Based on the mission statement, the team has identified the following 13 essential missions that they believe will collectively contribute to the overall accomplishment of the Phase Zero force:

- Civil Support
- Train the local defense force
- Equip the local defense force
- Build relations with foreign nations
- Restore critical infrastructure
- Anti-smuggling operations
- Anti-terrorism operations
- Anti-illegal fishing operations
- Force protection against threats
- Anti-piracy operations
- Information sharing
- Freedom of navigation
- Non-combatant evacuation operations

Given that there were similarities in terms of how these missions would be executed, and the types and characteristics of platforms involved, the team was able to consolidate the missions into three key ones, namely information sharing, anti-smuggling and civil support, using a multidimensional scaling technique. Figure 1 is the generated perceptual map illustrating how the various missions were perceived to be similar to one another. They are represented by their physical proximities on the map, based on surveyed inputs from individuals across NPS, including members from Operations Research and Systems Engineering Departments, the Naval War College and subgroup leads within the project team.

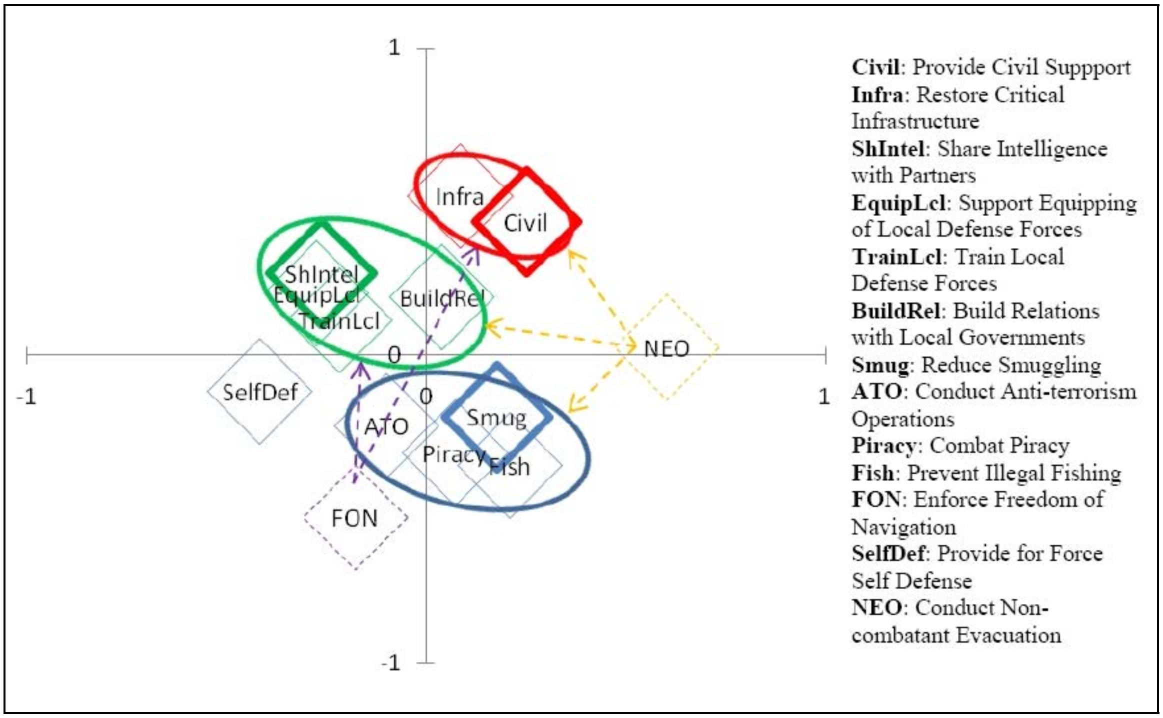

Figure 1. Phase Zero Perception Map (from [1])

Based on these three primary missions, the formulation of the force structure was carried out in the following six phases:

- Consolidate the background information required for modeling the force structure, covering studies on the threat environments, platform availability and capabilities, etc.,

- develop mission requirements and scenarios to allow for further analysis in identifying the critical attributes that will impact the accomplishment of these missions,
- perform gap analysis on current forces used for Phase Zero type missions and develop lessons learned,
- develop initial force structures that could meet the mission requirements at the various levels defined. For each level, two force structures are required, one based on current platforms in the U.S. inventory only and the other with future platforms deployable before 2020.
- apply optimization to determine the lowest cost configuration and fine-tune the results as required to produce the final force structures, and
- conduct a logistics requirement study to work out the overall capabilities and costs for each force structure and with that, recommend the one that is deemed most suited for the Phase Zero missions.

Two mission scenarios were created to simulate the Civil Support and Anti-smuggling missions in the Latin American area of responsibility. Latin America was chosen because there was a rich archive detailing past Phase Zero type missions conducted there that would provide the necessary background information for the team to construct the mission scenarios. The other reason was that Latin America was one of the key areas where drug trafficking and humanitarian crises prevailed.

The Anti-smuggling scenario was constructed using a barrier patrol concept to simulate an effort to quell drug smuggling along the western coast of Mexico. The aviation elements and the size and speed of intercept vessels were found to be the most important force attributes in identifying and interdicting drug smugglers in that area. The Civil Support scenario was modeled after the need to support the Latin American populace following a natural disaster based on three different levels of severity, and it was found that the forces' shipboard cargo capacity and its airlift capacity were most crucial in accomplishing the missions. Information Sharing requirements were studied as part of the two scenarios based on how it could be employed to support the two operations, and in both cases, a reliable and fast means for sharing information was found to be a force multiplier to the missions.

Six force structures were generated and after going through the optimization, fine-tuning and logistics considerations, the one devised for the high-severity scenario with the inclusion of future platforms was eventually recommended as the force structure most suited for the Phase Zero missions. The recommended force structure is summarized in Table 1 and its amortized annual cost is estimated at $360M, which allows four such task forces to be deployed at different areas of responsibility (AOR) given the $1.5B annual budget.

S/N	**Ship**	**Organic Assets**
1.	One JMSDF DDH class destroyer	Seven CH-53K Sea Stallion helicopters and six RQ-8 Firescout UAVs
2.	One LPD-17 San Antonio class amphibious assault support vessel	Two SH-60S Seahawk helicopters, six RQ-8 UAVs and two M-80 Stiletto
3.	One Joint High Speed Vessel (JHSV)	Nil
4.	One Visby class corvette	Six RQ-8 Firescout UAVs

Table 1. Recommended Force Structure For Phase Zero Mission

The SH-60 version was not explicitly stated in the report [1] under the recommendation section but based on the quoted performance specifications and the references made in other sections of that report, it can be inferred to be SH-60S (or the equivalent MH-60s).

The specific capabilities for the platforms in the recommended force structure are provided in the Appendix A.

D. RELATED WORK

1. Related Work in Airlift Operation Modeling

There were studies found involving the modeling of airlift operations but performed in a dissimilar context or using different tools/approaches with respect to this thesis work. They are summarized below:

- Curtin [2] has analyzed the Sea Based Logistics (SBL) concept involving inter-ship and intra-ship movement of material in his thesis work. A DES-based software package known as ARENA was used to simulate the inter-ship process of transferring pallets of load from a supply ship to a LHD class amphibious ship using vertical replenishment (VETREP) with CH-46 helicopters followed by the intra-ship movements of the pallets from the landing spots to the storage area using forklifts. The analysis focused on the operational impact due to the number and lift capacity of the aircraft used. The study concluded that increasing the aircraft lift capacity will significantly reduce the total cycle time, whereas having more aircraft only marginally reduced the cycle time.

- Kang, Doerr, Bryan and Ameyugo [3] have looked into another aspect of the SBL concept, i.e., to provide replenishment and logistics support for a deployed force ashore through direct Ship-To-Objective Maneuver (STOM). A DES model was developed to assess the STOM operations using an LHD-class amphibious ship as a sea base supported by 12 MV-22 Osprey airlift platforms to transfer pallets (of load), bladders (of water), fuel and personnel ashore over a 15-day mission. The simulation results indicated that the number and reliability of the aircraft, as well as the sustainment requirements for the force ashore, were the critical factors for mission success based on those scenarios set up for the study.

- Granger, Krishnamurthy and Robinson [4], on the other hand, have conducted a macro level analysis on a global airlift network across wider geographical locations involving intermediate airfields. Two stochastic models employing different techniques were developed to support the analysis work, and at same time, to compare the capabilities of the techniques used for such work. The first model was simulation based, developed using a commercial software package known as ProModel, while the second model employed a network approximation method and was built using another commercial software package known as MPX. The models mimicked the transfer of cargo from an Aerial Port of Embarkation (APOE) to the Aerial Port of Debarkation (APOD) with three intermediate airfield options as depicted in Figure 2. Based on the experiment setting, the analysis has shown that increasing the variability of ground times would correspondingly increase the waiting time at airfields and that fleet size has an opposing impact on airlift operation completion times and delivery flow times. The study has also demonstrated that the approximation method based model was much more efficient than the simulation model, utilizing only 2% of the time taken by the latter model to complete analysis, but at the expense of potential loss in accuracy. The authors further suggested that the combination of the two techniques would likely yield better performance than using either of them standalone, and warrants future work.

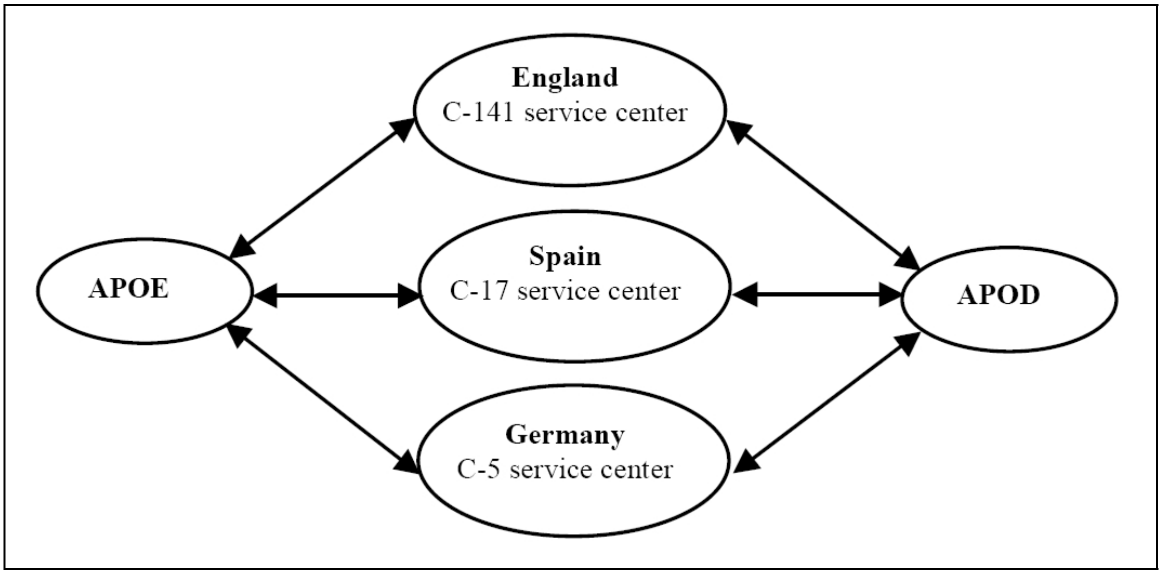

Figure 2. Airlift Network Model (from [4])

2. Related Work in DES

DES is a modeling technique widely used to simulate systems where the phenomena of interest changes value or state at discrete points in time, rather than continuously across the time horizon [5]. As an alternative to the traditional time-stepping simulation, DES provides a much more efficient means of modeling such systems as it skips through all dormant moments in time where there are no occurrences that would matter to the simulation outcome. DES is particularly useful in supporting analysis work with its inherent abilities to compress/expand time, control sources of variation, restore system state, stop anytime for review and facilitate replications [2]. The following are examples of some recent studies done using DES to support the analysis work:

- Ouerghi [6] has employed DES together with X3D visualization in his thesis work to look into problems related to ground traffic incursions and provide insights into possible cases that could result in potential accidents. Specifically, models mimicking aircraft arrivals and departures in an airport were developed to analyze the impact as the aircraft try to gain access to the taxiway and runway at the same time. The findings concluded that the approach has demonstrated “a proof-of-concept capability worthy of future work.”

- Wong and Ong [7] have demonstrated the feasibility of using DES and the multi-agent system (MAS) to validate an air defense plan in their thesis work. In their study, MAS was used to generate an aggressor’s air strike plans based on tactics described in air strike doctrines with DES models constructed to simulate the air defense assets and their interaction with the aggressor’s fighters. The developed system has also proven useful for air defense planners for looking into the dynamics of the causal effects between their air defense plans against the various possible strike plans.

- Alexander [8] has explored DES in the manufacturing process setting to analyze cycle time and timing interactions between process phases as an alternative to the conventional approach of using static methods to lay out the batch sequencing and scheduling with tools like Microsoft Project or Microsoft Excel. A sample DES model was developed to assess the water-for-injection (WFI) system usage under some proposed batch sequence improvements, which will drive up its demand. The simulation result has surfaced the critical factor for achieving the most desirable WFI system performance, which was to increase the storage capacity. It has also successfully demonstrated the DES capability of providing a reasonable performance approximation of the WFI system, as well as the manufacturing systems.

E. ORGANIZATION

This report is organized into the following chapters to provide a structured flow on how the thesis work was conceived through its deliverable end:

- <u>Chapter I – Introduction</u>. This chapter introduces the problem statement and provides the objective and scope set for the thesis work. It also provides background information on Project SEA-15 for readers to better understand the basis and considerations made for this thesis work, as well as the other related work in the same field.

- Chapter II – Methodology. This chapter describes the general methodology adopted for this work, covering the development approach, operation analysis, performance measures and the software development environment.

- Chapter III – Baseline Airlift Operation Model. This chapter describes the purpose, modeling approach, assumptions, design and implementation of the baseline airlift operation model, including the simulation findings.

- Chapter IV – Final Airlift Operation Model. This chapter describes the modeling approach and differences (versus the baseline model), and the design and implementation of the final airlift operation model.

- Chapter V – Testing and Verification. This chapter describes the testing and verification work conducted for the final airlift operation model.

- Chapter VI – Design of Experiments. This chapter describes the various experiments conducted to demonstrate the final airlift operation model's capability, compare the results under different simulation modes and evaluate the load transfer capability of the recommended Phase Zero force.

- Chapter VII – Conclusion. This chapter summarizes the thesis findings and provides recommendations for future work on the developed model to better support the intended objectives.

II. METHODOLOGY

A. DEVELOPMENT APPROACH

An iterative development approach was adopted to allow for a baseline model to be developed quickly in the early project phase based on available information to demonstrate the feasibility of using DES to address the issues under study. The model could then be used as the platform, if still applicable, for the incremental build up of its details and capability to meet the end objective. The adopted approach was meant to facilitate the refinement and realignment of the software model, if required, as more information was gathered over the project phase.

For the baseline model, the same high-level considerations and parameters used in Project SEA-15 were adopted so as to first verify whether an alternative DES model could produce or support the force structure solutions as recommended by that project. Once verified, the model output could also serve as a proxy for Project SEA-15, i.e., in areas where there is no documented information, for comparison with the final model output. For example, the project report only stated that the required missions could be completed within the given time, but it did not provide the expected completion time. In order to cut down on the development time, existing DES components developed under the OA3302 System Simulation course work will be utilized to formulate the baseline model.

B. OPERATION ANALYSIS

1. Airlift Operation in Project SEA-15

The Civil Support mission defined in Project SEA-15 was comprised of two key missions; to support populace life-sustenance by saving lives and providing/ facilitating humanitarian relief assistance to the victims, and to restore critical infrastructure so as to stabilize the affected area and restore it to normalcy [1]. Airlift support is essential to accomplish these missions, being the only means for transporting the required resources into the affected area as assumed by that project, i.e., taking worst case situations where all other forms of access are cut off.

Based on Project SEA-15's final recommended force structure, the platforms that have direct involvement in the air operations were three ship classes, namely JMSDF DDH class destroyer, LPD-17 and JHSV, and the two helicopter types: CH-53K and SH-60S. These platforms will herein be referred as JMSDF, LPD-17, JHSV, CH-53 and SH-60 respectively. The project has identified the forces' shipboard cargo capacity and its airlift capacity as the crucial attributes in accomplishing the missions. However, the importance of the shipboard cargo capacity was established from the overall sea-based storage perspective with no further analysis on how the load distribution across the ships would impact the actual airlift operation in executing the final delivery to site.

2. Airlift Operation Process

A literature research was conducted on the airlift operation process in order to identify the involved elements that have an influential effect on the operation. Several references have to be used to piece together the process that is of relevance to the study context with some assumptions made. The Shipboard-Helicopter Operational Procedures Manual [9] and Multiservice Helicopter Sling Load: Basic Operations and Equipment manual [10] were the two main reference documents used. With that, the airlift operation workflow was broadly categorized into six phases (elements) as summarized below, supported by a central management system responsible for planning and coordinating the involving activities:

- <u>Preparation Phase</u>. This is the phase prior to the aircraft arrival, where the load is moved to the landing spot from the holding space (if necessary) and set up for the loading to minimize the actual load-up time. The load can be airlifted two ways: inside the aircraft or below the aircraft suspended from the cargo hook (known as sling load operation) [10]. For this study, the load type and its airlift methods will be based on that defined for

Project SEA-15, i.e., cargo and equipment as sling load, while passengers are to be transferred inside the aircraft. For sling load, the ground crew must check to ensure that the load is properly prepared, rigged, and inspected for sling loading [10].

- Loading Phase. This is the phase where the aircraft arrives and the load is physically transferred to it. For sling load operation, the hook-up team will stay by the load for the hook-up and the approaching aircraft will be directed into position over the load by a signalman. When the aircraft gets in position and is in steady hover, the hook-up team will perform the hook-up and ensure that the connection (cargo hook and apex fitting) is secured, while grounding the cargo hook prior to any contact and throughout the process. The hook-up team will then get clear of the spot and the signalman will direct the aircraft to move up for a final visual check on the load before giving the take-off signal [10]. In the case of passenger loading, the aircraft will have to be grounded and chocked, at minimum, when the ship is stationary and in the case of ship underway, TALON or primary tie downs will have to be used before transferring passengers [9].

- Delivery Phase. This is the phase where the aircraft delivers the load from the ship to the designated target area. With sling load operations, there may be restrictions on the aircraft airspeed and maneuvering capabilities in order to maintain the load stability.

- Unloading Phase. This is the phase where the aircraft arrives at the target site and unloads. The landing site would have been prepared with the ground crew standing by to receive the load prior to the aircraft's arrival. Similar to the lading process, the aircraft will be directed into position by the signalman on the ground. For sling load operations [11], the aircraft will lower the load to the ground at the release point and then hover to one side before the signalman issues the "release load" sign to prevent the apex fitting from falling on the load. The aircrew are generally the ones opening the cargo hook to release the load, and in the event that they fail to do so, the ground crew will step in to manually release the load. Once the load is properly released, the aircraft will be given the "take-off" signal to return to ship. For the unloading of passengers, the aircraft will have to be grounded without the need for chock or tie downs.

- Recovery Phase. This is the phase where the aircraft returns to the ship from the designated target area. At this juncture, the aircraft would have been informed of which ship to head to for the next assignment or to seek service support.

- Servicing Phase. This is the phase where the aircraft is temporarily "taken out" of the mission to be serviced. There are two aspects to the servicing: refuel and repair. Helicopter refueling operations on ships can either be cold (engines off) or hot (rotors turning or engines operating). Cold refueling may be accomplished by pressure or gravity while hot refueling is limited to the use of pressure only [12]. Repair (or corrective maintenance) is necessary when the aircraft encounters failure and is deemed no longer "fit" for the mission. Most helicopter maintenance is conducted on the flight deck of the ship.

In a multi-ship environment, the airlift aircraft can be assigned to any ship to pick up the load so long as the loading spot can accommodate that aircraft type. As for servicing support, it depends on whether the ship has the facilities set up to support that aircraft type.

The final airlift operation model was designed based on this abstraction of the process, which is described in a later chapter.

C. PERFORMANCE MEASURES

1. Primary Measures

The performance measures defined under Project SEA-15 for the Civil Support mission would naturally be included for the models developed under this thesis work, since they were the primary parameters of immediate importance used to define the force structure; they are described in the following subsections.

(a) Measure of Effectiveness (MOE) / Measure of Performance (MOP) for Civil Support Mission

As highlighted in Chapter I, there were three mission scenarios established for the Phase Zero force to support the Latin American populace following a natural disaster of different severity levels. Its role is only to provide "temporary critical support, while a more suitable and substantial force can be formed and dispatched, and not as complete civil relief" [1]. The MOEs listed in the following table were defined and the associated MOPs are detailed in the next table.

S/N	Performance Measure	Requirements
A.	**Personnel Supported**	
1.	Affected population to be assisted for • Low Severity Scenario • Mean Severity Scenario • High Severity Scenario	 50,000 pax 100,000 pax 150,000 pax
2.	Seriously injured medical assistance:	5% of affected population
B.	**Supply Delivered**	
3.	Food	2.5 lbs per person per day
4.	Water	0.5 gal per person per day
5.	Shelter	50% of population affected

Table 2. MOE For Civil Support Mission (after [1])

S/N	Performance Measure
A.	**Personnel Supported**
1.	"Camp" sites provide for 20,000 displaced personnel per site.
2.	One doctor and four nurses for every 400 injured.
3.	One surgeon and two assistants for every 800 injured, in addition to the doctors and nurses required.
4.	50% of doctors accessed off site via telecommunications.
B.	**Supply Delivered**
5.	First supplies to be delivered within 24 hours.
6.	All supplies to be delivered within five days.
C.	**Overall**
7.	Five-day endurance prior to subsequent force arrival.
8.	Penetration inland from sea (with ships stationed five nm offshore) for : • Low Severity Scenario: five miles • Mean Severity Scenario 25 miles • High Severity Scenario: 50 miles
9.	Sea based command center with 200nm communications range.
10.	Adequate communications capability to support operations including remote doctor telecom.

Table 3. MOP For Civil Support Mission (after [1])

(b) Consolidated Measures for Airlift Operation

Based on the defined MOE/MOP, and having taken into consideration the other resources required to support the operation, the Project SEA-15 team has further consolidated and derived the following sets of performance measures in Table 4 to be used for the task force. The measures under Section C of the table are the ones specific for the airlift operation. Essentially, the performance measures for the airlift operation have been decomposed to the maximum delivery rates (per day) for the three different load types, namely cargo, equipment and passengers.

S/N	Parameters	Scenario Severity			Unit
		Low	Mean	High	
A.	**Storage**				
1.	Store (in lbs)	718,000	1,429,500	2,141,000	lbs
2.	Store (in ft3)	33,362	66,458	99,553	ft3
3.	Vehicle	2,220	3,520	5,780	ft2
B.	**Personnel**	**170 (158)**	**292**	**506 (491)**	**pax**
4.	Medical	43	83	123	pax
5.	Marines	127	209	383	pax
C.	**Airlift**				
6.	Max Cargo	413,600	825,900	1,238,200	lbs/day
7.	Max Equipment	6	11	16	sets/day
8.	Max Passenger	32	72	99	pax/day

Table 4. Consolidated Measures For Civil Support Mission (after [1])

2. Detailed Measures

Based on the airlift operation process described in earlier sections, the following are the additional parameters deemed essential for measuring operation effectiveness and/or providing insights to the operation workflow efficiency for conducting operational/tactical level analysis, and hence incorporated in the final model:

- Mission Completion Time. This is time taken for all the loads to be delivered to the designated target site (or affected area).
- Mission Sorties. This is the total number of delivery sorties flown in order to transport all the loads to the designated target site with breakdown for each aircraft type.
- Aircraft Utilization. This is the overall utilization rate for all airlift aircraft in the task force over a mission day with breakdown for each aircraft type.

The "idle" state is defined as the period where the aircraft is ready for a delivery sortie but with no assignment given.

- Landing Spot Utilization. This is the overall utilization rate for all landing spots onboard the ships over a mission day with breakdown for each ship. The "idle" state is defined as the period where the landing spot is not used for any ongoing activity or in standby (planned) for an impending activity.
- Crew Utilization. This is the overall utilization rate for all logistics crew onboard the ship over a mission day with breakdown for each ship. The "idle" state is defined as the period where the crew is not supporting any ongoing activity.
- Duration of Aircraft in Various Operation Phases. This is the average time the aircraft spent in a particular phase of the operation (e.g., delivery, recovery, etc.) over a mission day.
- Load Delivered Over Time. This is the quantity of the various load types delivered to the designated target sites measured at fixed time intervals over a mission day.

The baseline model was not meant to support this level of analysis by objective.

D. SOFTWARE DEVELOPMENT ENVIRONMENT

The following are the software tools and development environment used for constructing the models.

1. Java

Java is a free, open-source High Level Language (HLL) developed by Sun Microsystems and released in 1995 as a core component of Sun Microsystems' Java platform. The language's syntax is very much derived from C and C++ but has a simpler object model and fewer low-level facilities. Portability is the key strength of Java, which allows applications written in the language to run similarly on any supported hardware/operating-system platform. This is achieved by compiling the Java language code to bytecode (class file) instead of directly to platform-specific machine code, which can be run on any Java Virtual Machine (JVM) regardless of computer architecture. End-users will use a Java Runtime Environment (JRE) installed on their own machine for standalone Java applications, or in a Web browser for Java applets [13].

2. Simkit

Simkit is a free, open-source programming toolkit developed by Professor Arnold Buss of NPS to create DES models from an Event Graph methodology, i.e., the simplest and most natural way of presenting the model. It is written in Java and runs on any Java 2 platform and modern Web browsers, and is installable from the Web [14].

Every element in an Event Graph model has a corresponding element in Simkit, which uses a component framework based on a listener design pattern. Basic models encapsulating a single Event Graph are implemented in Simkit by subclassing the SimEntityBase class, i.e., an abstract base class that implements most of the functionality required by a DES component. The component framework relies on two forms of the Listener Pattern, the SimEventListener and the PropertyChangeListener patterns, to allow modelers to connect the basic models together to create larger models of greater complexity. This component framework is called Listener Event Graph Objects (LEGO). Figure 3 illustrates the conceptual design on how two basic components, i.e., Arrival Process and Multi-Server Queue, are linked through a SimEventListener to create a simple queuing model using Simkit [15].

Simkit also incorporates a framework for generating random variates and numbers to support simulation using different probability distributions without the need for any re-editing of the source code and recompilation. This capability is particularly important for the LEGO framework as it is undesirable to have every conceivable random variable implemented as a different component class [15].

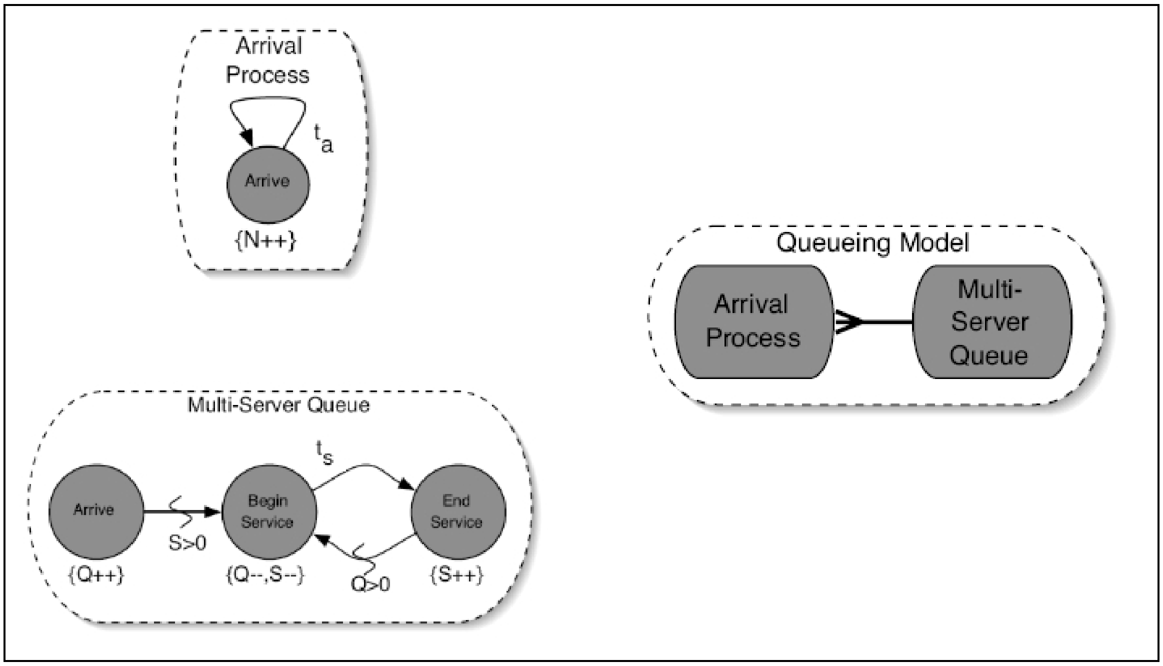

Figure 3. Illustration of the LEGO Framework using Simkit (from [16])

3. NetBeans Integrated Development Environment (IDE)

NetBeans [17] is a free, open-source IDE for software developers that is easy to install and use straight out of the box and runs on multiple platforms including Windows, Linux, Mac OS X and Solaris. It comes with a suite of tools that allows developers to

- create professional desktop applications using its GUI Builder with Swing Application Framework and Beans Binding support,
- build Web applications using Ajax, JavaScript and CSS with support for frameworks including JSF, Struts, Spring, and Hibernate,
- create, test and debug GUI applications that run on mobile phones, set-top boxes, and PDAs, with support for JavaFX Mobile and the Java ME SDK 3.0 Platform, and
- create open-source projects and host them on Kenai.com.

NetBeans features language-aware editors for JavaFX, JavaScript, CSS, Python, PHP, Groovy and Grails, Ruby and Ruby on Rails, including code completion, documentation pop-ups, and debugging integration. It also incorporates C/C++ editor, debugger, project templates, support for multiple project configurations, remote development, and packaging of completed projects.

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III. BASELINE AIRLIFT OPERATION MODEL

A. DESIGN

As highlighted in Chapter II, the baseline model was meant to be a simplified model that can be quickly assembled to capture the essence of the study question scenario in order to set one's bearing. The model is essentially designed based on the queuing concept with parallel-servers and multiple customer types. In this case, the aircraft are modeled as the "servers" and the load as the "customers," as described below:

- The different loads are generated at the onset of the simulation and form their respective queues waiting to be to be airlifted (served) as and when the aircraft are available.
- The number of loads that can be airlifted per sortie (service) is subject to the aircraft's capacity.
- The service duration is the round-trip travel time taken to cover the distance between the ship and the target area, based on the aircraft speed for each leg (an aircraft flies slower when it carries a sling load) plus the loading and unloading time.
- The queue that can be served will depend upon the aircraft's airlift capability. For example, SH-60 is incapable of airlifting equipment [1] and hence will not serve that particular queue.
- The queue to serve first (i.e., load-to-aircraft assignments) will further depend on the aircraft's relative transfer advantage, in terms of their capacity ratio, so as to optimize the airlift resources. For example, while the SH-60 has lower absolute capacities in transporting both passengers and cargo, as compared to CH-53, it is relatively more efficient for carrying passengers based on the capacity ratio of 12–55 (pax) versus 4,500–27,000 (lbs) respectively. For this reason, the SH-60 will always serve the passengers first.

The simulation will run and stop in accordance with the duration defined, which in this case is modeled as the daily operating hours for airlift operation.

B. ASSUMPTIONS

Based on the above-mentioned design concept, the following are the further considerations and assumptions made, which are consistent with those made in Project SEA-15 [1] where applicable:

- Only aircraft types in the recommended force structures were modeled, i.e., SH-60 and CH-53.
- The airlift operation was modeled on a daily-operation basis and, in this case, to meet the maximum delivery rate as required for the task force, based on the defined scenarios.
- The load hook-up, delivery, drop-off and recovery for each aircraft sortie are collapsed and treated as a single round-trip process with a deterministic time factor that is only dependent on the load type for each defined mission scenario.
- The loads are consolidated and supplied from a single source (disregarding the fact that they could be stored on different ships).
- All load types are ready and waiting to be airlifted at the landing spots.
- There are unlimited landing spots, i.e., all aircraft can perform hook-ups concurrently.
- The refueling time for each aircraft is treated as a single time block (regardless of the number of refueling operations), deducted from the daily operating hours.
- The expected failure and repair time for each aircraft type are accounted for using operational availability to pro-rate the “usable hours” based on the reduced operating hours (i.e., after deducting the refueling time).

- A basic set of statistical utilities are incorporated to generate data similar to those from the Project SEA-15 so that comparisons can be made.

C. IMPLEMENTATION

The baseline airlift operation model is implemented in Simkit. It is comprised of two components, the LoadCreator and AirliftServer. The SimEventListener structure is depicted in Figure 4. The parameters and state variables for the model are listed in the next two tables (which will be referenced in the follow-on event graphs) with the model component details provided in the subsequent subsections.

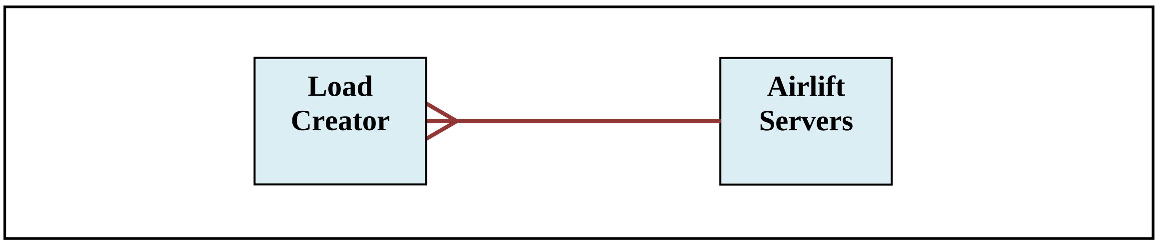

Figure 4. SimEventListener Structure for Baseline Airlift Operation Model

S/N	Field	Parameters
1.	n_i	Total number to be transferred for each load type i, i.e., i = 0, 1 and 2 for cargo, equipment and passengers respectively. *data type: int*
2.	$t_{S(CH)\_i}$	Sequence of possibly random service times (i.e., sortie times) for CH-53 aircraft type to transfer load type i. *data type: simkit.random.RandomVariate*
3.	$t_{S(SH)\_i}$	Sequence of possibly random service times (i.e., sortie times) for SH-60 aircraft type to transfer load type i. *data type: simkit.random.RandomVariate*
4.	c_{CH_i}	Transfer capacity of CH-53 aircraft type for load type i. *data type: int*
5.	c_{SH_i}	Transfer capacity of SH-60 aircraft type for load type i. *data type: int*
6.	k_{CH}	Total number of CH-53 aircraft type.

S/N	Field	Parameters
		data type: int
7.	k_{SH}	Total number of SH-60 aircraft type. *data type: int*

Table 5. Parameters for Baseline Airlift Operation Model

S/N	Field	State Variables
1.	N_i	Number of arrivals for load type i, i.e., i = 0, 1 and 2 for cargo, equipment and passenger respectively; initial value is 0. *data type: int*
2.	Q_i	Remaining quantity of load type i; initial value is 0. *data type: int*
3.	M_i	Quantity transferred for load type i; initial value is 0. *data type: int*
4.	S_{CH}	Number of available CH-53 aircraft type for load transfer; initial value is k_{MH}. *data type: int*
5.	S_{SH}	Number of available SH-60 aircraft type for load transfer; initial value is k_{SH}. *data type: int*
6.	F_{CH}	Number of CH-53 sorties flown (i.e., took off); initial value is 0. *data type: int*
7.	F_{SH}	Number of SH-60 sorties flown (i.e., took off); initial value is 0. *data type: int*
8.	U_{CH}	Cumulative flight time for the CH-53 sorties flown; initially undefined. *data type: double*
9.	U_{SH}	Cumulative flight time for the SH-60 sorties flown; initially undefined. *data type: double*
10.	**T**	Mission time based on the last completed sortie; initially undefined. *data type: double*

Table 6. State Variables for Baseline Airlift Operation Model

1. LoadCreator Component

The component is responsible for creating all the loads for the three different load types at the simulation onset and passing the individual load items to the AirliftServers as and when they are created. The following figure depicts the component event graph and the specific events are described in Table 7.

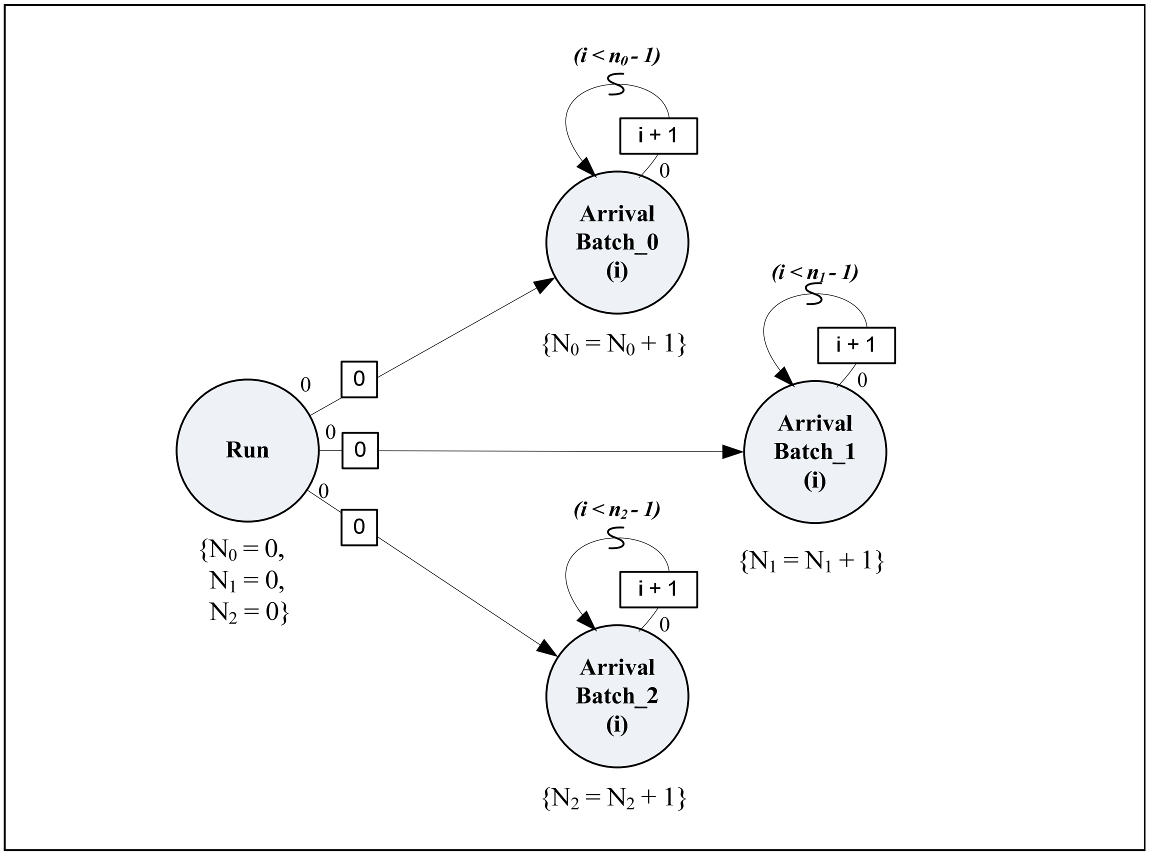

Figure 5. Event Graph for LoadCreator Component

S/N	Event	Description
1.	*Run*	Performs initialization of all load type arrivals (**N_i**) to zero and immediately triggers the other three events at the start of simulation.
2.	*ArrivalBatch_0*	Creates individual cargo item and passes it to *AirliftServers*. The total transfer quantity is created by looping through the event for that number of times.
3.	*ArrivalBatch_1*	Same as *ArrivalBatch_0* event but for equipment load type.
4.	*ArrivalBatch_2*	Same as *ArrivalBatch_0* event but for passenger load type.

Table 7. Events for LoadCreator Component

2. AirliftServers Component

The component is responsible for modeling the whole airlift operation for both aircraft types. The sequential arrivals of the load (at time 0) will trigger the appropriate aircraft to start their respective airlift operations when the mounting numbers in the queue reaches the aircraft capacity or at the end of the load arrivals. The remaining number in queue (Q_{t+1}) after each new sortie is computed using the max function, i.e., picking the maximum between 0 and the value of subtracting the load capacity (c) from the remaining number in queue (Q_t), as depicted by the following mathematical notation:

$$Q_{t+1} = \max(0, (Q_t - c))$$

The load transfer amount (j_t) will either be the load capacity, if the remaining existing number in queue is bigger than the load capacity, or otherwise, the existing number in queue, as depicted by the following mathematical notation:

$$j_t = \begin{cases} c, Q_t > c \\ Q_t, otherwise \end{cases}$$

The following figure depicts the component event graph and the specific events are described in Table 8.

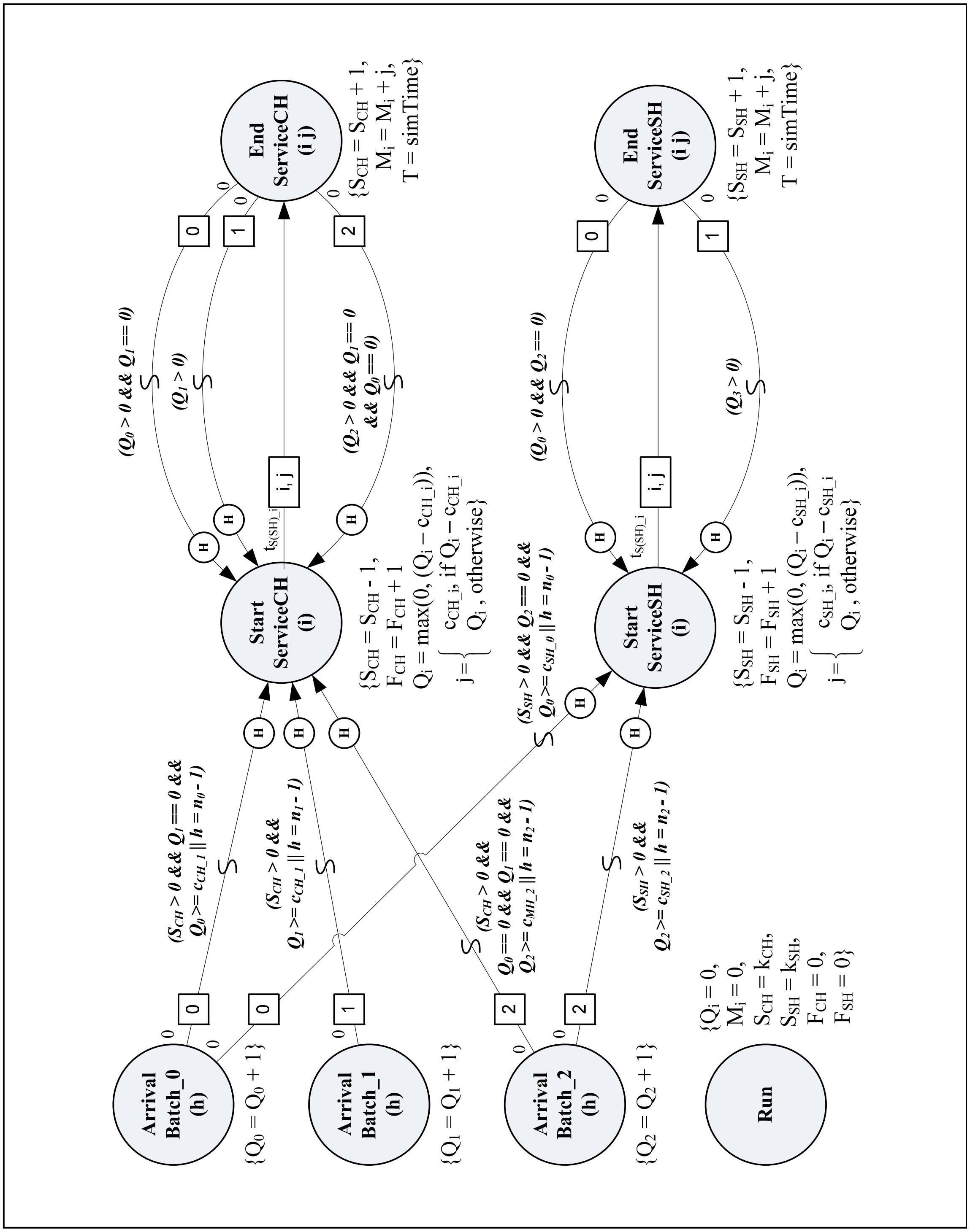

Figure 6. Event Graph for AirliftServers Component

S/N	Event	Description
1.	Run	Performs initialization for the following state variables: • initialize remaining quantity for each load type (**Q_i**) to zero • initialize transferred quantity for each load type (**M_i**) to zero • initialize number of available CH-53 aircraft type (**S_{CH}**) to its total number (**k_{CH}**) • initialize number of available SH-60 aircraft type (**S_{SH}**) to its total number (**k_{SH}**) • initialize number of CH-53 sorties flown (**F_{CH}**) to zero • initialize number of SH-60 sorties flown (**F_{SH}**) to zero • initialize mission time for last completed sortie (**T**) to zero
2.	ArrivalBatch_0	Listens for cargo item arrival from *LoadCreator* and increments the remaining quantity (**Q_0**) each time. Triggers the appropriate *StartService* event and provides the load type identifier if the conditions are met, which is dependent on the available aircraft capability and capacity, as well as what other load types are left to be transferred (as discussed under the design concept).
3.	ArrivalBatch_1	Same as *ArrivalBatch_0* event but for equipment load type.
4.	ArrivalBatch_2	Same as *ArrivalBatch_0* event but for passenger load type.
5.	StartServiceCH	Commences an airlift sortie for CH-53 aircraft and performs state transition for the following variables: • decrease number of available CH-53 aircraft type (**S_{CH}**) by one • increase number of CH-53 sorties flown (**F_{CH}**) by one • decrease remaining quantity for the load type (**Q_i**) using max function, i.e., $Q_{t+1} = \max(0, (Q_t - c))$ Computes load transfer amount (**j**) using the cited formula, i.e., $j_t = \begin{cases} c, Q_t > c \\ Q_t, otherwise \end{cases}$ Triggers *EndServiceCH* event after **$t_{S(CH)\_i}$** time delay, passing load transfer amount and load type identifier as argument.
6.	EndServiceCH	Completes the airlift sortie for CH-53 aircraft and performs state

S/N	Event	Description
		transition for the following variables: • increase number of available CH-53 aircraft type (SCH) by one • increase transferred quantity for the load type (Mi) by the load transfer amount (j) • timestamp the mission time for last completed sortie (**T**) Triggers *StartServiceCH* event immediately and provides the load type identifier if the conditions are met, depending on the aircraft's capability and its priority load, as well as the remaining load quantity.
7.	StartServiceSH	Same as *StartServiceSH* event but for SH-60 aircraft type.
8.	EndServiceSH	Same *as EndServiceSH* event but for SH-60 aircraft type.

Table 8. Events for AirliftServers Component

D. TESTING SETUP AND RESULTS

1. Input Data

As the main objective is to verify whether the alternative DES approach would support Project SEA-15 findings on the recommended force structure using future force assets, the testing has adopted the same input data as the project [1]. Table 9 depicts the aircraft parameters, and Table 10 summarizes the scenario requirements and settings, as well as the computed capability for the force structure. The capability is essentially measured by the excess capacity for transferring the cargo load type, conditional on meeting the transfer requirements for the other two load types, based on the data that was presented in Project SEA-15 report.

The testing was performed for all three scenarios against the suggested capabilities for the force structure (Section B of Table 10) based on the 7.65 effective operating hours for the day. In other words, the suggested capacities for the various load types are injected into the model as the quantities to be transferred within the defined time. A comparison can then be made with the model outputs, based on the quantity delivered, resource utilization and any additional comments generated by the model.

S/N	Parameters	SH-60	CH-53
A.	**Capacity and Capability**		
11.	For Cargo	4,500 lbs	27,000 lbs
12.	For Equipment	Not Capable	2 sets
13.	For Personnel	12 pax	55 pax

Table 9. Aircraft Parameter Input Data for Baseline Airlift Operation Model

S/N	Scenario	Scenario Severity		
		Low	**Mean**	**High**
A.	**Load Transfer Requirement**			
1.	For Cargo (lbs)	413,600	825,900	1,238,200
2.	For Equipment (sets)	6	11	16
3.	For Personnel (pax)	32	72	99
B.	**Load Transfer Capability**			
4.	For Cargo (lbs)	1,300,000 (314%)	855,000 (103%)	1,377,000 (111%)
5.	For Equipment (sets)	6 (100%)	11 (100%)	16 (100%)
6.	For Personnel (pax)	32 (100%)	72 (100%)	99 (100%)
C.	**Aircraft Quantity (i.e., the force structure recommended)**			
7.	For CH-53 (ea)	1	2	7
8.	For SH-60 (ea)	2	2	2
D.	**Operating Profile**			
9.	Normal Operating Hours (hr)	12		
10.	Refuel Time and Non-Mission Overheads (hr)	3		
11.	Operational Availability (A_o)	0.85		
12.	Effective Operating Hours (hr) [i.e., ((9) – (10))*(11)]	7.65		

S/N	Scenario	Scenario Severity		
		Low	Mean	High
D.	**Round-Trip Time for CH-53**			
13.	For Cargo (hr)	0.11	0.51	0.91
14.	For Equipment (hr)	0.11	0.51	0.91
15.	For Personnel (hr)	0.23	0.52	0.81
D.	**Round-Trip Time for SH-60**			
16.	For Cargo (hr)	0.13	0.61	1.10
17.	For Equipment (hr)	N.A.	N.A.	N.A.
18.	For Personnel (hr)	0.24	0.58	0.92

Table 10. Scenario Requirement Input Data for Baseline Airlift Operation Model (after [1])

The round-trip time for transferring personnel is relatively longer versus the other two load types for the low severity scenario, and shorter for the high severity scenario. This is because the round-trip time has a fixed loading/unloading time component and a varying traveling time component, which is distance-dependent. As the higher severity scenarios have a longer associated travel distance, the resultant round-trip time for transporting passengers becomes relatively shorter due to its longer loading/unloading time.

2. Simulation Results

The following figures are the output results generated by the model for the three test scenarios. Table 11 summarizes the test results with comparison to the suggested capability from Project SEA-15.

Simulation duration set: 7.65 hours

	CH-53	SH-60	Total
	-----	-----	-----
Number of platforms deployed :	1	2	3
Cargo transferred (in lbs) :	1007500	292500	1300000 (100%)
Equipment transferred (in sets) :	6	N.A.	6 (100%)
Passengers transferred (in pax) :	0	32	32 (100%)
Sorties flown :	41	68	109
Average Utilization :	60.43%	59.76%	60.09%

Number of cargo left : 0 lbs
Number of equipment left : 0 sets
Number of passengers left : 0 pax
All loads have been transferred.
Time last sortie completed delivery : 4.62 hours

Figure 7. Results for Low Severity Scenario using Baseline Airlift Operation Model based on Project SEA-15 Findings

Simulation duration set: 7.65 hours

	CH-53	SH-60	Total
	-----	-----	-----
Number of platforms deployed :	2	2	4
Cargo transferred (in lbs) :	648000	81000	729000 (85%)
Equipment transferred (in sets) :	11	N.A.	11 (100%)
Passengers transferred (in pax) :	0	72	72 (100%)
Sorties flown :	32	26	58
Average Utilization :	100.00%	100.00%	100.00%

Number of cargo left : 63000 lbs
Number of equipment left : 0 sets
Number of passengers left : 0 pax
There are still loads in transition.
Time last sortie completed delivery : 7.65 hours

Figure 8. Results for Mean Severity Scenario using Baseline Airlift Operation Model based on Project SEA-15 Findings

Simulation duration set: 7.65 hours

	CH-53	SH-60	Total
	-----	-----	-----
Number of platforms deployed :	7	2	9
Cargo transferred (in lbs) :	1296000	22500	1318500 (95%)
Equipment transferred (in sets) :	16	N.A.	16 (100%)
Passengers transferred (in pax) :	0	99	99 (100%)
Sorties flown :	58	16	74
Average Utilization :	96.31%	100.00%	98.15%

Number of cargo left : 0 lbs
Number of equipment left : 0 sets
Number of passengers left : 0 pax
There are still loads in transition.
Time last sortie completed delivery : 7.25 hours

Figure 9. Results for High Severity Scenario using Baseline Airlift Operation Model based on Project SEA-15 Findings

S/N	Parameters	SEA-15	Baseline Model Results	
		Capability	Capability	Resource Utilization
A.	**Low Severity Scenario**			
1.	Cargo (lbs)	1,300,000	1,300,000 (100%)	660.09%
2.	Equipment (sets)	6	6 (100%)	
3.	Passenger (pax)	32	32 (100%)	
B.	**Mean Severity Scenario**			
4.	Cargo	855,000	729,000 (85%)	1100.00%
5.	Equipment	11	11 (100%)	
6.	Passenger	72	72 (100%)	
C.	**High Severity Scenario**			
7.	Cargo	1,3770,000	1,318,500 (95%)	98.15%
8.	Equipment	16	16 (100%)	

S/N	Parameters	SEA-15	Baseline Model Results	
		Capability	Capability	Resource Utilization
9.	Passenger	99	99 (100%)	

Table 11. Test Results for Baseline Airlift Operation Model versus Project SEA-15 Reported Data

The test results have shown inconsistencies with the findings from Project SEA-15:

- For the low severity scenario, the model is able to deliver all the loads within the given timeline but the low resource utilization rate of about 60% suggested that the task force is capable of delivering more load, i.e., Project SEA-15 could have under-specified the transfer capability.
- For the mean severity scenario, the resource utilization rate is 100% but the cargo quantity delivered is only 85%, suggesting that Project SEA-15 could have over-specified the transfer capability in this case.
- Similar to the high severity scenario, the cargo quantity delivered did not meet 100%, but in this case, the resource utilization is at 98.15%. Based on the additional information generated by the model output (refer Figure 8), i.e., the observed number of cargo left being zero and the comment that "there are still loads in transition," it can now be inferred that all loads have already been picked up but delivery is incomplete because there are still delivery sorties transiting to the target site. This explains why the utilization rate is not 100%, as some aircraft would have completed their last delivery sorties and were in "idle" state when the simulation ended. Again, this suggested an over-specification by Project SEA-15 on the transfer capability.

Given that these inconsistencies were found, a thorough verification was conducted on the model algorithms as well as the Project SEA-15 reported data.

3. Verification Findings

The verification work has shown that the capability figures presented in the Project SEA-15 report were incorrect, based on mathematical computation and optimization analysis using linear programming. The optimization model was formulated using the Solver utility in Windows Excel software and the input parameters were based on the same ones used by Project SEA-15 and the baseline airlift model as summarized in the earlier tables (Table 9 and Table 10).

For the high severity scenario case, the load transfer capabilities for the various load types, and the maximum number of CH-53 sorties that can be conducted (and completed) within the given timeline were used as the constraints for the optimization model to determine the minimum number of SH-60 sorties required. Fifty-six CH-53 sorties (48 and eight for transporting cargo and equipment respectively) and 27 SH-60 sorties (18 and nine for transporting cargo and passengers respectively) were the output figures computed by the model. By summing up the timings required for each of these sorties, it can be shown that 1,377,000 lbs of cargo cannot be delivered within 7.65 hrs while meeting the transfer capabilities for the other two load types. The following table illustrates the required sorties that would have been imposed on each aircraft in order to meet the stated capabilities, which clearly shows that the two SH-60s will not complete the sorties in time.

Aircraft	Sortie type (number of sorties / time taken in hrs)			Total duration (hrs)
	for Equipment	for Passengers	for Cargo	
CH-53#1	2 / 1.82	0 / 0	6 / 5.46	7.28
CH-53#2	1 / 0.91	0 / 0	7 / 6.37	7.28
CH-53#3	1 / 0.91	0 / 0	7 / 6.37	7.28
CH-53#4	1 / 0.91	0 / 0	7 / 6.37	7.28
CH-53#5	1 / 0.91	0 / 0	7 / 6.37	7.28
CH-53#6	1 / 0.91	0 / 0	7 / 6.37	7.28
CH-53#7	1 / 0.91	0 / 0	7 / 6.37	7.28
SH-60#1	0 / 0	5 / 4.6	9 / 9.9	14.5
SH-60#2	0 / 0	4 / 3.68	9 / 9.9	13.58

Table 12. Example of the Aircraft Sorties Required to meet the Load Transfer Capability stated in Project SEA-15 Report for High Severity Scenario

Using the same methodology, the capability figures stated in the Project SEA-15 report for the low and mean severity scenarios were also proven to be incorrect, as suggested by the baseline airlift model.

The same methodology was also applied to the baseline airlift model to verify its output results. For the mean and high severity scenarios, the figures for the cargo quantity delivered in Figure 8 and Figure 9, i.e., 729,000 and 1,318,500 lbs respectively, were used as input to the model so as to generate the required sorties to be verified by the optimization model. For the low severity scenario case, a direct mathematical calculation suggested that the cargo transfer capability should be 2,232,000 lbs, which was injected to the model to generate the required output for verification. The next three figures are the results from the airlift model, and Table 13 summarizes the sorties required, with a comparison to that generated by the optimization model.

Simulation duration set: 7.65 hours

	CH-53	SH-60	Total
	-----	-----	-----
Number of platforms deployed :	1	2	3
Cargo transferred (in lbs) :	1728000	504000	2232000 (100%)
Equipment transferred (in sets) :	6	N.A.	6 (100%)
Passengers transferred (in pax) :	0	32	32 (100%)
Sorties flown :	67	115	182
Average Utilization :	98.75%	99.64%	99.19%

Number of cargo left : 0 lbs
Number of equipment left : 0 sets
Number of passengers left : 0 pax
All loads have been transferred.
Time last sortie completed delivery : 7.64 hours

Figure 10. Force Structure Capability for Low Severity Scenario using Baseline Airlift Operation Model

Simulation duration set: 7.65 hours

	CH-53	SH-60	Total
	-----	-----	-----
Number of platforms deployed :	2	2	4
Cargo transferred (in lbs) :	648000	81000	729000 (100%)
Equipment transferred (in sets) :	11	N.A.	11 (100%)
Passengers transferred (in pax) :	0	72	72 (100%)
Sorties flown :	30	24	54
Average Utilization :	99.96%	94.59%	97.27%

Number of cargo left : 0 lbs
Number of equipment left : 0 sets
Number of passengers left : 0 pax
All loads have been transferred.
Time last sortie completed delivery : 7.65 hours

Figure 11. Force Structure Capability for Mean Severity Scenario using Baseline Airlift Operation Model

```
Simulation duration set: 7.65 hours
                                              CH-53      SH-60        Total
                                              -----      -----        -----
 Number of platforms deployed  :                7          2            9
 Cargo transferred (in lbs)  :               1296000    22500    1318500 (100%)
 Equipment transferred (in sets)  :            16        N.A.       16 (100%)
 Passengers transferred (in pax)  :             0         99        99 (100%)
 Sorties flown  :                              56         14           70
 Average Utilization  :                      94.83%     89.61%       92.22%

 Number of cargo left  :                       0 lbs
 Number of equipment left  :                   0 sets
 Number of passengers left  :                  0 pax
 All loads have been transferred.
 Time last sortie completed delivery  :      7.25 hours
```

Figure 12. Force Structure Capability for High Severity Scenario using Baseline Airlift Operation Model

Aircraft	**Optimization Model**			**Airlift Model**
	for Equipment	**for Passengers**	**for Cargo**	
A. Low Severity Scenario				
CH-53 Sorties	64	3	0	67
SH-60 Sorties	112	0	3	115
B. Mean Severity Scenario				
CH-53 Sorties	24	6	0	30
SH-60 Sorties	0	18	6	24
C. High Severity Scenario				
CH-53 Sorties	48	8	0	56
SH-60 Sorties	0	5	9	14

Table 13. Test Results Comparison for Baseline Airlift Operation Model

Based on the figures presented in Table 13, it can be shown that the sorties computed by the optimization model do sum up to the number generated by the baseline airlift model and hence, verify the validity of its simulation outcome.

In the course of verification, data refinement was found to be necessary in order to overcome rounding errors caused by various sources (e.g., documented data, software tools, etc.) that could result in a very different outcome. For example, based on the 7.65 effective operating hours for the day and the round-trip time for CH-53 to transfer cargo and equipment under the mean severity scenario (i.e., 0.51 hr.), a direct calculation will show that the aircraft can complete 15 sorties per day. However, using the 0.51 hr. as an input to the airlift model in the NetBean IDE, the model would suggest that the aircraft can only perform 14 sorties for the day. By decreasing the round-trip time value in the order of 10^{-5}, the model will generate the "correct" answer of 15 sorties.

4. Summary

Table 14 summarizes the force structure capabilities suggested by the baseline airlift model as well as that stated in the Project SEA-15 report, both using the same input parameters. The presented figures for the airlift model are strictly based on the input parameters described in this chapter, which are related to the aircraft used for the airlift operation and not for the ships involved. For example, the model suggested that the cargo transfer capability is 2,286,000 lbs for the low severity scenario but the ships may not necessarily have the storage space or logistics crew to handle that load.

S/N	Scenario	Scenario Severity		
		Low	Mean	High
A.	**Load Transfer Capability based on Project SEA-15 Report [1]**			
19.	For Cargo (lbs)	1,300,000 (314%)	855,000 (103%)	1,377,000 (111%)
20.	For Equipment (sets)	6 (100%)	11 (100%)	16 (100%)
21.	For Personnel (pax)	32 (100%)	72 (100%)	99 (100%)
B.	**Load Transfer Capability based on Baseline Airlift Model**			
22.	For Cargo (lbs)	2,286,000 (522%)	729,000 (85%)	1,318,500 (106%)
23.	For Equipment (sets)	6 (100%)	11 (100%)	16 (100%)
24.	For Personnel (pax)	32 (100%)	72 (100%)	99 (100%)
B.	**Aircraft Quantity (i.e., the force structure)**			
25.	For CH-53 (ea)	1	2	7
26.	For SH-60 (ea)	2	2	2

Table 14. Test Results Comparison for Baseline Airlift Operation Model

Based on the verified airlift model results, the force structure does not meet the airlift requirement for the mean severity scenario. In order to satisfy the 825,900 lbs and the other two load type transfer requirements, the airlift model suggested that another CH-53 aircraft would be required, increasing the force structure to a three CH-53 and two SH-60 configuration, which would create excess capacity with an enhanced cargo transfer capability of 1,13M lbs (137%). Figure 13 depicts the simulation results for the suggested force structure using the load transfer capabilities as input for the load transfer requirements.

Simulation duration set: 7.65 hours

	CH-53	SH-60	Total
	-----	-----	-----
Number of platforms deployed :	3	2	5
Cargo transferred (in lbs) :	1053000	81000	1134000 (100%)
Equipment transferred (in sets) :	11	N.A.	11 (100%)
Passengers transferred (in pax) :	0	72	72 (100%)
Sorties flown :	45	24	69
Average Utilization :	99.96%	94.59%	97.27%

Number of cargo left :	0 lbs
Number of equipment left :	0 sets
Number of passengers left :	0 pax
All loads have been transferred.	
Time last sortie completed delivery :	7.65 hours

Figure 13. Revised Force Structure Capability for Mean Severity Scenario Using Baseline Airlift Operation Model

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IV. FINAL AIRLIFT OPERATION MODEL

A. DESIGN

1. Modeling Approach

The baseline model encapsulated the whole airlift operation as a single process with only three essential events, i.e., load arrival, start and end delivery. This level of abstraction limits the analysis to only those basic performance measures as shown in Chapter III. In order to support operational/ tactical level analysis to answer questions such as the operation impact due to unavailability of landing spots, aircraft failure, etc., the airlift operation needs to be modeled in greater depth.

The final model mimics the airlift operation by abstracting the process into six main phases with a central management system responsible for planning and coordinating the involving activities as described in Chapter II. Figure 14 illustrates the broad-level modeling approach for the airlift operation workflow.

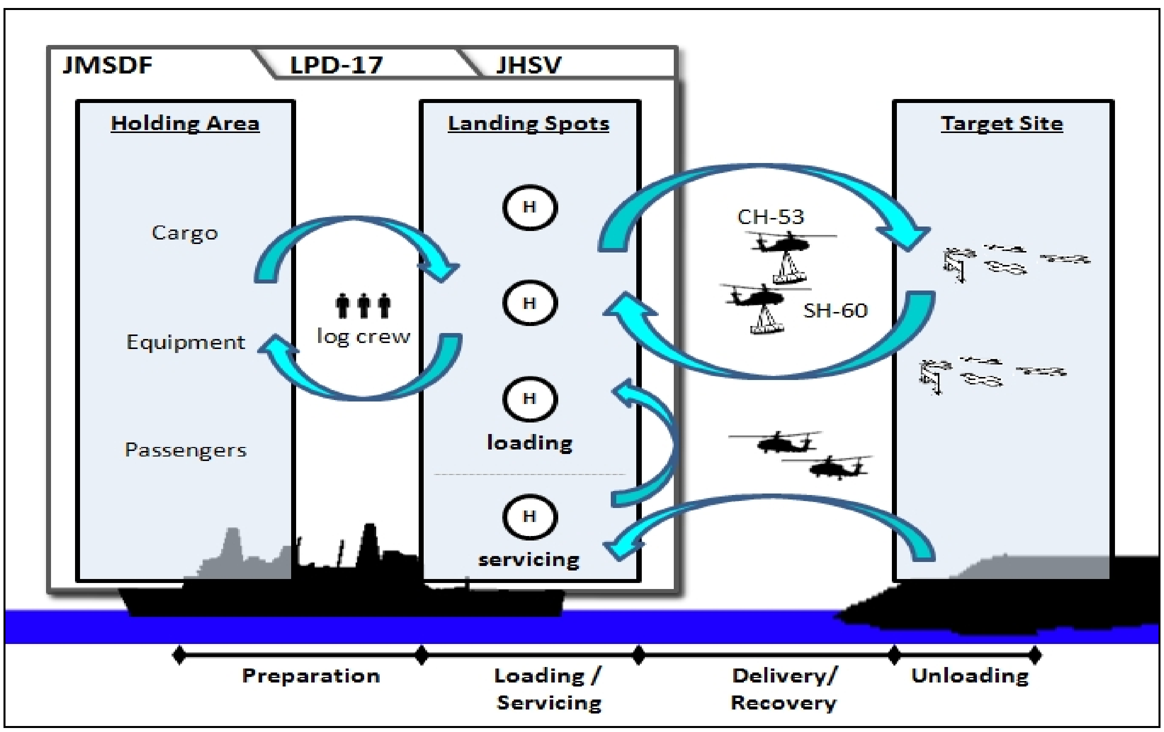

Figure 14. Airlift Operation Workflow Modeling

The modeled task force was based on the final force structure recommended by Project SEA-15 comprising three ships, namely JMSDF, LPD-17 and JHSV, and nine aircraft, i.e., seven CH-53s and two SH-60s. The RQ-8 and Visby were excluded because they do not play a direct role in the airlift operation. Each ship is a unique entity having its own set of landing spots and logistics (or ground) crew to support the airlift operation with an allocated quantity of loads to be transferred. In this case, there are three load types to be transferred; cargo, equipment and passengers, as defined in Project SEA-15. Each set of logistics crew is assumed to be an independent group that is capable of performing all the subtasks involved in preparing the load and for the load-up.

In terms of the workflow, all loads will first go through the preparation phase to be transferred from the holding area to the landing spot and set up for loading by the logistics crew. When the load is ready, the assigned aircraft (if available) will be called in for the load-up, again supported by the logistics crew. Once loaded up, the aircraft will commence the delivery sortie and the logistics crew and landing spots will be freed up to prepare for another loading. The aircraft will unload upon reaching the designated target site and recover back to the ship after that. If the aircraft is still in serviceable state, i.e., not requiring refueling or repair work, it will continue with the next airlift assignment. Otherwise, it will seek service support first, before continuing with the next assignment, in which case, a landing spot would be required for each aircraft servicing operation. For each of these six phases, there is an associated variable "service time" to perform the tasks involved, based on a mean value with a distribution function. The cycle will repeat itself for the whole mission duration until all the loads have been transferred.

In essence, the logistics crew, landing spots and aircraft are direct resources supporting the airlift operation with the ships serving as depots to supply the load and provide facilities (other than landing spots) for the service support, e.g., fueling system, maintenance crew, etc., which are not explicitly modeled. The aircraft, however, can become a constraint to the operation at times, such as when they require service support, which then draws landing spots away from supporting the airlift operation.

Table 15 summarizes the parameters modeled for the baseline and final airlift operation models.

<table>
<tr><th>S/N</th><th>Parameters</th><th>Baseline Model</th><th>Final Model</th></tr>
<tr><td>1.</td><td>Aircraft airlift capacity</td><td colspan="2">Specific to load types</td></tr>
<tr><td>2.</td><td>Aircraft airlift capability</td><td colspan="2">Specific to load types</td></tr>
<tr><td>3.</td><td>Load-to-aircraft assignment</td><td colspan="2">Based on relative advantage using capacity ratio</td></tr>
<tr><td>4.</td><td>Preparation time</td><td>All loads assumes ready for airlift at mission start time</td><td>Independent stochastic time factor</td></tr>
<tr><td>5.</td><td>Loading time</td><td rowspan="4">Treated as single round-trip process with deterministic time factor</td><td>Independent stochastic time factor</td></tr>
<tr><td>6.</td><td>Unloading time</td><td>Independent stochastic time factor</td></tr>
<tr><td>7.</td><td>Aircraft delivery time</td><td>Independent stochastic time factor</td></tr>
<tr><td>8.</td><td>Aircraft recovery time</td><td>Independent stochastic time factor</td></tr>
<tr><td>9.</td><td>Aircraft refueling time</td><td>Block reduction on the daily operating hours (deterministic)</td><td>Independent stochastic time factor</td></tr>
<tr><td>10.</td><td>Aircraft time-to-failure</td><td rowspan="2">Based on A_o on the reduced operating hours (deterministic)</td><td>Independent stochastic time factor</td></tr>
<tr><td>11.</td><td>Aircraft time-to-repair</td><td>Independent stochastic time factor</td></tr>
<tr><td>12.</td><td>Aircraft</td><td colspan="2">Individual entities</td></tr>
<tr><td>13.</td><td>Ships</td><td>Treated as single entity</td><td>Individual entities</td></tr>
<tr><td>14.</td><td>Landing spots on ship</td><td>Unlimited</td><td>Finite and ship-specific</td></tr>
<tr><td>15.</td><td>Logistics crew on ship</td><td>Unlimited</td><td>Finite and ship-specific</td></tr>
</table>

Table 15. Parameters Modeled for the Baseline and Final Airlift Models

2. Broad Level Design

There is a radical change in the design between the baseline and the final model, i.e., switching from a "load arrival" to a "landing spot arrival" triggered process. This switch is primarily to enable the "central management system" to plan ahead for the load type and the quantity that a landing spot needs to prepare, based on the next anticipated aircraft that will be available for the load-up.

The design for the operation process is best described using a flow chart, which is depicted in Figure 15 and summarized as follows:

- The simulation commences with the creation of resources (aircraft, ships, logistics crew and landing spots) and allocation of loads to the various ships based on user inputs. This is followed by a check to identify any failed aircraft (i.e., aircraft that has encountered failure), which will be transferred to the "Need Support List."
- A landing spot from each ship will be triggered next and removed from the available list to check for a new task, and to find out whether there are aircraft requiring service support (refuel and/or repair) and if so, whether there are enough landing spots already set aside to support them (in the "Support LS list," which is empty at this point). The consideration for the number of landing spots is further discussed under the Support Landing Spot Allocation subsection. If, indeed, a landing spot is required, it will then check whether there is already an aircraft waiting for the service support and if so, to commence the service or otherwise, it will be added to the "Support LS list" to standby for the aircraft.
- If the landing spot is not required for service support, it will next check for an available logistics crew, remaining load left for transfer, and unassigned aircraft, which there will be for all of them at this juncture. In the event that any of these is not available, which will happen as the mission proceeds, the landing spot will be reinserted back to the available list and wait for the next trigger event to occur.

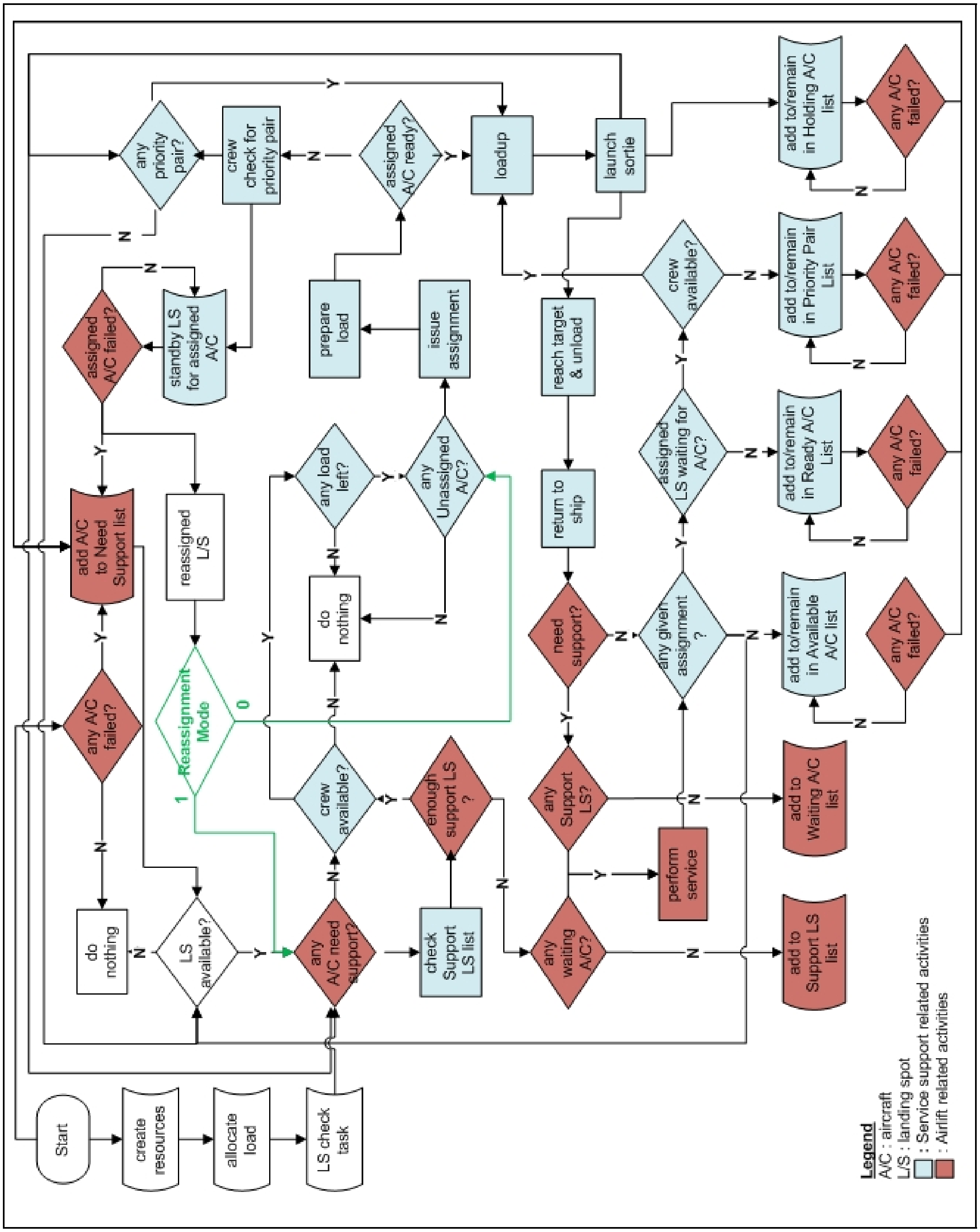

Figure 15. Flow Chart for Final Airlift Operation Model

- Based on some preset criteria, which is further discussed under the Load Allocation subsection, an assignment will be issued, specifying the assigned aircraft, load type and the quantity that the landing spot needs to prepare for. The landing spot will then proceed with load preparation and use a set of logistics crew to support it.
- Upon completion of the load preparation, the landing spot will check whether the assigned aircraft is ready. If the aircraft is ready, loading will commence, and once completed, the aircraft will begin its delivery sortie and the landing spot will restart the "check task" process. As for the relieved crew, it will first check whether there is a landing spot with its assigned aircraft ready and waiting for loading (the priority pair) and if there is, loading will commence for that pair. Otherwise, the "check task" event will be triggered if there are other available landing spots and the crew will just stand by for the next assignment.
- If the aircraft is unavailable, the logistic crew will be relieved to support another assignment and will perform the checks described earlier. As for the landing spot, it will stand by and wait for the assigned aircraft to be ready unless the aircraft has encountered failure. Under such circumstances, the landing spot will either "return" the load to the holding space and restart the "check task" process, or request another unassigned aircraft to "take over" the prepared load. The decision will depend on the reassignment scheme used for that simulation run, which is further discussed under the Landing Spot Reassignment subsection.
- As the aircraft commences the delivery sortie, it will also put in a request for the next assignment (by adding the aircraft to the Holding A/C list). The aircraft will provide the expected return time to allow for the assignment detailing, taking into consideration the (mean) refueling time if it requires a refuel upon return to ship.

- The aircraft will next reach the target site and unload, following which it will return to ship. Should the aircraft fail anytime between the loading and recovery phase, it will continue and complete the assignment on the assumption that the failure is not catastrophic, which would warrant an alternative action to be taken immediately. An aircraft failure would be made known instantly to trigger any available landing spot to start the "check task" process. If the aircraft has put in a request for a next assignment and had not been given one yet, the request will be withdrawn. Otherwise, the assigned landing spot will request either a new task or a replacement aircraft, as described earlier.

- Upon returning to ship, the aircraft will check whether it needs service support. If it does, and there are landing spots reserved to support that, the service will commence. Otherwise, the aircraft will have to wait and be added to the Waiting A/C List.

- If service support is not required and the aircraft has a next assignment with the assigned landing spot and logistics crew available, loading will commence and the follow-on process is as described earlier. If the aircraft has not been assigned, or any of the required resources are not available, the aircraft will be added to appropriate list and wait for the next trigger. Should the aircraft have failed while waiting, it will be transferred to the "Need Support List" to seek support.

(a) Support Landing Spot Allocation

The number of landing spots that can be set aside for service support was designed to be user-input controllable using two parameters, except under a special condition. The first parameter is the minimum number of landing spots each ship must have at any one time to cater to activities directly related to the airlift operation, i.e., the preparation and loading events. In other words, the difference between this number and the total number of landing spots is the maximum allowable support landing spots a ship can set aside to provide service support. The second parameter is the maximum allowable support landing spots that the whole fleet (of three ships) can set aside to provide service support, which forms the ceiling regardless of whether the individual ships have reached their respective quota.

This "maximum rule" will apply for each ship under all conditions except when it has completed all the load transfers, which in this case makes sense to open up the landing spots to provide service support, since they will not be utilized otherwise.

(b) Load Allocation

The model has incorporated two user-selectable schemes to manage the load allocation for the airlift assignment. As highlighted under the baseline model design in Chapter III, the load-to-aircraft assignment is driven by the aircraft's relative transfer advantage based on its capacity ratio in order to optimize the aircraft usage, and the same logic is inherited in this final model.

The first scheme adopts a micro management approach whereby the allocation of load is optimized at the ship-level only. In other words, the model will only check for the remaining load onboard the ship and determine the optimal load type that the landing spot should prepare for the next anticipated aircraft that will be available. For example, if the next available aircraft is a SH-60, which has the relative advantage of transporting passengers, passengers would be assigned to the landing spot if it is among the load types remaining onboard the associated ship. Otherwise, the landing spot will be assigned the next optimal load that is onboard the ship for the SH-60; the model will not consider holding off the aircraft for another ship that still has passengers onboard.

The second scheme, on the other hand, will do that in an attempt to optimize the load allocation at the fleet-level. The general concept is to get the next available aircraft for both aircraft types and, based on their expected available time difference and the remaining load in the fleet to determine the load type and aircraft for the assignment. The model does so by performing the following:

- With a landing spot request for a new assignment, the model will check for the next available aircraft in the holding list for both the aircraft types (i.e., CH-53 and SH-60). If there is only one aircraft type on the list, or the optimal load type is available onboard the ship for the aircraft type with an earlier expected available time, the model will assign the load type and aircraft to the landing as per the first scheme.
- Otherwise, the model will compute the expected available time difference for the aircraft and compare it to a user-defined threshold value. This threshold value is essentially the wait time that the user is willing to accept in order to have the "more suited" aircraft pick up the remaining load onboard that ship. If the time difference exceeds this threshold value, the model will proceed to assign the load for first available aircraft as per the first scheme. For example, if the threshold value is five minutes and a CH-53 is expected to be available seven minutes before the next SH-60, the model will assign passengers to the CH-53 if it is the only load type left onboard the ship, even though the optimal load type (equipment) for the CH-53 may be available onboard the other ships, and the SH-60 is in the holding list waiting for its assignment.
- However, if the time difference is within the threshold value, and the optimal load type for the earlier available aircraft can be found onboard the other ships, the model will assign the later available aircraft and its optimal load type to the landing spot instead. For the cited example, the model would have assigned the SH-60 and passengers as the load type to the landing spot, and hold off the CH-53 for a later assignment.
- In the event where the optimal load type for an aircraft type has been fully transferred, the same logic applies for the next optimal load type, and so forth.

As the study is about a new naval force structure, the two options will at least allow one to analyze the impact of employing different management schemes to the said situation.

(c) Landing Spot Reassignment

The model has two user-selectable schemes incorporated to handle situations when a landing spot has prepared the load but the assigned aircraft failed before it could pick up the load. For the first scheme (i.e., mode #0 as depicted in the flow chart diagram), which is a substitution approach, the landing spot will find the next available replacement of the same aircraft type as the failed aircraft so that the prepared load can be readily transferrable to the newly assigned aircraft. The second scheme (i.e., mode #1 in the flow chart diagram) is essentially a "start fresh" approach whereby the prepared load will be returned to the holding space to free up the landing spot to check for the next task.

Again, the options are implemented to analyze the various possibilities of handling the stated situations.

B. ASSUMPTIONS

Based on the above-mentioned design concept, the following are the further considerations and assumptions made:

- All ships have facilities to support the refueling and repair for both aircraft types.
- All ships are stationary and positioned at the same distance from the designated target sites.
- No adverse weather conditions that will substantially impact the aircraft airspeed.
- There are ample landing spots and ground crew support at the target sites, i.e., no queuing required for unloading.

- The recovery of the cargo nets, pallets, and hoisting slings used for the sling operations can be performed as part of the recovery sortie after transporting passengers to the target site with no additional lead-time.

C. IMPLEMENTATION

The final airlift operation model was implemented using simkit, which is comprised of five unique components, namely AircraftInitializer, AircraftServer, ShipServer, Scheduler and Recorder. The SimEventListener structure for the mode is depicted in Figure 16.

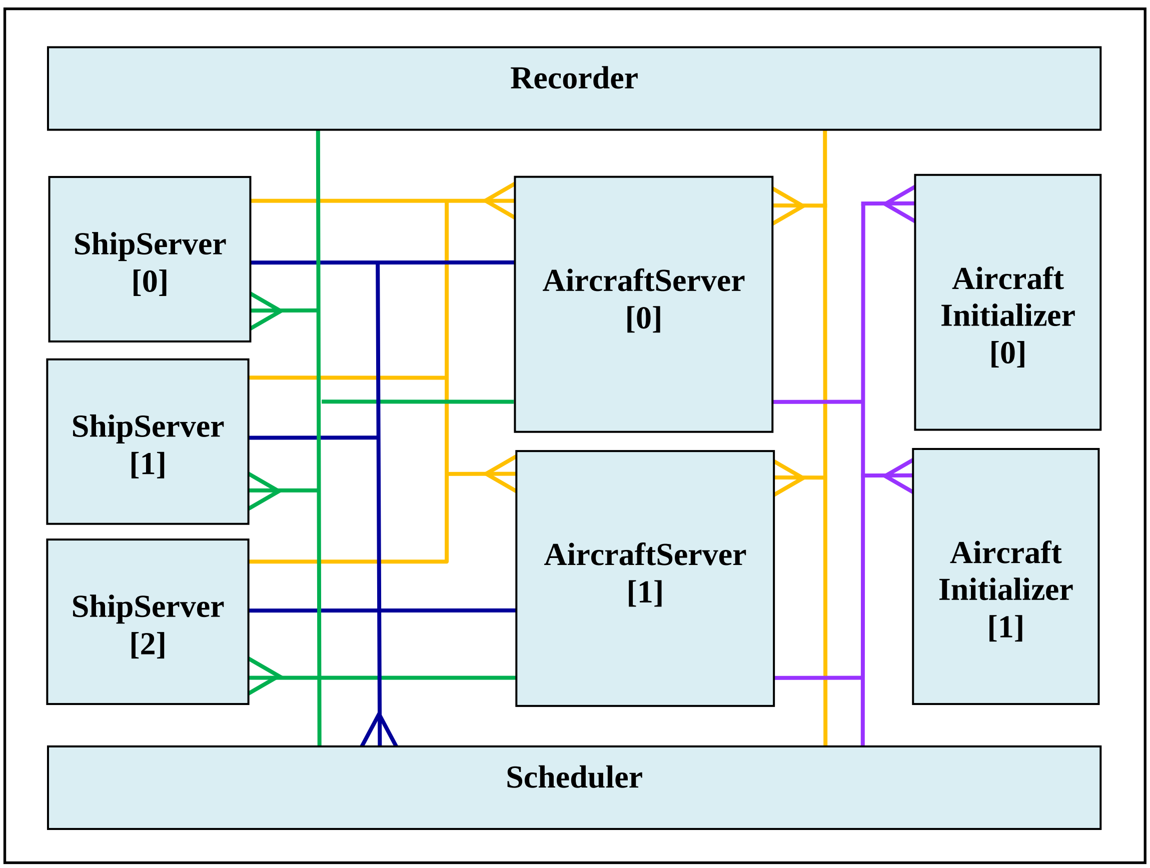

Figure 16. SimEventListener Structure for Final Airlift Operation Model

The parameters and state variables for the model are listed in the next two tables with the SimEntity objects and the model components described in the follow-on subsections:

S/N	Field	Parameters
1.	$\mathbf{a_i}$	Ship entity with identifier i, i.e., i = 0, 1 and 2 for JMSDF, LPD-17 and JHSV respectively. *data type: int*
2.	$\mathbf{b_i}$	Landing spot entity for ship entity with identifier i. *data type: LandingSpot*
3.	$\mathbf{c_k}$	Aircraft entity of type k, i.e., k = 0 and 1 for CH-53 and SH-60 respectively. *data type: int*
4.	$\mathbf{m}$	Total number of ships. *data type: int*
5.	$\mathbf{n_i}$	Total number of landing spots for ship entity with identifier i. *data type: int for ShipServer and int[] for Scheduler*
6.	$\mathbf{n_{Li}}$	Minimum number of landing spots that must be available at any one time for direct airlift operation support (i.e., for load preparation and loading activities only) for ship entity with identifier i. *data type: int*
7.	$\mathbf{n_S}$	Maximum number of landing spots for the whole fleet that can be set aside for support services (refuel and repair). This is herein referred to as maximum number support landing spots *data type: int*
8.	$\mathbf{r_i}$	Total number of logistics crew for ship entity with identifier i. *data type: int*
9.	$\mathbf{q_{i[l]}}$	Quantity allocated to ship entity with identifier i for load type l, i.e., l = 0, 1, 2 for cargo (in lbs), equipment (in sets) and passengers (in pax) respectively. *data type: int[]*
10.	$\mathbf{q_{T[l]}}$	Total load quantity to be transferred for load type l, i.e., l = 0, 1, 2 for cargo (in lbs), equipment (in sets) and passengers (in pax) respectively.

S/N	Field	Parameters
		data type: int[]
11.	$\mathbf{p_k}$	Total number of aircraft of type k. *data type: int*
12.	$\mathbf{S_{kl}}$	Transfer capacity for aircraft of type k for load type l. *data type: int*
13.	$\mathbf{t_I}$	Time interval for recording the load quantity delivered over the mission time (simulation duration). *data type: double*
14.	$\mathbf{t_{Pik[j]}}$	Sequence of possibly random service times to perform load preparation of load type j by ship with identifier i for aircraft type k. *data type: simkit.random.RandomVariate[]*
15.	$\mathbf{t_{Lik[j]}}$	Sequence of possibly random service times to perform loading for load type j by ship with identifier i for aircraft type k. *data type: simkit.random.RandomVariate[]*
16.	$\mathbf{t_{Dk[j]}}$	Sequence of possibly random sortie times to deliver load type j from ship to target site for aircraft type k. *data type: simkit.random.RandomVariate[]*
17.	$\mathbf{t_{Rk[j]}}$	Sequence of possibly random sortie times to recover from target site to ship after unloading load type j for aircraft type k. *data type: simkit.random.RandomVariate[]*
18.	$\mathbf{t_{Uk[j]}}$	Sequence of possibly random service times to unload load type j at target site for aircraft type k. *data type: simkit.random.RandomVariate[]*
19.	$\mathbf{t_{RFk}}$	Sequence of possibly random service times to refuel aircraft type k. *data type: simkit.random.RandomVariate*
20.	$\mathbf{t_{RPk}}$	Sequence of possibly random service times to repair aircraft type k. *data type: simkit.random.RandomVariate*
21.	$\mathbf{t_{Fk}}$	Sequence of possibly random time-to-failure for aircraft type k. *data type: simkit.random.RandomVariate*
22.	$\mathbf{t_W}$	Expected arrival time difference that a ship is wiling to wait in order to get a better aircraft match (optimized) for the remaining load onboard the ship, based on the unassigned aircraft in the holding list. This parameter is only

S/N	Field	Parameters
		applicable under Allocation Mode #1 scheme. *data type: double*

Table 16. Parameters for Final Airlift Operation Model

S/N	Field	State Variables
1.	$\mathbf{A_H}$	List of assignments that have been issued for the airlift operation with the details on the involved landing spot, aircraft, amount and type of load transferred, timing for various phases, etc. *data type: java.util.LinkedList<Item>*
2.	$\mathbf{A_H}$	List of sorted aircraft of all types based on their expected time available for next assignment; initial value is 0. The list is used by the Scheduler for detailing assignments and is herein referred to as the aircraft holding list. *data type: : java.util.LinkedList<Aircraft>*
3.	$\mathbf{A_{Rk}}$	List of ready aircraft of type k with new assignment but its assigned landing spot is unavailable yet; initial value is 0. The list is herein referred to as the ready aircraft list. *data type: java.util.LinkedList<Aircraft>*
4.	$\mathbf{A_{Pk}}$	List of aircraft of type k with new assignment but it is not ready yet; initial value is 0. The list is herein referred to as the planned aircraft list. *data type: java.util.LinkedList<Aircraft>*
5.	$\mathbf{A_S}$	List of aircraft requiring support service (refuel and/or repair) that has not been allocated a support landing spot yet; initial value is 0. *data type: java.util.LinkedList<Aircraft>*
6.	$\mathbf{A_W}$	List of aircraft requiring support service that has returned to ship and is waiting for an available support landing spot, which may or may not have been allocated one; initial value is 0. *data type: java.util.LinkedList<Aircraft>*
7.	$\mathbf{C_i}$	Number of available logistics crew for ship entity with identifier i; initial value is total number of logistics crew for that ship ($\mathbf{r_i}$). *data type: int*
8.	$\mathbf{D_{[l]}}$	Quantity delivered to site for load type l; initial value is 0. *data type: int[]*

S/N	Field	State Variables
9.	$\mathbf{D}_{k[l]}$	Quantity delivered to site by aircraft type k for load type l; initial value is 0. *data type: int[]*
10.	$\mathbf{D}_{[l][t]}$	Quantity delivered to site for load type l at time interval t; initial value is 0. *data type: int[][]*
11.	$\mathbf{F}_{k}$	Number of airlift sorties flown by aircraft type k; initial value is 0. *data type: int*
12.	$\mathbf{L}_{Ai}$	List of available landing spots for ship entity with identifier I; initial value is total number of landing spots for that ship (n_i). *data type: java.util.LinkedList<LandingSpot>*
13.	**H**	List of records on the timing when an aircraft has made a request for new/next assignment and when it is given one or it has retracted the request to due to aircraft failure. *data type: java.util.LinkedList<Entry>*
14.	$\mathbf{I}_{C}$	Indicator for the delivery completion for all load type, i.e., 0 and 1 for incomplete and complete respectively; initial value is 0. *data type: int*
15.	$\mathbf{L}_{Ai}$	List of available landing spots for ship with identifier i; initial value is null. *data type: java.util.LinkedList<LandingSpot>*
16.	$\mathbf{L}_{Li}$	List of landing spots with active ongoing activities (preparing or loading) directly related to an assignment for s with identifier i; initial value is null. The list is herein referred to as active landing spot list. *data type: java.util.LinkedList<LandingSpot>*
17.	$\mathbf{L}_{Pi}$	List of loaded landing spots with ready aircraft waiting for the next set of available logistics crew to perform loading for ship entity with identifier i; initial value is null. The list is herein referred to as the priority list. *data type: java.util.LinkedList<LandingSpot>*
18.	$\mathbf{L}_{R}$	List of landing spots requiring a replacement aircraft to take over the load prepared for an earlier assigned aircraft that has failed for ship with identifier I; initial value is null. This variable is only applicable under the Replacement Mode #0 scheme. *data type: java.util.LinkedList< LandingSpot >*
19.	$\mathbf{L}_{S}$	List of landing spots reserved to perform support services for the whole fleet; initial value is null. The list is herein referred to as support landing

S/N	Field	State Variables
		spot list. *data type: java.util.LinkedList<LandingSpot>*
20.	$\mathbf{L_{Wi}}$	List of loaded landing spots for ship with identifier i waiting for aircraft arrival to perform next load-up for ship entity with identifier I; initial value is null. The list is herein referred to as standby landing spot list. *data type: java.util.LinkedList<LandingSpot>*
21.	$\mathbf{N_{Ak}}$	Number of available aircraft of type k; initial value is 0.
22.	$\mathbf{N_{Ak}}$	Number of aircraft of type k in process of loading up; initial value is 0.
23.	$\mathbf{N_{Dk}}$	Number of aircraft of type k in process of delivering load from ship to target site; initial value is 0.
24.	$\mathbf{N_{Uk}}$	Number of aircraft of type k in process of unloading at target site; initial value is 0.
25.	$\mathbf{N_{Rk}}$	Number of aircraft of type k in process of recovering from target site to ship; initial value is 0.
26.	$\mathbf{N_{RFk}}$	Number of aircraft of type k in process of refueling; initial value is 0.
27.	$\mathbf{N_{RPk}}$	Number of aircraft of type k undergoing repair; initial value is 0.
28.	$\mathbf{N_{Wk}}$	Number of aircraft of type k waiting for load-up or support service; initial value is 0.
29.	$\mathbf{N_{Ai}}$	Number of available landing spots for ship with identifier i; initial value is 0. *data type: int*
30.	$\mathbf{N_{Li}}$	Number of landing spots with active ongoing activities (preparing or loading) directly related to an assignment for ship with identifier i; initial value is 0. *data type: int*
31.	$\mathbf{N_{Si}}$	Number of landing spots reserved to perform support services for ship entity with identifier i; initial value is 0. *data type: int*
32.	$\mathbf{N_{Wi}}$	Number of standby landing spots awaiting for aircraft arrival to perform next load-up for ship entity with identifier i; initial value is 0. *data type: int*
33.	$\mathbf{Q_{i[l]}}$	Remaining quantity of load type l for ship entity with identifier i; initial value is the total quantity of that load type allocated to the ship ($\mathbf{q_{i[l]}}$).

S/N	Field	State Variables
		data type: int[] for ShipServer and int[][] for Scheduler
34.	$\mathbf{Q_{[l]}}$	Remaining quantity of load type l for the whole fleet; initial value is the sum of total quantity of that load type allocated to each ship. *data type: int[]*
35.	$\mathbf{Q_{T[l]}}$	Total quantity of load type l; initial value is 0. *data type: int[]*
36.	$\mathbf{T_C}$	The completion time when all load types have been transferred to target site; initial value is 0. *data type: double*

Table 17. State Variables for Final Airlift Operation Model

1. SimEntity Objects

There are two categories of SimEntity objects created to support the simulation. The first category is used to model the real-world physical entities, i.e., aircraft, ship and landing spot. The second category is generated for keeping track of simulation data to support the simulation as well as for post-simulation review.

(a) Aircraft SimEntity

The Aircraft SimEntity is a generic object that models both the CH-53 and SH-60 aircraft types; the parameters defined for the object differentiate them. An Aircraft object is instantiated for each aircraft entity simulated in the scenario. The attributes defined for this object class are described in the following table.

S/N	Attribute	Description
A.	**Parameter**	
1.	id	Identifier for the aircraft entity. *data type: int*
2.	type	Platform type for the aircraft entity, i.e., CH53 or SH60. *data type: String*
3.	capacity	Transfer capacity for different load types for the aircraft entity. There are currently three different load types that the model is designed for, i.e., cargo, equipment and passengers, and an array (of three elements) is used to store the values in that sequence. *data type: int[]*
4.	speed	Speed transiting between ship and target site for the aircraft entity. As the aircraft may travel slower when carrying load, especially during sling load operations, different speeds will need to be defined for the delivery and recovery phase. There are currently three different load types that the model is designed for, i.e., cargo, equipment and passengers, and a 3x2 dimensional array is used to store the values with the row designated for the load type in the same sequence. The first column is meant for the delivery speed and the second for recovery speed. *data type: int[][]*
5.	meanHookOffTime	The meantime to hook-off (unload) the load from the aircraft entity. There are currently three different load types that the model is designed for, i.e., cargo, equipment and passengers, and an array (of three elements) is used to store the values in that sequence. *data type: double[]*
6.	minBufferTime	Minimum buffer time that an aircraft must be able to hold in the air upon returning to ship in case there is no available landing spot for landing. The parameter is used for refueling considerations. *data type: double*

S/N	Attribute	Description
7.	minBufferFactor	Minimum buffer factor based on the travel distance between the ship and target site that an aircraft must cater for a sortie for refueling considerations. (For example, a factor of 0.1 for a ship and the target area that are 50 nm apart means that the aircraft will only carry out the sortie if it has enough fuel to cover at least 110 nm.) *data type: double*
8.	maxDistance	The maximum distance that the aircraft entity can travel in between refuels. *data type: double*
B.	**State Variable**	
9.	needRepair	A state for the aircraft entity to indicate that it needs repair. This value is referenced by the Scheduler to allocate a landing spot to support the service task. *data type: boolean*
10.	needRefuel	A state for the aircraft entity to indicate that it needs to refuel. This value is referenced by the Scheduler to allocate a landing spot to support the service task. *data type: boolean*
11.	distanceTravelled	The distance travelled by the aircraft entity since the start of simulation or last refuel, whichever is the later event. This value is referenced by the AircraftServer instances to determine when refueling is required. *data type: int*
12.	expectedReturnTime	The expected time that the aircraft entity will return to ship, complete the refuel (if required) and be ready to execute the next assignment. This value is referenced by the Scheduler for detailing assignments. *data type: double*
13.	assignment	Assignment that the aircraft entity has been given and is currently being executed, i.e., from the point loading commences till the aircraft returns to ship and is ready for its next assignment (including refueling and repairing work). *data type: Item*

S/N	Attribute	Description
14.	entry	Record of when the aircraft entity has last requested an assignment and time when it was given one or when it retracted the request due to aircraft failure. *data type: Entry*
15.	nextLandingSpot	Landing spot that the aircraft is assigned to for the new/next assignment. *data type: LandingSpot*
16.	totalSorties	Total number of sorties flown (or delivery made) by the aircraft entity. *data type: int*
17.	state	Enumerator to indicate the current phase that the aircraft entity is in, that is, available with no assignment (0) waiting to execute next assignment (1), loading up (2), delivering load to target site (3), unloading (4), recovering to ship (5), refueling (6), and repairing (7). *data type: int*
18.	status	Enumerator to indicate whether an aircraft entity has been given a new/next assignment, that is, not assigned (0) and assigned (1). *data type: int*

Table 18. Attributes for Aircraft SimEntity Object

(b) Ship SimEntity

The Ship SimEntity is a generic object that can model any of the ship types, JMSDF, LPD-17 and JHSV; the parameters defined for the object differentiate them. A Ship object is instantiated for each ship entity simulated in the scenario. The attributes defined for this object class is described in the following table.

S/N	Attribute	Description
A.	**Parameter**	
1.	id	Identifier for the ship entity. *data type: int*
2.	type	Platform type for the ship entity, i.e., JMSDF, LPD17 or JHSV. *data type: String*
3.	totalLandingSpots	Total number of landing spots for the ship entity. *data type: int*
4.	totalLogCrew	Total number of logistics crew (set) on the ship entity. *data type: int*
5.	landingSpotList	List of landing spot entities for the ship entity. *data type: java.util.LinkedList<LandingSpot>*
B.	**State Variable**	
6.	allocatedLoad	Quantity for each load type onboard the ship entity. *data type: int[]*

Table 19. Attributes for Ship SimEntity Object

(c) LandingSpot SimEntity

The LandingSpot SimEntity is a generic object created to model the landing spots for all the ships. A LandingSpot object is instantiated for each landing spot as it needs to maintain its own unique states at any given time during simulation. The attributes defined for this object class is described in the following table.

S/N	Attribute	Description
A.	**Parameter**	
1.	id	Identifier for the landing spot entity. *data type: int*
2.	associatedShipId	Identifier for the ship entity that the landing spot is associated with, i.e., with value = 0, 1 and 2 for JMSDF, LPD-17 and JHSV respectively. *data type: int*
B.	**State Variable**	
3.	assignment	Airlift assignment (object) given to the landing spot. *data type: Item*
4.	supportAircraft	Aircraft (object) that the landing spot is tasked to provide support services (refuel and repair) to. *data type: Aircraft*

Table 20. Attributes for LandingSpot SimEntity Object

(d) Item SimEntity

The Item SimEntity object is created to keep track of each individual assignment data that is used to support the simulation, as well as for post-simulation review. Table 18 describes the attributes defined for the entity.

S/N	Attribute	Description
A.	**Parameter**	
1.	id	Identifier for the assignment entity. *data type: int*
B.	**State Variable**	
2.	assignmentTime	The time when the assignment entity is created. *data type: double*
3.	landingSpot	The landing spot entity that is assigned to this assignment entity. *data type: LandingSpot*

S/N	Attribute	Description
4.	aircraft	The aircraft entity that is assigned to this assignment entity. *data type: Aircraft*
5.	loadType	The load type to be transferred under this assignment. *data type: int*
6.	loadQuantity	The quantity of the assigned load type to be transferred under this assignment. *data type: int*
7.	startPrepareTime	The time when the load preparation starts. *data type: double*
8.	endPrepareTime	The time when the load preparation ends. *data type: double*
9.	startLoadingTime	The time when the loading starts. *data type: double*
10.	endLoadingTime	The time when the loading ends. *data type: double*
11.	startSortieTime	The time when the assigned aircraft starts the sortie (leaves the ship). *data type: double*
12.	reachTargetTime	The time when the assigned aircraft reaches the target site and start unloading. *data type: double*
13.	leaveTargetTime	The time when the assigned aircraft completes unloading and leaves the target site. *data type: double*
14.	endSortieTime	The time when the assigned aircraft returns to ship. *data type: double*
15.	startRefuelTime	The time when the assigned aircraft starts refueling. *data type: double*
16.	endRefuelTime	The time when the assigned aircraft ends refueling. *data type: double*

S/N	Attribute	Description
17.	startRepairTime	The time when the repair work for the assigned aircraft starts. *data type: double*
18.	endRepairTime	The time when the repair work for the assigned aircraft starts. *data type: double*
19.	readyTime	The time when the assigned aircraft is ready to execute its next assignment, which marks the end of this assignment. *data type: double*
20.	expectedDuration	The expected sortie duration, i.e., the time between when the assigned aircraft starts and ends a sortie. This duration is computed based on the sum of the travel time to and from the target site (dividing distance by speed), the mean time to unload and mean time to refuel (if the aircraft needs to be refueled upon return to ship for this assignment). *data type: double*
21.	actualDuration	The actual sortie duration, i.e., the measured time between when the assigned aircraft starts and ends a sortie. *data type: double*
22.	remainingLoad	The remaining quantity for all load types left to be transferred, after discounting the quantity to be transferred under this assignment. There are currently three different load types that the model is designed for, cargo, equipment and passengers. An array (of three elements) is used to store the values in that sequence. *data type: int[]*

Table 21. Attributes for Item SimEntity Object

(e) Entry SimEntity

The Entry SimEntity object is used to keep track of when an aircraft is added and removed from the holding list to support the simulation as well as for post-simulation review. The following table describes the attributes defined for the entity.

S/N	Attribute	Description
A.	**Parameter**	
1.	id	Identifier for the record entry entity. *data type: int*
B.	**State Variable**	
2.	aircraft	The aircraft entity that the record entry is created for. *data type: Aircraft*
3.	startTime	The time when the record entry is created, i.e., when an aircraft requests for new/next assignment. *data type: double*
4.	endTime	The time when the record entry is closed, i.e., when the aircraft gets its assignment or when it retracts the request because it encountered failure. *data type: double*

Table 22. Attributes for Entry SimEntity Object

2. AircraftInitializer Component

This component is responsible for the creation and initialization of the list of entities for each aircraft type. Two AircraftInitializer components are therefore instantiated for the simulation, one for the CH-53 and the other for the SH-60 aircraft type. The following figure depicts the component event graph, and the specific events are described in Table 23.

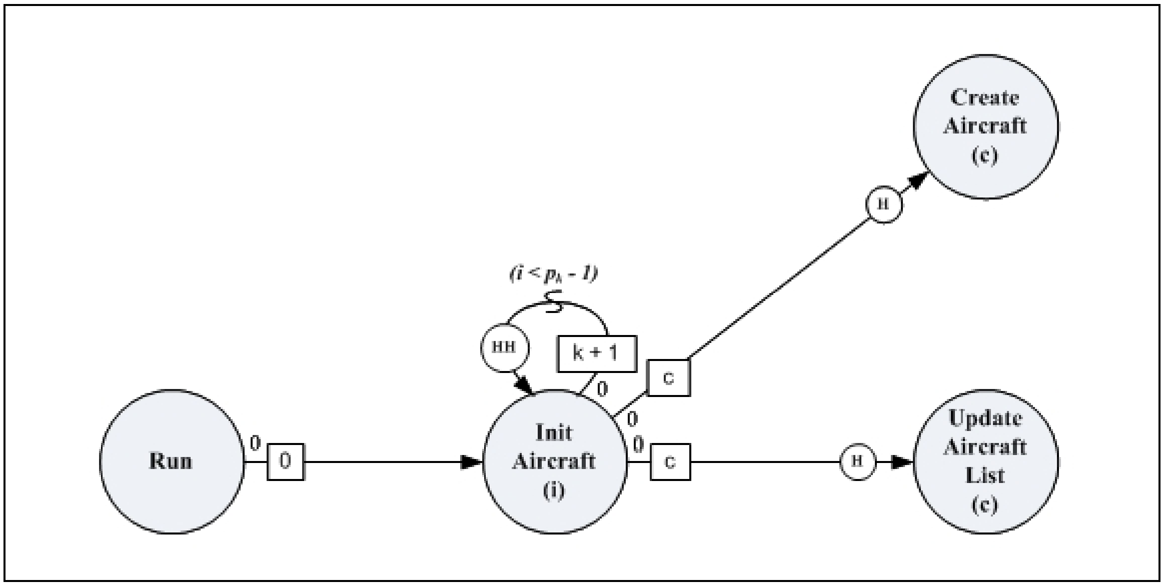

Figure 17. Event Graph for AircraftInitializer Component

S/N	Event	Purpose
1.	*Run*	Triggers the *InitAircraft* event immediately at the start of simulation.
2.	*InitAircraft*	Creates aircraft entity, sets its parameters and initializes its state variables, i.e., • set aircraft identifier, • set aircraft type, • set aircraft capacity, • set aircraft speed, • set aircraft mean time for unloading the various load types, • set aircraft maximum range (i.e., before requiring refueling), • set aircraft minimum buffer time, • set aircraft minimum buffer factor, • initialize aircraft need for refuel to false, • initialize aircraft need for repair to false, • initialize aircraft expected return time to ship to zero,

S/N	Event	Purpose
		• initialize aircraft's next assigned landing spot to null, • initialize aircraft's assignment to null, • initialize aircraft's total sorties flown to zero, • initialize aircraft status to zero, • initialize aircraft state to zero, and • initialize aircraft travelled distance from zero for the first aircraft up to half the maximum range for the last aircraft with constant increment. This is to simulate some staggering in the refueling need for the aircraft fleet, which is more representative of actual operations. Loops itself for ($\mathbf{p_k}$ – 1) times so as to generate the total number for that aircraft type, and passes the aircraft entity to Scheduler and AircraftServer instances via *UpdateAircraftList* and *CreateAircraft* event respectively.
3.	*UpdateAircraftList*	Does nothing; meant to be heard by Scheduler.
4.	*CreateAircraft*	Does nothing; meant to be heard by AircraftServer instances.

Table 23. Events for AircraftInitializer Component

3. AircraftServer Component

The AircraftServer component is responsible for managing the entities of a specific aircraft type by keeping track of their status, and updates the Scheduler and ShipServer components as and when information is required to coordinate the activities. It is also responsible for generating the "aircraft-led" events, which fall under the delivery, unloading, recovery and servicing phases of the airlift operation process. The following two figures depict the component event graph, and the specific events are detailed in Table 24.

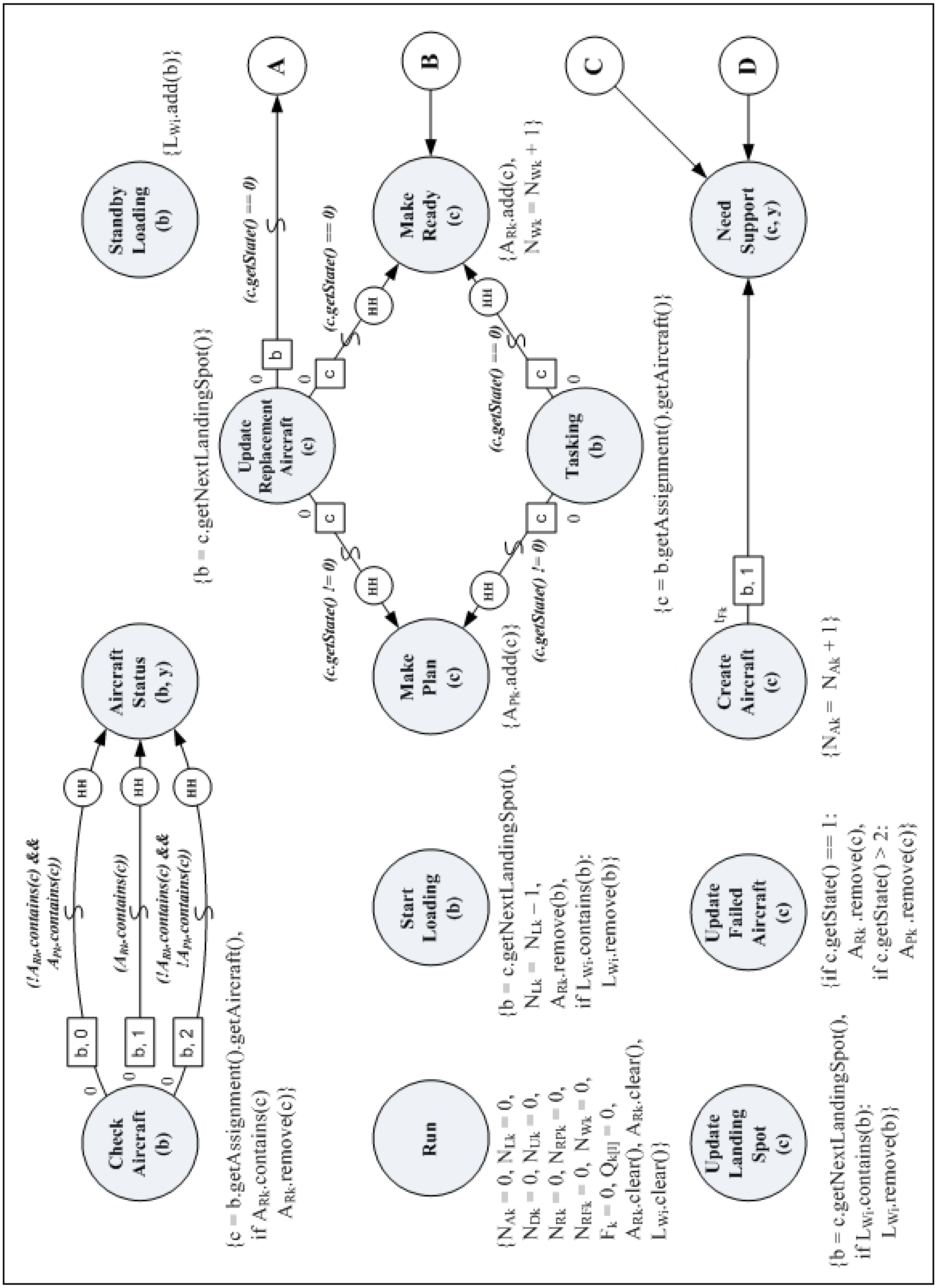

Figure 18. Event Graph for AircraftServer Component (Part 1)

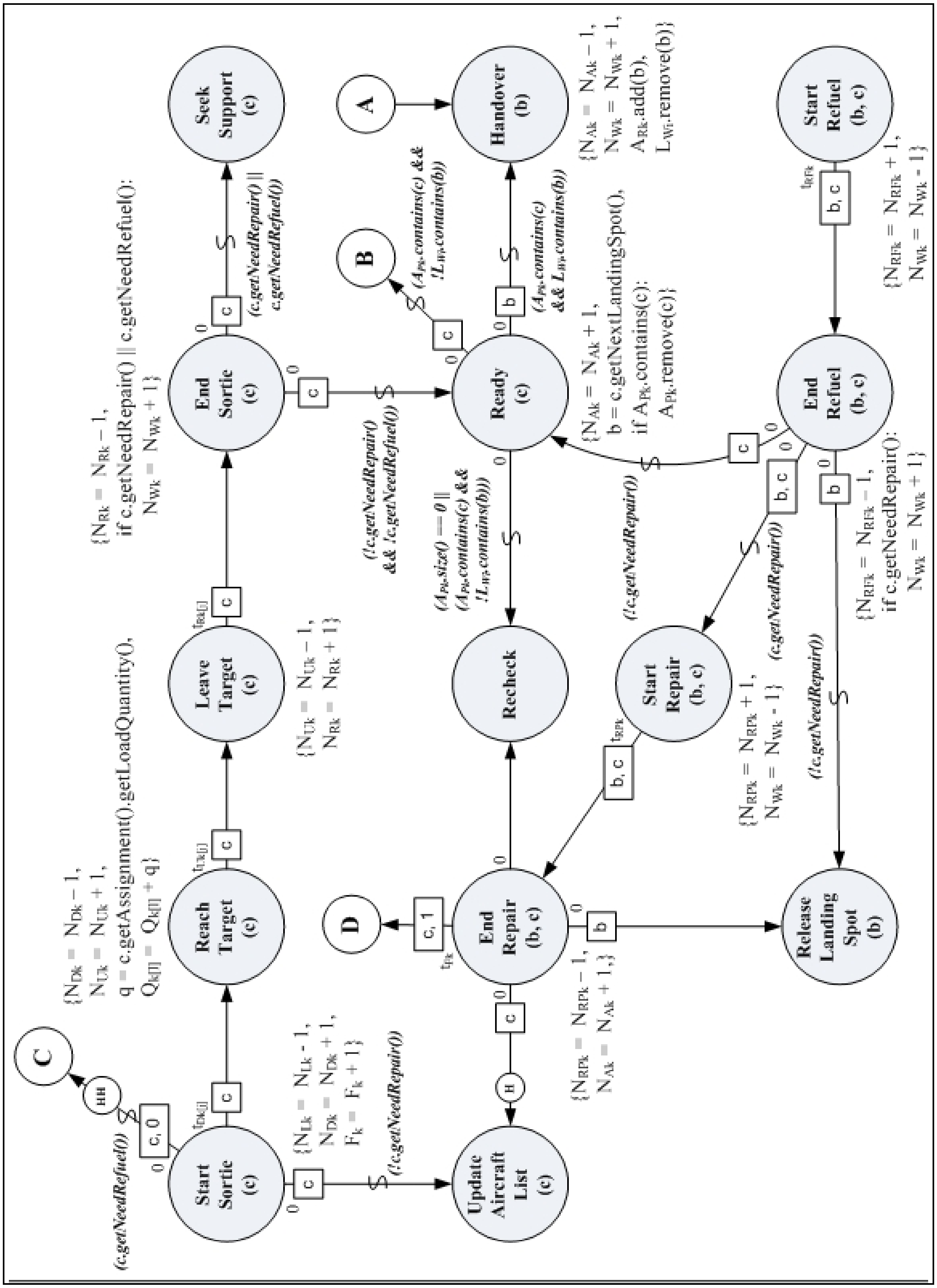

Figure 19. Event Graph for AircraftServer Component (Part 2)

S/N	Event	Purpose
1.	*Run*	Performs state initialization for the following variables at the start of simulation, i.e., • initialize the lists of ready aircraft ($\mathbf{A_{Rk}}$) and planned aircraft ($\mathbf{A_{Pk}}$) to null, • initialize the numbers of aircraft for the various recording, i.e., available, loading, delivery, unloading, recovery, refueling, repairing and waiting ($\mathbf{N_{Ak}}$, $\mathbf{N_{Lk}}$, $\mathbf{N_{Dk}}$, $\mathbf{N_{Uk}}$, $\mathbf{N_{Rk}}$, $\mathbf{N_{RFk}}$, $\mathbf{N_{RPk}}$ and $\mathbf{N_{Wk}}$ respectively), to zero, • initialize the standby landing spot list ($\mathbf{L_{Wi}}$) to null, • initialize the number of load delivered ($\mathbf{Q_{k[l]}}$) by aircraft type k to zero, and • initialize the number of sorties flown ($\mathbf{F_k}$) by aircraft type k to zero.
2.	*CreateAircraft*	Listens to *AircraftInitializer* for newly created aircraft and performs the following: • update aircraft status and state accordingly, • increase the number of available aircraft ($\mathbf{N_{Ak}}$) by one, and • trigger *NeedSupport* event after $\mathbf{t_{Fk}}$ time delay with the aircraft and support type (i.e., with value 1) passed on as argument to simulate a downstream aircraft failure.
3.	*NeedSupport*	Does nothing; meant to be heard by Scheduler
4.	*Tasking*	Listens to Scheduler for load assignment (via the assigned landing spot) and performs one of the following: • trigger *MakeReady* event and pass the assigned aircraft as argument if the aircraft is available, or otherwise • trigger *MakePlan* event for the assigned aircraft and pass the assigned aircraft as argument.
5.	*MakeReady*	Adds aircraft to the ready list ($\mathbf{A_{Rk}}$) and increases the number of waiting aircraft ($\mathbf{N_{Wk}}$) by one.
6.	*MakePlan*	Adds aircraft to the planned list ($\mathbf{A_{Pk}}$).
7.	*CheckAircraft*	Listens to ShipServer instances for landing spot and checks whether its assigned aircraft is ready for next assignment. If the aircraft is ready, removes it from the ready list ($\mathbf{A_{Rk}}$) and

S/N	Event	Purpose
		assigns the landing spot to it. Triggers *AircraftStatus* event immediately with the aircraft readiness status passed on as argument.
8.	*AircraftStatus*	Does nothing; meant to be heard by ShipServer instances.
9.	*StartLoading*	Listens to ShipServer instances for landing spot to commence loading of its assigned aircraft and performs the following: • update the aircraft state accordingly, • decrease number of waiting aircraft ($\mathbf{N_{Wk}}$) by one, • remove landing spot from standby list ($\mathbf{L_{Wi}}$) if it is in it, • remove aircraft from the ready list ($\mathbf{A_{Rk}}$), and • increase the number of loading aircraft ($\mathbf{N_{Lk}}$) by one.
10.	*StandbyLoading*	Adds landing spot entity to the standby list ($\mathbf{L_{Wi}}$), i.e., to wait for the assigned aircraft to be ready for load-up.
11.	*StartSortie*	Listens to ShipServer instances for an assigned aircraft to commence the delivery sortie and performs the following: • update the aircraft state accordingly, • timestamp mission time and update its assignment record, • increase number of sorties flown ($\mathbf{F_k}$) by one, • decrease number of loading aircraft ($\mathbf{N_{Lk}}$) by one and add it to the number of delivery aircraft ($\mathbf{N_{Dk}}$), • compute expected return time for aircraft, • trigger *ReachTarget* event after $\mathbf{t_{Dk[j]}}$ time delay to simulate travel time with the landing spot entity passed on as argument, • trigger *NeedSupport* event immediately with the aircraft passed on as argument together with the support type (i.e., value = 0), if it requires refueling upon return to ship, and • trigger *UpdateAircraftList* event immediately with the aircraft passed on as argument for Scheduler to detail the next assignment, if it does not require repair at this juncture.
12.	*UpdateAircraft List*	Does nothing; meant to be heard by Scheduler.
13.	*ReachTarget*	Reaches designated target area to start unloading and performs

S/N	Event	Purpose
		the following: • update aircraft state and its travelled distance accordingly, • timestamp mission time and update its assignment record, • increase number of loads delivered ($\mathbf{Q_{k[l]}}$) by the load transfer amount as stored in its assignment record, • decrease number of delivery aircraft ($\mathbf{N_{Dk}}$) by one add it to the number of unloading aircraft ($\mathbf{N_{Uk}}$), and • trigger *LeaveTarget* event next with $\mathbf{t_{Uk[j]}}$ time delay to simulate the unloading process and the aircraft is passed on as argument.
14.	*LeaveTarget*	Completes unloading process with the aircraft returning to ship and performs the following: • update the aircraft state accordingly, • timestamp mission time and update its assignment record, • decrease number of unloading aircraft ($\mathbf{N_{Uk}}$) by one, add it to the number of recovery aircraft ($\mathbf{N_{Rk}}$), and • trigger *EndSortie* event next with $\mathbf{t_{Rk[j]}}$ time delay to simulate the travel time and the aircraft is passed on as argument.
15.	*EndSortie*	Completes the sortie and performs the following: • update aircraft state and its travelled distance accordingly, • timestamp mission time, compute actual time taken for sortie, update its assignment record, and • decrease the number of recovery aircraft ($\mathbf{N_{Rk}}$) by one. Triggers one of the following immediately with the aircraft passed on as argument based on the stated conditions: • *SeekSupport* event if the aircraft needs refueling and/or repair and increase the number of waiting aircraft ($\mathbf{N_{Wk}}$) by one, or otherwise • *Ready* event to indicate it is ready for next assignment.
16.	*SeekSupport*	Does nothing; meant to be heard by Scheduler.
17.	*StartRefuel*	Listens to Scheduler for aircraft to start refueling and performs the following:

S/N	Event	Purpose
		• update aircraft state accordingly, • timestamp mission time and update its assignment record, • decrease number of waiting aircraft (**N_{Wk}**) by one, • decrease number of refueling aircraft (**N_{RFk}**) by one, and • trigger *EndRefuel* event next with **t_{RFk}** time delay to simulate the refueling process and the aircraft is passed on as argument.
18.	*EndRefuel*	Completes refueling and performs the following: • update aircraft state, reset its refuel need and distance travelled accordingly, • timestamp mission time and update its assignment record, and • increase the number of refueling aircraft (**N_{RFk}**) by one. Triggers one of the following events immediately based on the stated conditions: • *StartRepair* event with the aircraft passed on as argument if aircraft needs to be repaired and increase number of waiting aircraft (**N_{Wk}**) by one, or otherwise • *Ready* event with the aircraft passed on as argument and ReleaseLandingSpot event with the landing spot passed on as argument to relieve the landing spot for next tasking. The support aircraft for the landing spot is set to null.
19.	*StartRepair*	Listens to Scheduler (and *EndRefuel* event) for aircraft to start the repairing work and performs the following: • timestamp mission time and update its assignment record, • decrease number of waiting aircraft (**N_{Wk}**) by one, • increase number of repairing aircraft (**N_{RPk}**) by one, and • trigger *EndRepair* event next with **t_{RPk}** time delay to simulate the repair process and the aircraft is passed on as argument.
20.	*EndRepair*	Completes refueling and performs the following: • update aircraft state and reset its repair need and support aircraft accordingly, • timestamp mission time and update its assignment record

S/N	Event	Purpose
		• decrease number of refueling aircraft (**N_{RFk}**) by one and add it to the number of available aircraft (**N_{Ak}**), • trigger *ReleaseLandingSpot* event immediately with the landing spot passed on as argument, • trigger *Recheck* event immediately, • trigger *UpdateAircraftList* immediately event with the landing spot passed on as argument to seek the next assignment, and • trigger *NeedSupport* event with **t_{Fk}** time delay to simulate another downstream failure and the landing spot is passed on as argument together with the support code.
21.	*Ready*	Prepares aircraft for next assignment and performs the following: • timestamp mission time and update aircraft's assignment record before resetting its assignment record to null, • update aircraft state accordingly, and • increase number of available aircraft (**N_{Ak}**) by one. Triggers one of the following events immediately: • *Handover* event with assigned landing spot passed on as argument and remove aircraft from the planned list (**A_{Pk}**), if the aircraft is scheduled for next assignment and the assigned landing spot is ready to start loading, or • *MakeReady* event with the aircraft passed on as argument and Recheck event and remove aircraft from the planned list (**A_{Pk}**), is scheduled for next assignment but the assigned landing spot is not ready (still preparing the load), or otherwise • *Recheck* event.
22.	*Handover*	Shortlists the landing spot for loading when the crew is next available since its assigned aircraft is ready by performing the following: • remove landing spot from standby list (**L_{Wi}**), • increase number of waiting aircraft (**N_{Wk}**) by one, • decrease the number of available aircraft (**N_{Ak}**) by one, and • add the aircraft to the ready list (**A_{Rk}**).

S/N	Event	Purpose
		The event is meant to be heard by ShipServer instances as well.
23.	*UpdateFailed Aircraft*	Removes aircraft from the ready list ($\mathbf{A_{Rk}}$) if it is in ready state or otherwise from the planned list ($\mathbf{A_{Pk}}$).
24.	*Recheck*	Does nothing; meant to be heard by ShipServer instances.
25.	*ReleaseLanding Spot*	Does nothing; meant to be heard by ShipServer instances.
26.	*Update Replacement Aircraft*	Listens to Scheduler for replacement aircraft and performs one of the following: • trigger *MakeReady* and *Handover* events with the aircraft and assigned landing spot passed on as argument respectively, if the aircraft is available, or otherwise • trigger *MakePlan* event with the assigned aircraft passed on as argument.
27.	*UpdateLanding Spot*	Listens to Scheduler for failed aircraft and removes its assigned landing spot from the standby list ($\mathbf{L_{Wi}}$), i.e., if the landing spot is loaded and waiting for the aircraft to perform the load-up.

Table 24. Events for AircraftServer Component

4. ShipServer Component

Initially, the ShipServer component is responsible for the creation and initialization of a specific ship entity. In this case, there are three ShipServer objects instantiated for the JMSDF, LPD-19 and HJSV respectively. Each ShipServer object manages the resources onboard the ship, including the logistics crew and landing spots,by keeping track of their status, and updates the Scheduler and ShipServer components as and when information is required to coordinate the activities. It is also responsible for generating the “landing spot-led” events, which fall under the preparation and loading phases of the airlift operation process. The following two figures depict the component event graph and the specific events are detailed in Table 25.

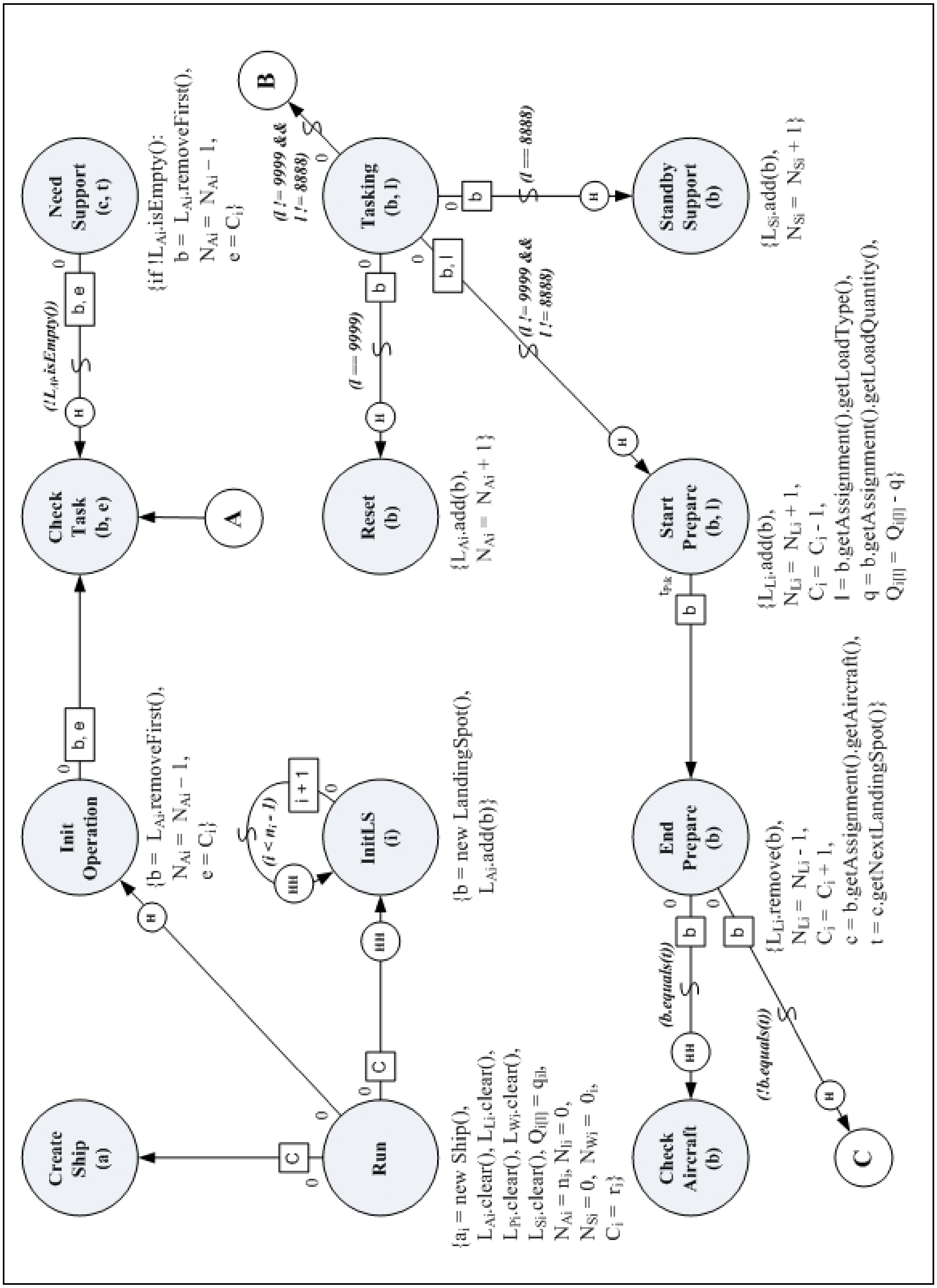

Figure 20. Event Graph for ShipServer Component (Part 1)

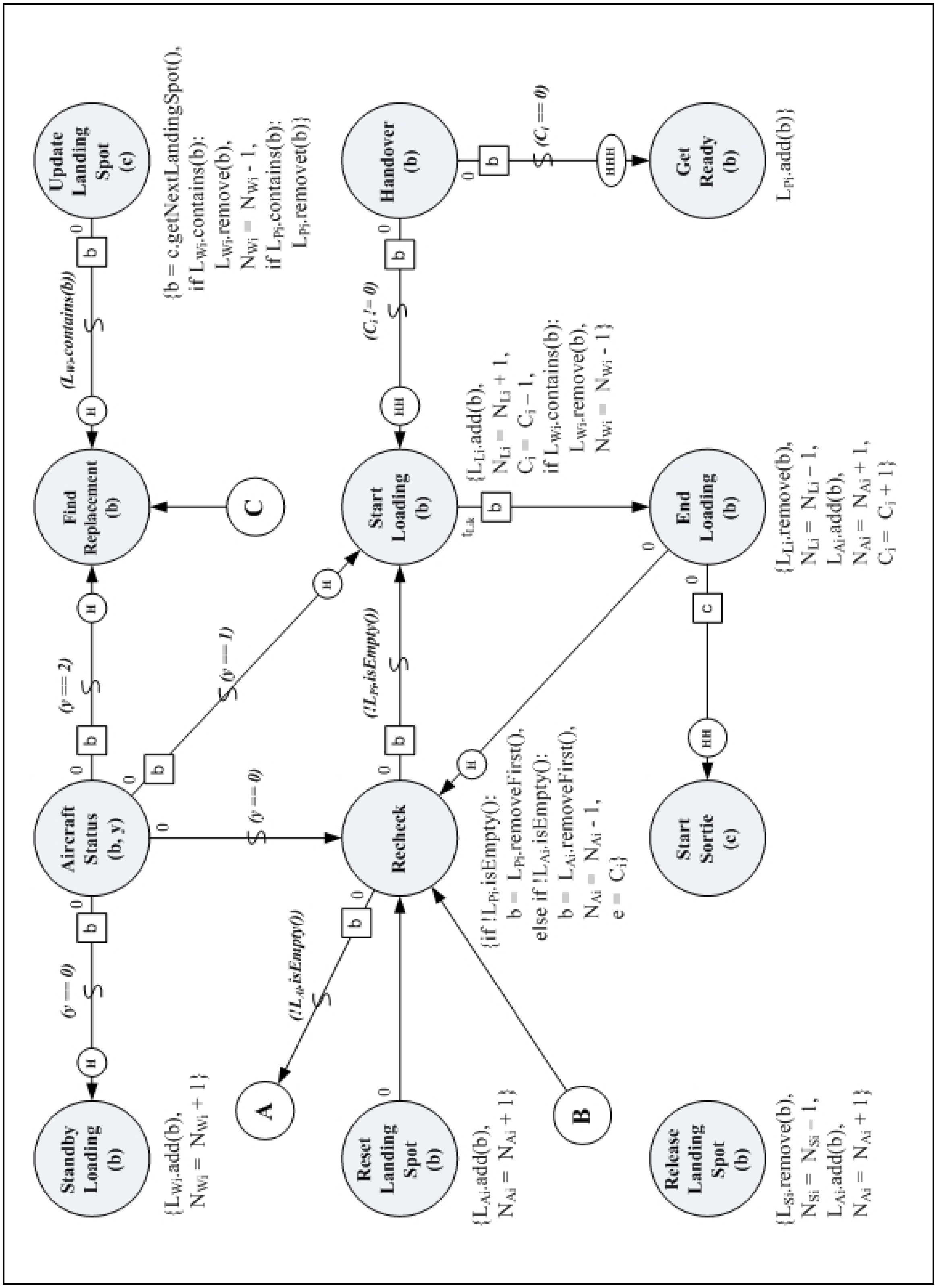

Figure 21. Event Graph for ShipServer Component (Part 2)

S/N	Event	Purpose
1.	*Run*	Creates a ship entity ($\mathbf{a}_i$) and sets/initializes its attributes at the start of simulation to: • set ship identifier i, i.e,. i = 0, 1 and 2 for JMSDF, LPD-17 and JHSV respectively, • set number of landing spots, • set number of logistics crew, • set meantime for preparing the various load types, which is specific to the aircraft type used for the airlift, • set meantime for loading the various load types, which is specific to the aircraft type used for the airlift, and • create a list of landing spots and initializes it to null. Performs initialization of the following state variables for each ship with identifier i: • initialize number of available crew (Ci) to total number of logistics crew (ri), • initialize number of available landing spots (NAi) to total number of landing spots (ni), number of landing spots defined for other recording purposes, i.e., active, standby and support (NAi, NWi and NSi) to zero, • initialize the landing spot lists defined for the various recording, i.e., available, active, priority, standby and support (LAi, LLi, LPi, LWi and LS respectively), to null, and • initialize remaining load (Qi[l]) to the quantity allocated to the ship (qil) for load type l, i.e., l = 0, 1, 2 for cargo, equipment and passengers respectively. Triggers the *InitLS* and *CreateShip* events immediately afterward.
2.	*InitLS*	Creates landing spot entity and sets/initializes its attributes to: • set landing spot identifier, • set landing spot's associated ship, • initialize assignment to null, • initialize support aircraft to null, and • insert landing spot entity to the ship's landing spot list.

S/N	Event	Purpose
		Adds landing spot entity to the available landing spot list ($\mathbf{L_{Ai}}$). Triggers the *InitLS* event immediately if the number of created landing spot entities is less than the ship's total number of landing spots ($\mathbf{r_i}$) and increase the number created (counter) each time.
3.	*InitOperation*	Removes first available landing spot from the list ($\mathbf{L_{Ai}}$) and decreases number of available landing spots ($\mathbf{N_{Ai}}$) by one. Triggers *CheckTask* event immediately and passes landing spot as argument to Scheduler to check for new task, which could be an airlift assignment or provide support service.
4.	*CreateShip*	Does nothing; meant to be heard by Scheduler and Recorder.
5.	*CheckTask*	Does nothing; meant to be heard by Scheduler.
6.	*Tasking*	Listens for tasking from Scheduler and triggers one of the following events immediately based on the tasking issued with the requesting landing spot entity passed on as argument, i.e., • StandbySupport, if landing spot is required to provide service support, or otherwise • StartPrepare, if there are loads to be transferred and crew is available, or otherwise • Reset.
7.	*StandbySupport*	Adds the landing spot to the support list ($\mathbf{L_S}$), reserved to provide support services, and increases number of standby landing spots for the associated ship ($\mathbf{N_{Si}}$) by one.
8.	*Reset*	Inserts landing spot entity back to the available list ($\mathbf{L_{Ai}}$) and increases number of available landing spots ($\mathbf{N_{Ai}}$) by one.
9.	*StartPrepare*	Commences load preparation for an airlift assignment and performs state transition for the following variables: • decrease number of available crew ($\mathbf{C_i}$) by one, • add landing spot to the active list ($\mathbf{L_{Li}}$) and increase number of active landing spots ($\mathbf{N_{Li}}$) by one, • decrease remaining quantity ($\mathbf{Q_{i[l]}}$) by the load transfer amount (as stored in the landing spot's assignment record), and • timestamp the mission time and update the assignment record. Triggers *EndPrepare* event after $\mathbf{t_{Pik}}$ time delay and passes the

S/N	Event	Purpose
		landing spot as argument.
10.	*EndPrepare*	Completes load preparation and performs state transition for the following variables: • increase number of available crew (**C_i**) by one, • remove landing spot from the active list (**L_{Li}**) and decrease number of active landing spots (**N_{Li}**) by one, and • timestamp the mission time and update the assignment record. Triggers one of the following events immediately with the landing spot passed on as argument: • *FindReplacement* event, if its assigned aircraft has been re-assigned (i.e., after it has failed and is being repaired), or otherwise • *CheckAircraft* event to check whether the aircraft is ready.
11.	*CheckAircraft*	Does nothing; meant to be heard by AircraftServer instances.
12.	*AircraftStatus*	Listens for aircraft status from AircraftServer instances and triggers one of the following events immediately with the landing spot passed on as argument: • *FindReplacement* event, if assigned aircraft is unserviceable, or otherwise • *StartLoading* event, if aircraft is available and in serviceable state with available crew, or otherwise • *StandbyLoading* and *Recheck* events for new task.
13.	*StartLoading*	Commences loading for an airlift assignment and performs state transition for the following variables: • decrease number of available crew (**C_i**) by one, • add landing spot to active list (**L_{Li}**) and increase number of active landing spots (**N_{Li}**) by one, • remove landing spot from standby list (**L_{Wi}**) if it is in the list, and • timestamp the mission time and update the assignment record. Triggers *EndLoading* event after **t_{Lik}** time delay with the landing spot entity passed on as argument. The event is meant to be heard by AircraftServer instances as

S/N	Event	Purpose
		well.
14.	*StandbyLoading*	Adds landing spot entity to the standby list ($\mathbf{L_{Wi}}$) and increases the number of standby landing spots ($\mathbf{N_{Wi}}$) by one, to wait for the assigned aircraft to be ready for load-up. The event is meant to be heard by AircraftServer instances as well.
15.	*Recheck*	Checks for available resources and performs one of the following: • triggers *StartLoading* event if there are available crew (Ci) and awaiting landing spot in the priority list (LPi). Removes the first landing spot from LPi and passes it as the argument, or • triggers CheckTask event if there are available logistics crew (Ci) and landing spot (LAi). Removes the first landing spot from LAi, decrease number of available landing spots (NAi) by one and pass landing spot as the argument together with current crew size, or • does nothing otherwise.
16.	*FindReplacement*	Does nothing; meant to be heard by Scheduler.
17.	*EndLoading*	Completes the loading for an airlift assignment and performs state transition for the following variables: • increase number of available crew (Ci) by one, • remove landing spot from active list (LLi) and decrease number of active landing spots (NLi) by one, • add landing spot to the available list (LAi) and increase number of available landing spots (NAi) by one, • timestamp the mission time and update the assignment record, and • hand over the assignment record to the aircraft and set the landing spot's assignment to null. Triggers *StartSortie* and *Recheck* event immediately with aircraft entity passed on as argument for StartSortie.
18.	*StartSortie*	Does nothing; meant to be heard by AircraftServer instances.
19.	*Handover*	Listens to *AircraftServer* instances for ready aircraft that has an assigned landing spot waiting to start the next assignment. Triggers *StartLoading* event if there is crew ($\mathbf{C_i}$) available or

S/N	Event	Purpose
		otherwise, *GetReady* event.
20.	*GetReady*	Adds landing spot to the priority list (**L_{Pi}**) so that it will be activated for loading when the next crew is available.
21.	*NeedSupport*	Listens to AircraftServer instances for aircraft requiring servicing (refuel and/or repair) and performs the following if there is available landing spot (**L_{Ai}**): • remove the first landing spot from **L_{Ai}**, • decrease number of available landing spots (**N_{Ai}**) by one, and • trigger *CheckTask* event and pass landing spot as the argument together with the crew size.
22.	*ReleaseLanding Spot*	Listens to AircraftServer instances for completed support service work and performs the following: • remove landing spot from support list (**L_S**) and decrease number of support landing spots for the associated ship (**N_{Si}**) by one, and • add landing spot to available list (**L_{Ai}**) and increase number of available landing spots (**N_{Ai}**) by one.
23.	*UpdateLanding Spot*	Listens to Scheduler for failed aircraft and performs the following if its assigned landing spot is in the standby list (**L_S**), i.e., waiting for the aircraft to start its next assignment: • remove landing spot from the standby list (**L_{Wi}**), • remove landing spot from priority list (**L_{Pi}**) if in the list, • decrease number of standby landing spots (**N_{Wi}**) by one, and • trigger *FindReplacement* event immediately with landing spot passed on as argument.
24.	*ResetLanding Spot*	Listens to Scheduler to redeploy the landing spot and performs the following: • add the load transfer amount (as stored in the landing spot's assignment record) to the remaining load (**Q_i**) for the ship, • reset landing spot's assignment to null, and • add landing spot to the available list (**L_{Ai}**) and increase number of available landing spots (**N_{Ai}**) by one, and

S/N	Event	Purpose
		• triggers *NeedSupport* event immediately after that. This event is only applicable when Replacement Mode #1 is selected for the simulation.

Table 25. Events for ShipServer Component

5. Scheduler Component

The Scheduler is essentially the overall management system for the fleet operation, handling all the tasking and resource allocation activities. The following three figures depict the component event graph. The specific events are described in Table 26.

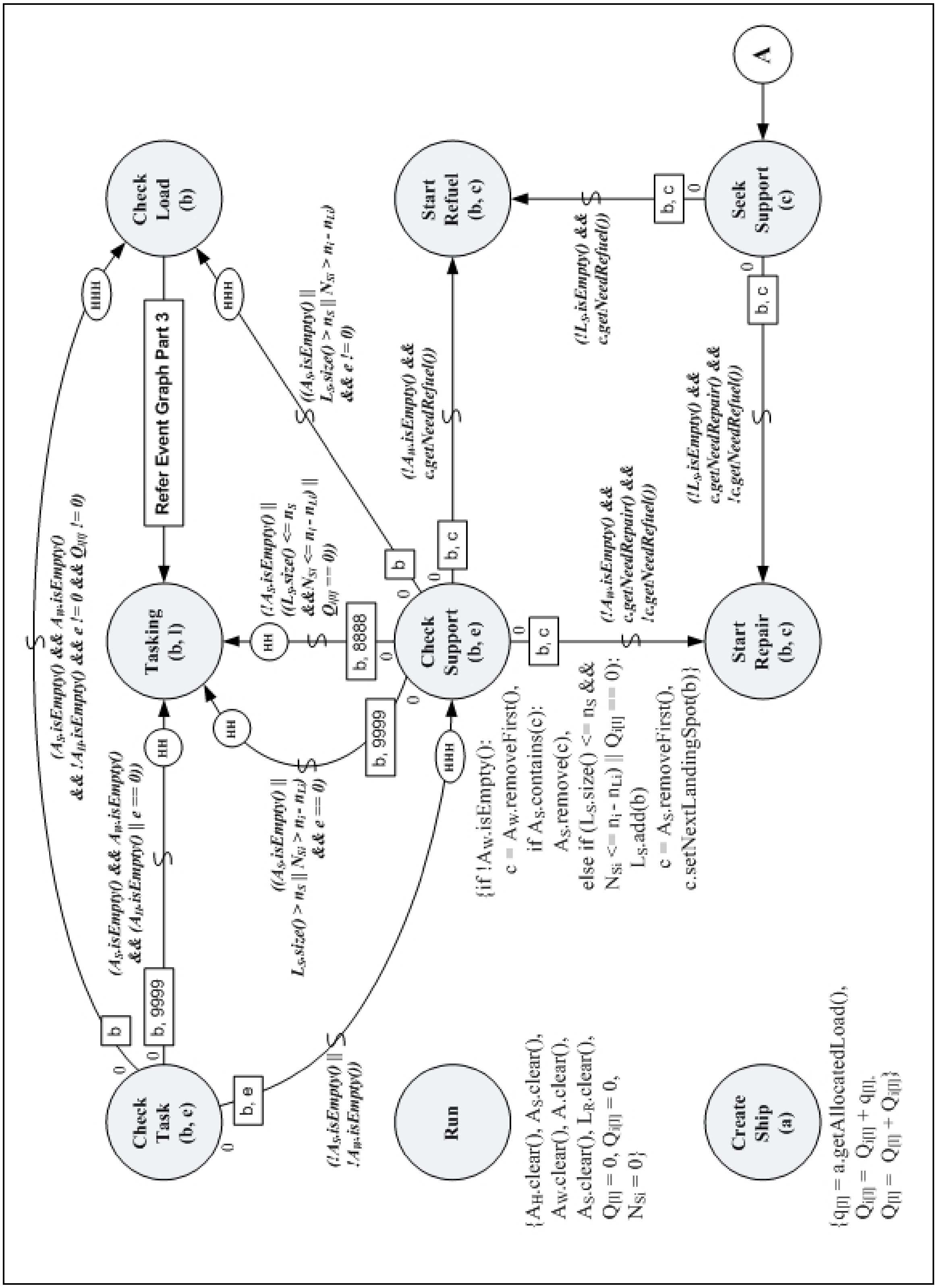

Figure 22. Event Graph for Scheduler Component (Part 1)

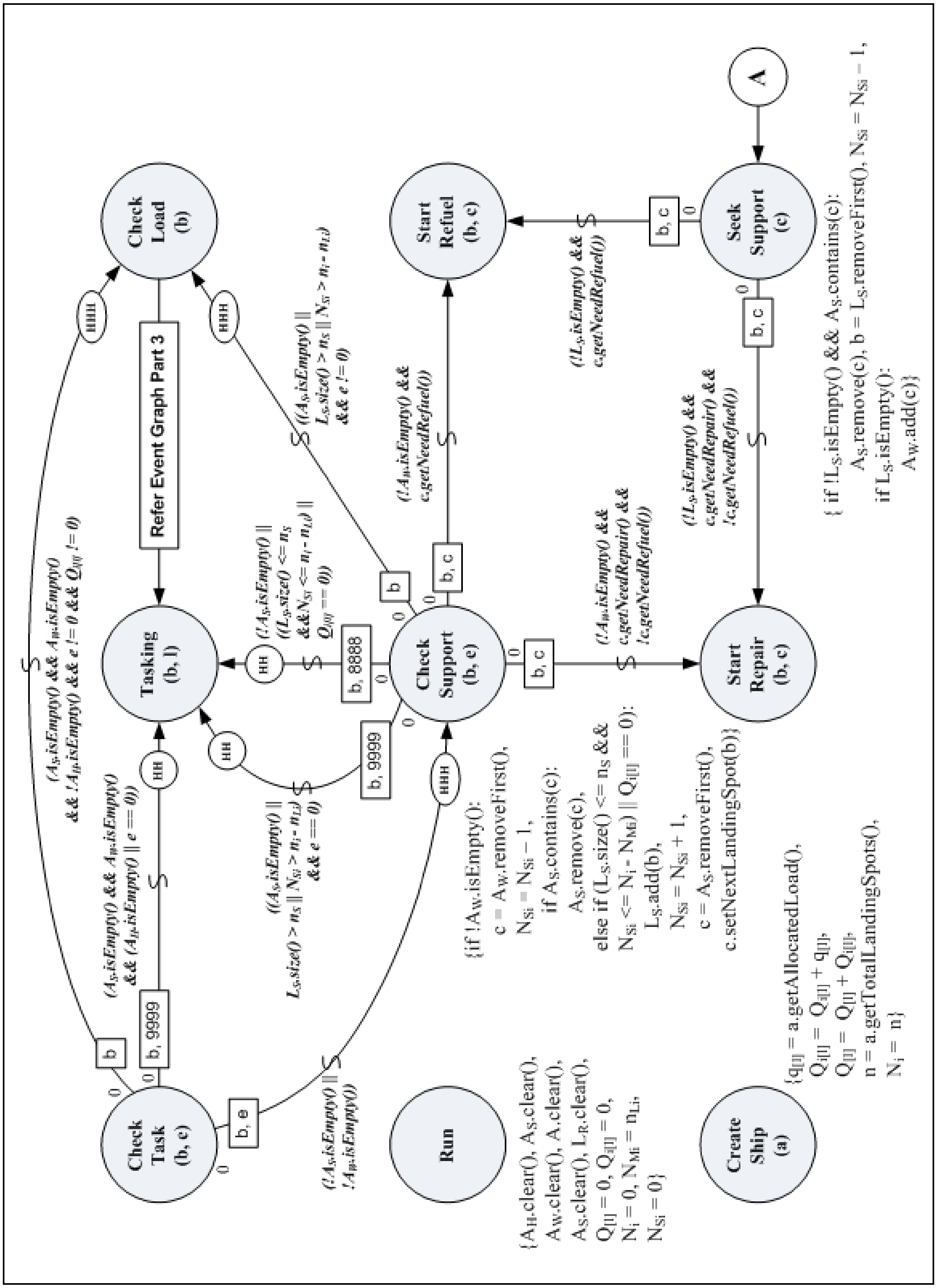

Figure 23. Event Graph for Scheduler Component (Part 2)

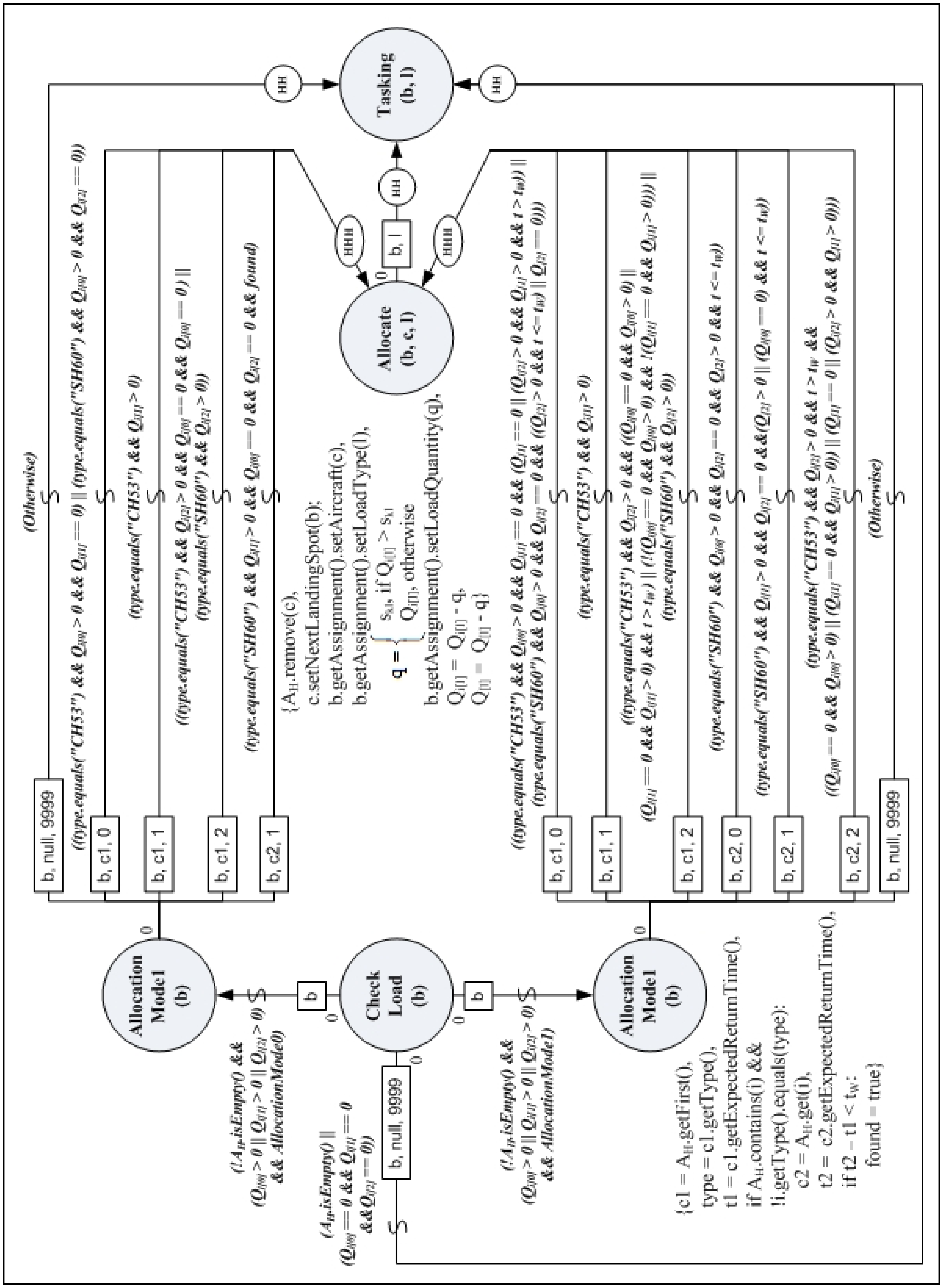

Figure 24. Event Graph for Scheduler Component (Part 3)

S/N	Event	Purpose
1.	*Run*	Performs initialization for the following state variables at the start of the simulation: • initialize assignment list ($\mathbf{A}$) to null, • initialize aircraft holding list ($\mathbf{A_H}$) to null, • initialize aircraft holding record ($\mathbf{H}$) to null, • initialize the list of aircraft requiring support ($\mathbf{A_S}$) to null, • initialize the list of aircraft waiting for support ($\mathbf{A_W}$) to null, • initialize landing spot replacement list ($\mathbf{L_R}$) to null, • initialize the support landing spot list ($\mathbf{L_S}$) to null, • initialize number of support landing spots from ship entity with identifier i ($\mathbf{N_{Si}}$) to zero, • initialize number of landing spots for ship entity with identifier i ($\mathbf{N_i}$) to zero, • initialize minimum number of landing spots required to for direct airlift operation support for ship entity with identifier i ($\mathbf{N_{Mi}}$) to $\mathbf{n_{Li}}$, • initialize remaining quantity of load type l for ship entity with identifier i ($\mathbf{Q_{i[l]}}$) to zero, and • initialize remaining quantity of load type l for the fleet ($\mathbf{Q_{[l]}}$) to zero.
2.	*UpdateAircraftList*	Listens to AircraftServer instances for aircraft requesting new assignment and performs the following: • create a new entry for the aircraft and set the time-in using current time, add it to the holding record ($\mathbf{H}$) and set aircraft's entry accordingly, and • add aircraft to the holding list ($\mathbf{A_H}$), sorted using aircraft's expected time available for next assignment. If Replacement Mode #0 scheme is selected for the simulation, the following will be performed: • the aircraft will be checked against the replacement list ($\mathbf{L_R}$) first to determine if there is a landing spot with an assigned aircraft of the same type before adding it to the holding list. If there is, a new assignment will be

S/N	Event	Purpose
		created for this aircraft instead, inheriting the assigned landing spot and prepared load from the failed aircraft. The landing spot is removed from the list (**L_R**), and • *UpdateReplacementAircraft* and *StandbyLoading* events will be triggered immediately with the aircraft and landing spot passed on as argument respectively, and • *AircraftStatus* event will also be triggered immediately with the landing spot and the aircraft's availability status passed on as argument.
3.	*UpdateReplacement Aircraft*	Does nothing; meant to be heard by AircraftServer instances.
4.	*StandbyLoading*	Does nothing; meant to be heard by AircraftServer and ShipServer instances.
5.	*AircraftStatus*	Does nothing; meant to be heard by ShipServer instances.
6.	*CreateShip*	Listens to ShipServer instances for the newly created ship entities and performs the following: • get the entity's allocated load quantity and update the remaining load quantity (**$Q_{i[l]}$**) for that ship and the remaining load quantity (**$Q_{[l]}$**) for the fleet, and • get the entity's total landing spots and update the number of landing spots (**N_i**) for that ship.
7.	*NeedSupport*	Listens to AircraftServer instances for aircraft requiring support services and performs the following: • set aircraft's need for refuel or repair indicator to true based on the support type required, • add aircraft to the need support list (**A_S**) if it is not in it, • trigger *UpdateResources* event immediately with the aircraft passed on as argument, if repair service is required, and • trigger *SeekSupport* event immediately with the aircraft passed on as argument, if aircraft is available or waiting for load-up.
8.	*CheckTask*	Listens to ShipServer instances for landing spot checking for task and triggers one of the following immediately: • *CheckSupport* event with the landing spot and crew

S/N	Event	Purpose
		size passed on as argument, if there is aircraft requiring or waiting for support (**A_W**), or otherwise • *CheckLoad* event with the landing spot passed on as argument, if the holding list (**A_H**) is not empty and crew is available, or otherwise • *Tasking* event with the landing spot and load type passed on as argument. The load type is set as "9999" to indicate no tasking.
9.	*CheckSupport*	Checks whether the landing spot is required for support service by performing one of the following: • if there is aircraft waiting for support (**A_W**), ▪ trigger either StateRefuel or StartRepair event immediately, based on the support type required with the aircraft and landing spot passed on as argument, ▪ remove aircraft from the need support list (**A_S**) if it is in it, ▪ decrease the number of support landing spots from its ship (**N_{Si}**) by one, ▪ trigger Tasking event immediately with the landing spot and load type passed on as argument. The load type is set as "8888" to indicate a support tasking, or • if the support landing spots from its ship has not exceeded the individual ship quota (i.e., **$N_{Si} < N_i - N_{Mi}$**) and overall list is (**L_S**) is less than the maximum number allowable for the fleet (**n_S**), or there are no remaining loads (**$Q_{i[l]}$**) left for the ship, ▪ add landing spot to the support list (**L_S**), ▪ increase the number of support landing spots from its ship (**N_{Si}**) by one, and ▪ trigger Tasking event immediately with the landing spot and load type passed on as argument. The load type is set as "8888" for the same reason, or • if there is crew available, trigger *CheckLoad* event with the landing spot passed on as argument, or otherwise • trigger *Tasking* event immediately with landing spot passed on as argument together with the load type set

S/N	Event	Purpose
		to “9999” to indicate no tasking.
10.	*CheckLoad*	Initiates load assignment process by performing one of the following: • trigger *Tasking* event immediately with landing spot and load type passed on as argument, if there is no aircraft in the holding list (**A_H**) or all loads for that ship (**$Q_{i[l]}$**) have been transferred. The load type is set as “9999” to indicate no tasking, or • trigger *AllocationMode0* or *AllocationMode1* event based on the selected for the simulation and pass on landing spot as argument.
11.	*AllocationMode0*	Performs load allocation based on ship-level consideration only, as per the discussion in the Design section. Triggers *Allocate* event immediately with landing spot, aircraft and load type passed on as argument, if there is a match or otherwise, the *Tasking* event with landing spot passed on as argument together with the load type set to “9999” to indicate no tasking.
12.	*AllocationMode1*	Performs load allocation based on fleet-level consideration only as per the discussion in the Design section. Triggers *Allocate* event immediately with landing spot, aircraft and load type passed on as argument, if there is a match or otherwise, the *Tasking* event with landing spot passed on as argument together with load type set to “9999” to indicate no tasking.
13.	*Allocate*	Performs load allocation for the landing spot and the assigned aircraft as follows: • remove aircraft from holding list (**A_H**), assign landing spot as its next landing spot, set time-out for its entry record using current time and change its status to one, • compute the load transfer amount (**j**) and update the assignment record based on the discussed formula, i.e., $q_l = \begin{cases} c_{kl}, Q_{i[l]} > c_{kl} \\ Q_{i[l]}, otherwise \end{cases}$ • decrease remaining load left for the ship (**$Q_{i[l]}$**) and fleet by (**$Q_{[l]}$**) the load transfer amount, and • trigger *Tasking* event immediately with the landing

S/N	Event	Purpose
		spot and load type passed on as argument.
14.	*Tasking*	Does nothing; meant to be heard by AircraftServer and ShipServer instances.
15.	*StartRefuel*	Does nothing; meant to be heard by AircraftServer instances.
16.	*StartRepair*	Does nothing; meant to be heard by AircraftServer instances.
17.	*SeekSupport*	Listens to AircraftServer instances for returned aircraft seeking support and performs one of the following: • if there are landing spots in the support list ($\mathbf{L_S}$), ▪ remove landing spot from support list ($\mathbf{L_S}$) and decrease number of support landing spots for the associated ship ($\mathbf{N_{Si}}$) by one, and ▪ trigger either *StateRefuel* or *StartRepair* event immediately based on the support type required with the aircraft and landing spot passed on as argument, or otherwise • add aircraft to the list awaiting for support ($\mathbf{A_W}$).
18.	*UpdateResources*	Updates resources due to an aircraft failure by performing the following: • remove failed aircraft from the holding list ($\mathbf{A_H}$) if it is on it, or otherwise, trigger *UpdateLandingSpot* immediately with aircraft passed on as argument, and • trigger *UpdateFailedAircraft* event immediately with aircraft passed on as argument.
19.	*UpdateLandingSpot*	Does nothing; meant to be heard by ShipServer instances.
20.	*UpdateFailedAircraft*	Does nothing; meant to be heard by AircraftServer instances.
21.	*FindReplacement*	Listens to ShipServer instances for landing spot requiring a replacement aircraft and performs one of the following based on the simulation mode selected: <u>For Replacement Mode #0 Scheme</u> If an aircraft is found in the holding list ($\mathbf{A_H}$) that matches the failed aircraft type that the landing spot was previously assigned to, • remove it from the list and set the time-out for its entry

S/N	Event	Purpose
		record using current time, • create a new assignment pairing up the aircraft and the landing spot (that is already loaded), and set the aircraft status accordingly, and • trigger *UpdateReplacementAircraft* and *StandbyLoading* events immediately with the aircraft and landing spot passed on as argument respectively. If there is no matching aircraft in $\mathbf{A_H}$, add landing spot to the replacement list ($\mathbf{L_R}$). <u>For Replacement Mode #1 Scheme</u> Add the load transfer amount (as stored in the landing spot's assignment record) to the remaining load for the affected ship ($\mathbf{Q_{i[l]}}$) as well as the fleet ($\mathbf{Q_{[l]}}$), and trigger *ResetLandingSpot* event immediately with the landing spot passed on as argument.
22.	*ResetLandingSpot*	Does nothing; meant to be heard by ShipServer instances.
23.	*StandbyLoading*	Does nothing; meant to be heard by ShipServer and AircraftServer instances.

Table 26. Events for Scheduler Component

In addition, the Scheduler component also has built-in utilities to output the list of assignments and the holding record into text files for that simulation run. One can then review the details off-line and understand how the operation process has taken place, if required.

6. Recorder Component

This is more of a peripheral component created solely for recording the following runtime data for each simulation run, such as:

- mission completion time, defined by the time when the last sortie reaches the target site to complete the load delivery, and
- quantity delivered for each of the three load types over the simulation duration with user-definable interval for the recording.

The data for each individual run is then collected by the main program to support the post-simulation statistical analysis. This component also has the built-in utility to output the quantity delivered over time to a text file. The following figure depicts the component event graph and the specific events are described in Table 27.

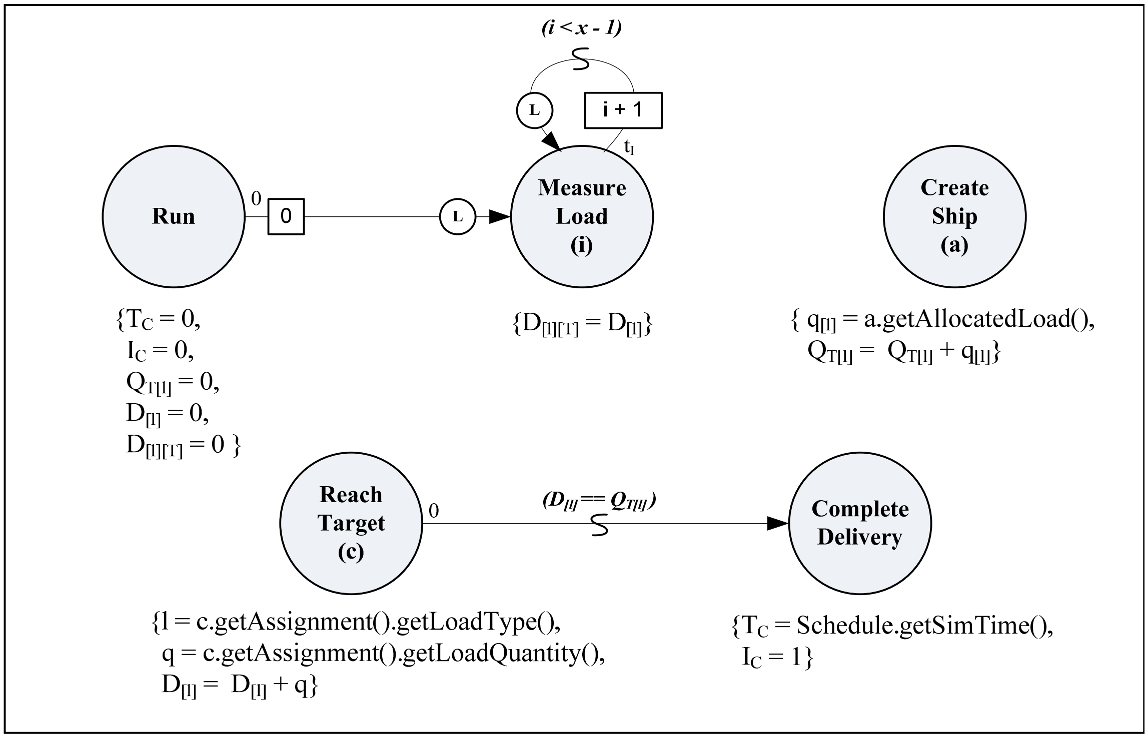

Figure 25. Event Graph for Recorder Component

S/N	Event	Purpose
1.	*Run*	Performs the following at the start of the simulation: • initialize delivery completion time (**T_C**) to zero, • initialize delivery completion indicator (**I_C**) to zero, • initialize total quantity for load type l (**$Q_{T[l]}$**) to zero, • initialize quantity delivered to site for load type l (**$D_{[l]}$**) to zero, and • create a **l** by **x** dimensional array for recording the quantity delivered for each load type l (**$D_{[l][t]}$**) at a user-defined time interval (**t_I**) over the simulation duration, where **l** is the number of load types and **x** is the number of intervals. Initialize the value for each array element to zero, and • triggers *MeasureLoad* event immediately with zero passed on as argument, i.e., the counter used for looping the event.
2.	*CreateShip*	Listens to ShipServer instances for newly created ship entity and adds its load quantity to total load (**$Q_{T[l]}$**).
3.	*MeasureLoad*	Updates the appropriate entry for the load quantity delivered (**$D_{[l][t]}$**) at that instance, increase the counter by one, and triggers itself after **t_I** time delay with the counter passed on as argument for (**x** – 1) times.
4.	*ReachTarget*	Listens to AircraftServer instances for the delivery aircraft and increases the load quantity delivered (**$D_{[l]}$**) by the load transfer amount as stored in the aircraft's assignment record. Triggers *CompleteDelivery* event immediately if all loads have been delivered, by comparing the values between (**$D_{[l]}$**) and (**$Q_{T[l]}$**).
5.	*CompleteDelivery*	Sets the delivery completion time (**$Q_{T[l]}$**) and delivery completion indicator (**I_C**).

Table 27. Events for Recorder Component

V. TESTING AND EVALUATION

A. OVERVIEW

The testing of the final airlift model was conducted in two parts. First of all, the final model was tested against the verified baseline model to ensure that it can produce consistent results when using the same input parameters under a deterministic setting. The testing then focused on the general event flow and the variable timing parameters to verify that the simulated airlift process abides with the paper's design.

B. VERIFICATION AGAINST BASELINE MODEL

1. Objective

The objective was to verify that the final airlift model will generate the same load transfer capabilities and the sorties as the baseline model for the three Civil Support mission scenarios and the respective force structures, such as those performed in Chapter III and summarized in the following table.

S/N	Scenario	Scenario Severity		
		Low	Mean	High
A.	**Load Transfer Capability based on Baseline Airlift Model**			
1.	For Cargo (lbs)	2,286,000	729,000	1,318,500
2.	For Equipment (sets)	6	11	16
3.	For Personnel (pax)	32	72	99
B.	**Number of Delivery Sorties**			
4.	For CH-53	67	30	56
5.	For SH-60	115	24	14
C.	**Aircraft Quantity (i.e., the force structure)**			
6.	For CH-53 (ea)	1	2	7
7.	For SH-60 (ea)	2	2	2

Table 28. Test Cases for Final Airlift Model against Baseline Model

2. Approach

A similar approach on how the baseline model was verified against Project SEA-15 findings was adopted. The same input parameters for the baseline airlift model were used for the final model in order for it to generate a deterministic output for comparison with the baseline model. The following are the main settings used for the final model:

- a single ship was modeled to supply all the required loads with a high number of logistics crew and landing spots (400 each),
- average time values were used for the loading, unloading, delivery and recovery phase (based on baseline model inputs), with the loading time set to zero,
- the endurance distance (without refueling) and the time-to-failure for the aircraft and were set to high values (10,000 nm and 10,000 hr respectively) to negate the need for refuel and repair, and
- reduced operating duration (7.65 hr based on baseline model input) to account for the time spent for refuel and repair.

Given that the final model can generate the list of conducted sorties with the involved timings, the approach was to inject a higher load transfer capability value (i.e., for cargo load type) as input to the model, so as to show the last sortie that can be completed within the mission time and the remaining load at that juncture. In this case, the quantity set was set just one more than the load transfer capability, i.e., 2,286,001, 729,001 and 1,318,501 lbs for the low, mean and high severity scenarios respectively.

2. Test Results

For all the three tested scenarios, the final airlift model generated the same load transfer capabilities and the required sorties as per the baseline model. The following is the extract of the model output for the high severity scenario test case, which showed that the 70th sortie was the last one that could be completed within the mission time (before 459 min, the equivalent of 7.65 hr), and the remaining load at that instance was one pound of cargo, the expected “right” answer for the testing. Refer to Appendix B for the complete model output files for the three test scenarios.

Assign#	Aircraft#	Load Type#	Transfer Qty	Start Loading Time	Start Sortie Time	Reach Target Time	Leave Target Time	End Sortie Time	Cargo Left	Eqpt Left	Passenger Left
#1	CH53#0	1	2	0	1	34	35	54.41	1318501	14	99
#2	CH53#1	1	2	0	1	34	35	54.41	1318501	12	99
#3	CH53#2	1	2	0	1	34	35	54.41	1318501	10	99
#4	CH53#3	1	2	0	1	34	35	54.41	1318501	8	99
#5	CH53#4	1	2	0	1	34	35	54.41	1318501	6	99
#6	CH53#5	1	2	0	1	34	35	54.41	1318501	4	99
#7	CH53#6	1	2	0	1	34	35	54.41	1318501	2	99
					....						
					....						
					....						
					....						
					....						
#68	CH53#4	0	27000	380.88	381.88	414.88	415.88	435.29	54001	0	0
#69	CH53#5	0	27000	380.88	381.88	414.88	415.88	435.29	27001	0	0
#70	**CH53#6**	**0**	**27000**	**380.88**	**381.88**	**414.88**	**415.88**	**435.29**	**1**	**0**	**0**
#71	SH60#0	0	1	405.89	406.89	448.14	449.14	471.59	0	0	0

Figure 26. Extract of the Final Airlift Model Output for High Severity Scenario Test Case

C. VERIFICATION FOR GENERAL EVENT FLOW AND TIMING PARAMETERS

1. Objective

The testing was to verify that the general event flow and the variable timing parameters of the simulated airlift processes are in accordance with the paper design, i.e., based on the event graphs and the inputs parameters used.

2. Approach

A straightforward testing approach was adopted by running the model with a set of input parameters and then verifying the output results using the verbose mode and the other generated files (similar to the one presented earlier) to ensure that the logged events have occurred in proper sequence and are reflective of the inputs used. In this case, uniform distribution was used for all random timing variates to facilitate verification. For each set of input parameters tested, multiple runs (i.e., 1,000) were conducted to verify that the random variates used would inject stochasticity into the simulation as well as sift out any latent anomalies that may not surface within a single run.

3. Results

The model was tested against ten sets of different input parameters. The generated event flows and timings were found to be consistent with the design and input parameters.

The verification scope was by no means comprehensive, given the number of parameters and their ranges that can be varied to meet different simulation needs. For the purpose of this thesis work, the verification conducted and the test results shown were deemed adequate to move on and experiment with the model's capability.

VI. DESIGN OF EXPERIMENT

A. OVERVIEW

Three sets of experiments were conducted. The first experiment was designed to demonstrate the final airlift model's ability to meet the objectives set for this thesis work with the next experiment to illustrate the difference in the outcomes (if any) of using the various simulation schemes implemented in the model. The last experiment was conducted to compare the load transfer capability computed by the final and baseline airlift models.

B. EXPERIMENT #1 – GENERAL PERFORMANCE MEASURES

1. Objectives

The experiment was designed to demonstrate that the final airlift model can support the list of performance measures established under Chapter II for assessing the airlift operation effectiveness and its workflow efficiency.

2. Experiment Setting and Input Parameters

The high severity scenario defined for the Civil Support mission was used as the backdrop for the experiment to assess the airlift operation performance of the recommended Phase Zero force. In a nutshell, three ships, i.e., JMSDF, LPD-17 and JHSV with seven CH-53 and two SH-60 are required to airlift 1,238,200 lbs of cargo, 16 sets of equipment and 99 passengers to an affected area that is 55 nm away from the ships within the mission day (i.e., 12-hour operation day). The input parameters adopted those used or referenced in Project SEA-15 or otherwise, were based on notional values. Refer to Appendix C for the model input parameters defined for this experiment.

The airlift model was run 1,000 times to gather a good statistical estimate for the performance measures.

3. Simulation Outcome

The main performance measures captured for the simulation are summarized in the following table.

S/N	Parameters	Value		
A.	**Overall Measures**			
1.	Average cargo delivered (lbs)	1,238,200 (100%)		
2.	Average equipment delivered (sets)	16 (100%)		
3.	Average passengers delivered (pax)	99 (100%)		
4.	Average time to complete delivery (hrs)	8.11 hrs		
5.	Minimum time to complete delivery (hrs)	7.24 hrs		
6.	Maximum time to complete delivery (hrs)	10.45 hrs		
7.	Standard deviation for delivery time (hrs)	0.48 hrs		
8.	Number of completed delivery	1000 (100%)		
B.	**Ship-related Measures**	**JMSDF**	**LPD-17**	**JHSV**
9.	Average cargo remaining (lbs)	0	0	0
10.	Average equipment remaining (sets)	0	0	0
11.	Average passengers remaining (pax)	0	0	0
12.	Crew utilization	16.39%	22.12%	26.41%
13.	Landing spots utilization	71.96%	63.43%	58.89%
	• Active preparation/loading activities	16.39%	22.12%	26.41%
	• Standby for load-up	13.58%	16.62%	24.69%
	• Service support	41.98%	24.69%	6.30%
C.	**Aircraft-related Measures**	**CH-53**	**SH-60**	
14.	Average cargo delivered (lbs)	1,209,669 (97.7%)	28,531 (2.3%)	
15.	Average equipment delivered (sets)	16 (100%)	0 (0%)	
16.	Average passengers delivered (pax)	6.9 (7%)	92.1 (93%)	
17.	Average sorties flown	54.7	14.5	
18.	Aircraft utilization	64.5%	66.7%	

S/N	Parameters	Value	
	• Waiting	2.57%	2.51%
	• Loading	1.13%	3.25%
	• Delivery	35.70%	30.90%
	• Unloading	1.13%	3.26%
	• Recovery	21.08%	22.71%
	• Refuel	1.77%	1.20%
	• Repair	3.10%	2.86%

Table 29. Performance Measures for Final Airlift Operation Model

The experiment has demonstrated the model's ability to support the defined performance measures for operational/tactical level analysis with the higher resolution modeling of the airlift operation process using DES. To illustrate, based on the assumptions and input parameters used, the model suggested that the recommended Phase Zero force would be able to support the high severity scenario with the following findings that can be drawn from the data collected:

- Mission Completion Time. The mission duration, on average, would last for 8.1 hrs with 95% confidence that the mission can be completed within 8.9 hrs based on the standard deviation observed (and through further statistical analysis).

- Mission Sorties. It would take about 70 sorties to complete the delivery where each CH-53 and SH-60 aircraft accounts for 7.8 and 7.25 sorties on average respectively. In this case, the higher sortie rate for CH-53 is largely attributed to its faster airspeed.

- Aircraft Utilization. The CH-53 and SH-60 aircraft would be utilized about two-thirds of the time, on average. There would be some waiting expected for the required resources to execute the load-up and/or provide the service support at times. Longer loading/unloading time for SH-60 aircraft would also be expected by virtue of the fact that it will be used more often for transporting passengers, due to its relative advantage in doing so as discussed earlier.

- Landing Spot Utilization. The utilization rate is dependent upon the amount of loads and the number of landing spots onboard the ship. The gathered data can facilitate the planning of the load distribution based on the resources available for each ship. For this experiment, the load distribution seemed reasonable, with an overall utilization rate difference of less than 10% off the average. The higher usage rates for service support observed for JMSDF and LPD-17 are because more landing spots were set aside for that purpose, especially for the JMSDF. For JHSV, there is only one landing spot and it was therefore set up to do load transfer full time until all the loads had been transferred, before providing service support.

- Crew Utilization. Similarly, crew utilization is dependent upon the amount of loads to be transferred and in this case, the JHSV has a higher utilization for the reason cited above.

- Duration of Aircraft in Various Operation Phases. The gathered data provided an indication of the expected time spent for each aircraft type in each of the operation phases. With good data on the mean-time-between-failure (MTBF) and mean-time-to-repair (MTTR) for the aircraft, the simulation would be able to provide a good indication on the overall A_o for the aircraft fleet based on the ship resource support/constraint.

- Load Delivered Over Time. In order to determine the load "arrival" rates, at the target site, for planning the supporting and follow-on ground activities, the model also generates the transferred load quantity over the mission duration based on the timing resolution that one is interested in monitoring. The following figure is the load-versus-time graph plotted, based on the data collected for experiment. In this case, the time interval was set at six minutes, and the delivered quantity presented in percentages, with reference to load transfer requirements.

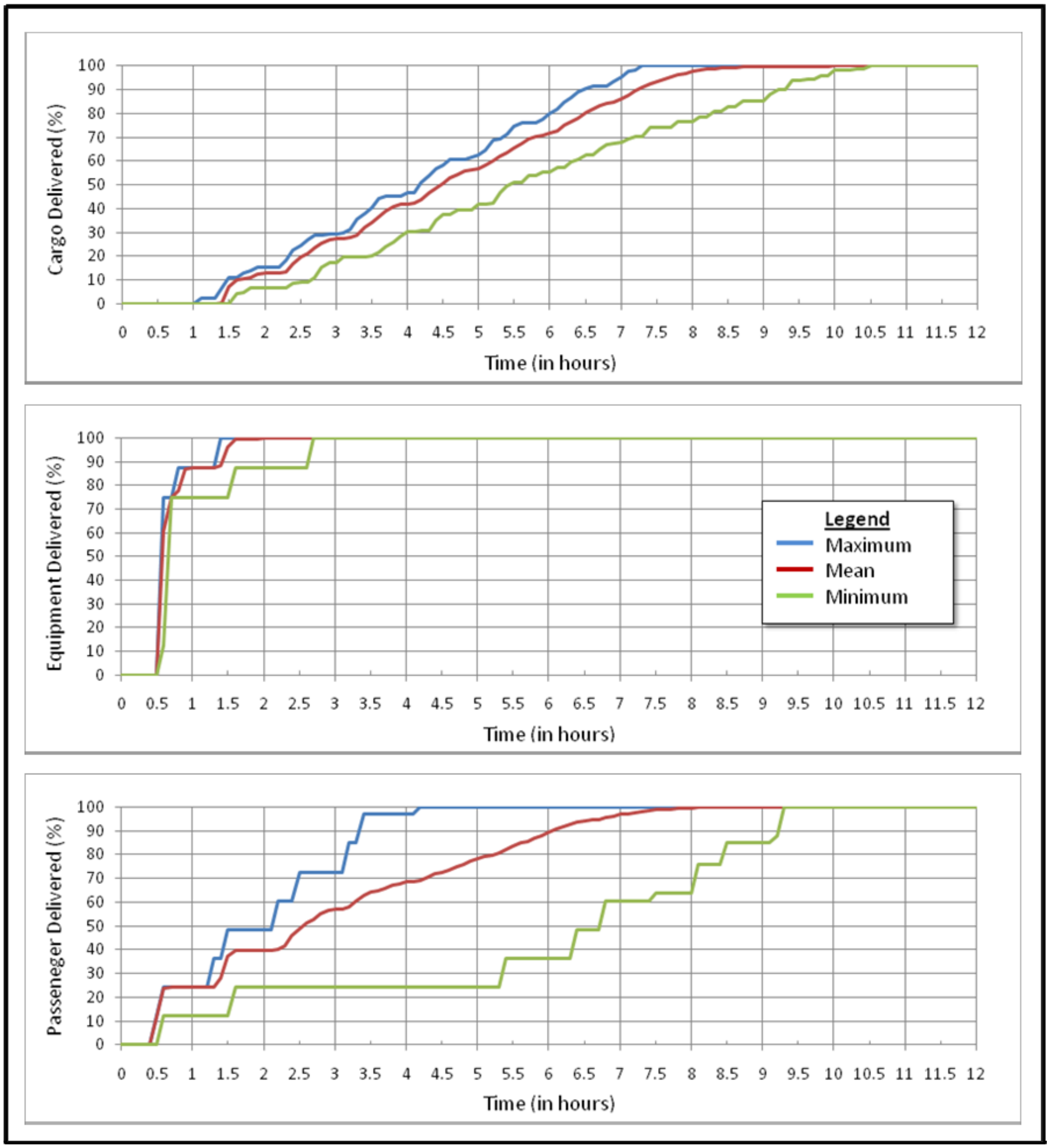

Figure 27. Load Delivered Over Time for High Severity Scenario

C. EXPERIMENT #2 – COMPARISON OF SIMULATION SCHEMES

1. Objectives

The experiment was designed to compare the simulation outcomes of using the different load allocation and landing spot reassignment schemes that were implemented in the model. To recap, the available modes are

- Load Allocation Mode #0 (LAM#0). The load allocation is optimised at the ship-level.
- Load Allocation Mode #1 (LAM#1). The load allocation optimization is attempted at the fleet-level based on a longer waiting time (set as five minutes) that one is willing to accept in order to get a better load-aircraft match, based on the list of aircraft that have requested assignments at the juncture.
- Landing Spot Reassignment Mode #0 (LRM#0). This is the substitution mode whereby the landing spot with assigned aircraft that have failed will find the next available replacement of the same aircraft type to takeover the prepared load.
- Landing Spot Reassignment Mode #1 (LRM#1). This is the reset mode whereby the landing spot will "return" the prepared load and check for the next task instead.

2. Experiment Setting and Input Parameters

The same high severity scenario and input parameters were used as baselines for this experiment, except for the load allocation and landing spot reassignment modes selected. Four sets of scenarios were simulated using the different combinations for the two modes available. Each set of scenarios was run 1,000 times to gather a good sample size for comparison.

3. Simulation Outcome

All loads can be delivered within the mission time for the all schemes implemented. The following table summarizes the key performance measures recorded for these four sets of simulated scenarios.

Parameters	LAM#0		LAM#1	
	LRM#0	LRM#1	LRM#0	LRM#1
Overall Parameters				
Average time to complete delivery (hrs)	8.15	8.13	8.11	8.11
Minimum time to complete delivery (hrs)	7.25	7.18	7.17	7.24
Maximum time to complete delivery (hrs)	11.61	11.38	10.84	10.45
Standard deviation for delivery time (hrs)	0.53	0.50	0.48	0.48
Ship-related Measures				
Average crew utilization	20.95%	21.39%	21.17%	21.64%
Average landing spots utilization	64.69%	64.94%	64.67%	64.48%
• Active preparation/loading activities	20.95%	21.39%	21.17%	21.64%
• Standby for load-up	19.16%	18.46%	19.36%	18.79%
• Service support	24.52%	25.09%	24.10%	24.33%
Aircraft-related Measures				
Cargo delivered by CH-53 (lbs)	1,208,066	1,208,113	1,210,103	1,209,669
Cargo delivered by SH-60 (lbs)	30,134	30,087	28,097	28,531
Equipment delivered by CH-53 (sets)	16	16	16	16
Equipment delivered by SH-60 (sets)	0	0	0	0
Passengers delivered by CH-53 (pax)	12.33	11.76	6.696	6.909

Parameters	LAM#0		LAM#1	
	LRM#0	LRM#1	LRM#0	LRM#1
Passengers delivered by SH-60 (pax)	86.67	87.24	92.304	92.091
Sorties flown by CH-53	54.93	54.95	54.72	54.73
Sorties flown by SH-60	14.19	14.22	14.38	14.46
Average Aircraft utilization	67.27%	66.70%	67.18%	66.59%
• Waiting	3.16%	2.59%	3.14%	2.54%
• Loading	2.11%	2.11%	2.19%	2.19%
• Delivery	33.36%	33.38%	33.18%	33.30%
• Unloading	2.11%	2.11%	2.19%	2.19%
• Recovery	21.72%	21.74%	21.82%	21.90%
• Refuel	1.46%	1.47%	1.49%	1.49%
• Repair	3.37%	3.29%	3.17%	2.98%

Table 30. Comparison Between Different Simulation Schemes Implemented in Final Airlift Model

Based on the gathered data, the average and maximum delivery completion times for both scenarios, using the fleet-level load allocation (i.e., LAM#1) were shorter, but of no significant difference. In fact, the overall performance profiles for the task force under these various schemes were found to be very similar except for the specific areas where the implemented schemes have a direct effect. Under the fleet-level load allocation scheme, there was a better load-aircraft match observed than expected, with more than a 5% increase in passengers being transported by SH-60 aircraft. As for the landing spot reassignment scheme, the landing spot usage for preparation/loading activities was observed to be slightly higher and correspondingly less time was spent standing-by for aircraft under both scenarios using the reset approach (i.e., LRM#1), which is to be expected. However, the secondary effect on the waiting time, which was found to be shorter (i.e., >20%), under the reset approach, was not something perceivable at the design stage.

D. EXPERIMENT #3 – LOAD TRANSFER CAPABILITY

1. Objectives

The experiment was conducted to assess the load transfer capability of the Phase Zero task force to support the high severity scenario based on the stochastic approach, using the final airlift model, and compare the results from the baseline model, which was deterministic based.

2. Experiment Setting and Input Parameters

The scenario input parameters were the same as those used for the first experiment, except that the cargo load quantity was increased to 2.5M lbs as a "goal" to assess how much the task force could transfer within the 12-hour mission day. Transfer capability for cargo load type was used for the experiment because it was the benchmark adopted by Project SEA-15 for the same purpose.

3. Simulation Outcome

The performance measures captured for the simulation are summarized in the following table with the "load delivered over time" graph depicted in Figure 28.

S/N	Parameters	Value		
A.	**Overall Measures**	**Min**	**Mean**	**Max**
1.	Cargo delivered (lbs)	1,697,000	2,049,000	2,242,000
2.	Equipment delivered (sets)	16	16	16
3.	Passengers delivered (pax)	96	99	99
B.	**Ship-related Measures**	**JMSDF**	**LPD-17**	**JHSV**
4.	Cargo allocated (lbs)	1,000,000	1,000,000	500,000
5.	Cargo remaining (lbs)	11,526	283,438	7,974
6.	Equipment allocated (sets)	6	6	4
7.	Equipment remaining (sets)	0	0	0
8.	Passengers allocated (pax)	63	24	12
9.	Passengers remaining (pax)	0	0	0

S/N	Parameters	Value		
10.	Crew utilization	25.50%	36.63%	52.71%
11.	Landing spots utilization	94.03%	96.79%	97.11%
	• Active preparation/loading activities	25.50%	36.63%	52.71%
	• Standby for load-up	22.23%	26.68%	40.68%
	• Service support	46.30%	40.68%	3.72%
C.	**Aircraft-related Measures**	**CH-53**	**SH-60**	
12.	Average cargo delivered (lbs)	1,994,291	54,340	
13.	Average equipment delivered (sets)	16	0	
14.	Average passengers delivered (pax)	0	99	
15.	Average sorties flown	86.0	22.2	
16.	Aircraft utilization	99.70%	99.53%	
	• Waiting	3.34%	2.90%	
	• Loading	1.17%	4.04%	
	• Delivery	55.13%	50.32%	
	• Unloading	1.63%	3.96%	
	• Recovery	31.29%	32.69%	
	• Refuel	2.63%	1.67%	
	• Repair	3.97%	3.95%	

Table 31. Load Transfer Capability for High Severity Scenario based on Final Airlift Model

The data gathered from the final airlift model suggested that the load transfer capability for Phase Zero force is, on average, about two million lbs for cargo. It met the equipment and passengers transfer requirements on most occasions, except for one instance where an additional sortie was required to complete passenger delivery. If this is disregarded, there is 95% confidence that the task force can deliver 2.18M lbs of cargo based on the observed standard of about 80K lbs.

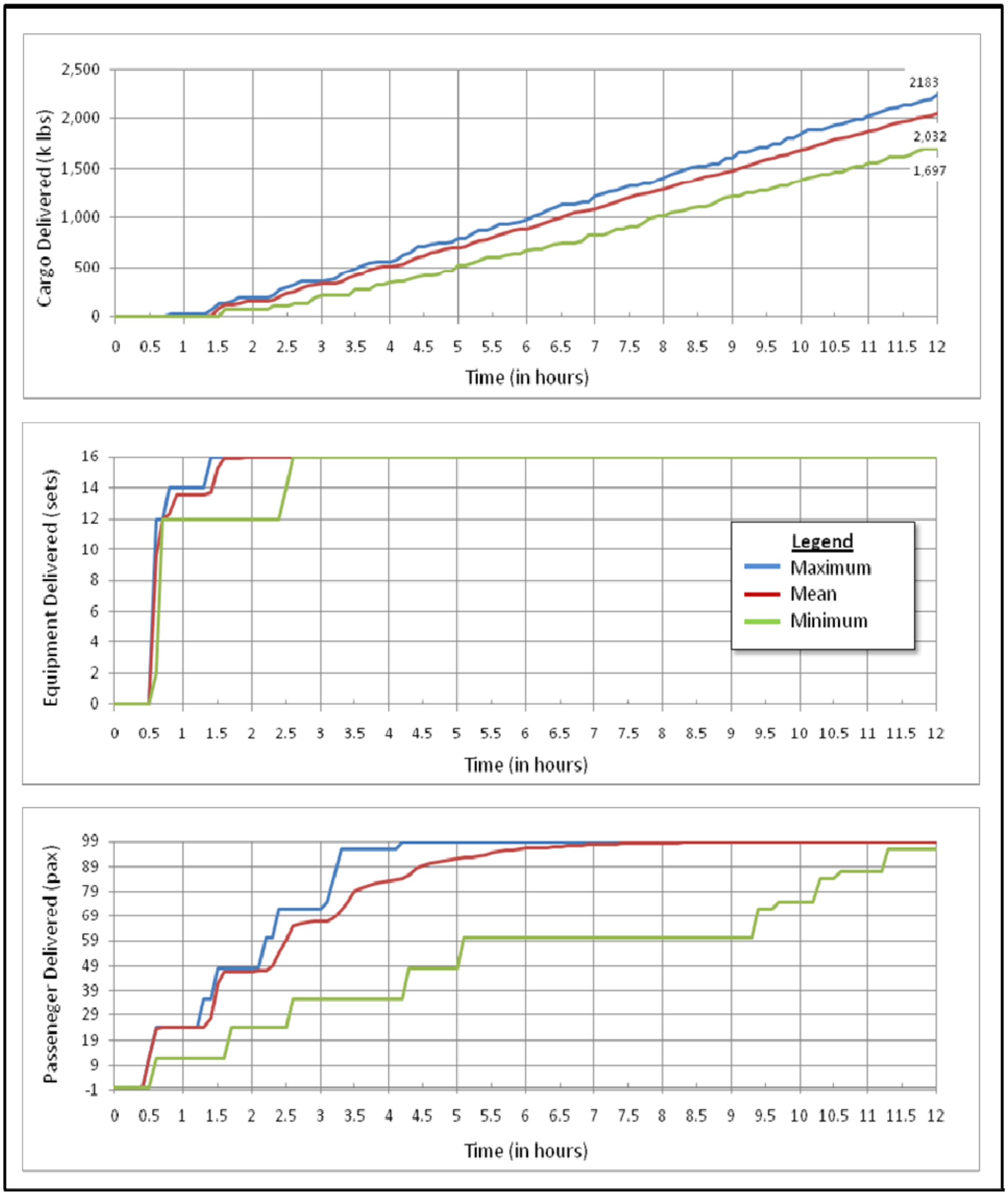

Figure 28. Load Transfer Capability over Time for High Severity Scenario based on Final Airlift Model

The average load transfer capability, based on this final airlift model, is substantially higher (>65%) than that obtained from the baseline model, i.e., 1,318,500 lbs. This vast difference is largely attributed to the assumptions made in deriving the effective operating hours. For the baseline model (and in the case of Project SEA-15), a three-hour block was set aside for refueling and other overheads with the further assumption of an 85% A_o, which resulted in the 7.65 effective operating hours for the mission day. For the final model, the settings for the meantime for refueling was five minutes, meantime for preparing cargo/equipment at 15 minutes and for passengers at five minutes, with MTBF and MTTR at 20-hours and 1-hour respectively (giving an equivalent A_o of about 95.2%) for both aircraft types. Based on the gathered aircraft utilization data in Table 31, the equivalent effective operating hours can be approximated by discounting the average time spent for each aircraft in the waiting, refueling and repair phases. This value worked out to be 10.85 hours, i.e., at least three hours more than what the other approach used.

To further illustrate the A_o impact on the load transfer capability, additional simulations were conducted with MTBF inputs ranging between 10 to 20 hours using a 2.5-hour time block and MTTR inputs between one to three hours with a 1-hour time block. Table 32 summarizes the computed A_o (based on MTBF and MTTR), observed effective operating hours, and the average load transfer capability for cargo for each of the scenarios (with 1,000 simulation runs each). Again, for most of the simulation runs, the delivery of passengers and equipment were complete. Figure 29 depicts the average load transfer capability trend over the tested ranges for MTTR and MTBF using linear interpolation based on the sampled points.

MTBF (hr)	MTTR (hr)	A_o	Effective Operating Hours (hr)	Transfer Capability for Cargo (lbs)
10	1	0.91	10.31	1,932,883
10	2	0.83	9.64	1,777,221
10	3	0.77	9.21	1,681,635
12.5	1	0.93	10.65	1,974,621
12.5	2	0.86	10.15	1,898,456
12.5	3	0.81	9.78	1,815,096
15	1	0.94	10.65	2,006,324
15	2	0.88	10.15	1,898,456
15	3	0.83	9.78	1,815,096
17.5	1	0.95	10.76	2,027,820
17.5	2	0.90	10.32	1,932,200
17.5	3	0.85	10.02	1,867,651
20	1	0.95	10.85	2,048,631
20	2	0.91	10.47	1,968,564
20	3	0.87	10.16	1,899,240

Table 32. Operational Availability Impact on Load Transfer Capability for High Severity Scenario based on Final Airlift Model

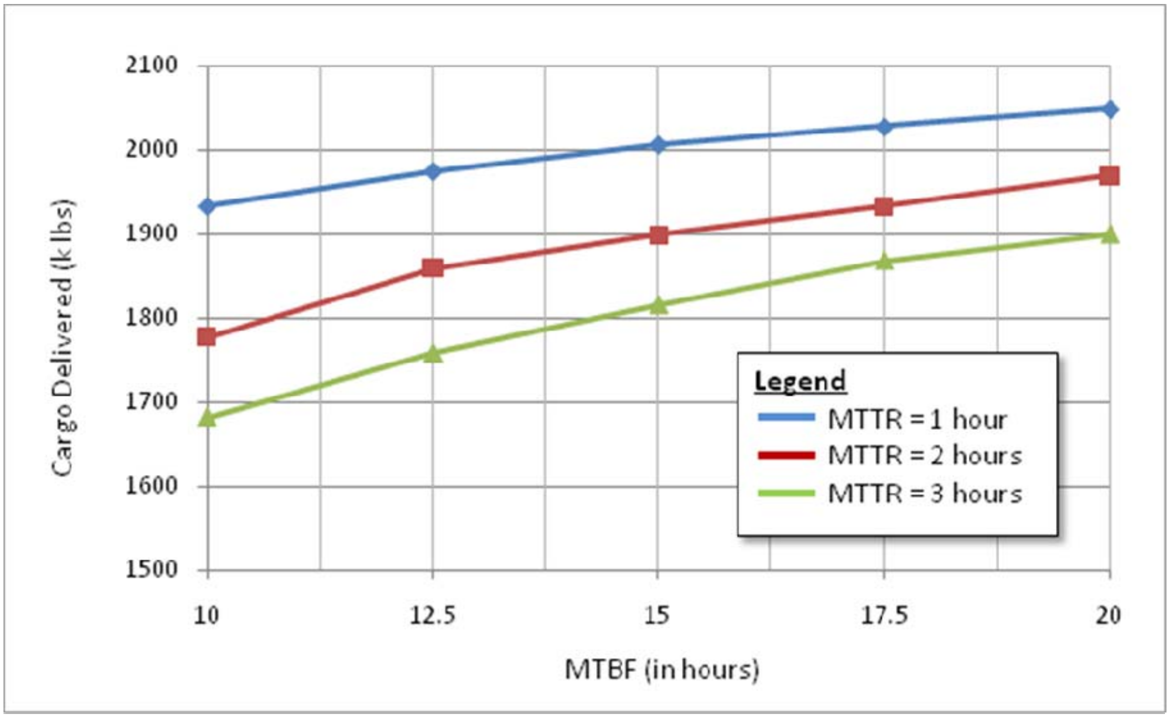

Figure 29. MTTR and MTBF impacts on Load Transfer Capability for High Severity Scenario based on Final Airlift Model

The simulation results still show a higher load transfer capability for the task force versus the deterministic approach for MTTR and MTBF ranges tested. For the "worst-case" scenario, with MTBF and MTTR set at 10-hours and 3-hours respectively, i.e., giving a lower 77% A_o than the 85% used for the baseline model, the average load transfer capability is still higher, at about 1.68M lbs and 27% more than the deterministic value.

VII. CONCLUSION

A. CONCLUSION

The objectives of this thesis were achieved with the successful implementation of a stochastic, dynamic model using DES that can be used to analyze the airlift operation performance of the naval force structure recommended by Project SEA-15 at the operational/tactical level.

An iterative development approach was adopted to allow a baseline model to be developed quickly in the early study phase, which demonstrated the feasibility of using DES to address the issues under study. The simulated results from the constructed baseline model were compared with Project SEA-15 findings, which sifted out some inconsistencies in the latter's reported data. Mathematical and linear optimization analyses were conducted as part of the verification process. The baseline model was subsequently used to generate the load transfer capability of the Phase Zero force, based on the same deterministic input parameters used by the project to serve as a proxy for comparison with the final model. The airlift operation was abstracted in the final model as a six-phase stochastic process with a scheduler responsible for planning and coordinating the activities involved

Three sets of experiments were conducted, with the first one set up to demonstrate the final airlift model's ability to meet the performance measures using the high severity scenario requirement as the case study. The experiment showed that the airlift mission could be accomplished within nine hours, with more than 95% confidence, and utilizing about 66% of the airlift fleet capacity for a mission day. Further experiments were conducted to assess the effectiveness of the different load allocation and landing spot reassignment (in the event of an assigned aircraft failure) schemes implemented in the model, and there were no significant performance differences observed. The final experiment, using the final airlift model (i.e., with stochastic data), suggested a much higher load transfer capability (>60%) for the Phase Zero force as compared to the baseline model, which was deterministic based. Further data were also collected to illustrate the collective impact of the aircraft MTBF and MTTR on the Phase Zero force's load transfer capability.

B. RECOMMENDATIONS AND FUTURE WORK

This thesis work has demonstrated the model's potential in assessing the Phase Zero force's airlift capability by providing operational/tactical level insights to the operation process. It should be considered for supporting future analysis work for the Phase Zero force if the stakeholders intend to bring the project to the next phase.

The model was developed primarily as a proof-of-concept, and as such, it did not cover all aspects of the airlift operation and/or the depths necessary to support full analysis work. With the Phase Zero force being the primary design focus, some aspects of the model were implemented specifically (e.g., hard-coded) to that task force. Hence, its immediate use for supporting other analysis work of a similar nature is limited. However, with the component-based framework adopted for the model, components can be readily added /replaced to expand the modeling scope or enhance the model fidelity to address these needs, as and when required. The following are possible future enhancements of the model's capability:

- There were no intermediate delivery requirements/conditions simulated in the model, e.g., the different load types must be delivered in sequence, or 50% of the equipment must be delivered first, before passengers can be delivered, etc., because there were no specifications for that based on the Project SEA-15 report. The model currently allocates the load based on what the aircraft is best suited for, which is reasonable, but there may be other overarching requirements, at times, that need to supersede that. Incorporating a utility to handle these additional delivery conditions will improve the model's robustness.
- The maintenance and logistics support for the aircraft, in terms of the required repair/refueling facilities and support crew, were not explicitly

modeled. Modeling these elements would provide more complete shipboard operation coverage and assess its impact on the airlift capability.

- The load delivery was modeled one-way, i.e., from the ship to the affected area, based on the mission scenarios defined for Phase Zero force. Expanding the model to cater to two-way delivery would be useful given that relief missions would include the need to evacuate affected personnel from disaster-hit sites.
- The airlift operation was modeled as a single continuous process (per simulation run), meant for analyzing the performance for a single-day (in the case of Project SEA-15) or 24/7 type of missions. Expanding the model's capability to simulate the operation as a "piecewise" continuous process, by retaining certain entities' state information at the break-points, would enable it to better mimic non-continuous multi-day missions (e.g., simulating daylight operation only).
- The setting up of a scenario is currently done within the NetBeans IDE and the interface may not necessarily be intuitive to a non-programmer. Providing a user-friendly front-end user interface would help to improve its usability.
- Parameterize or encapsulate the platform-specific built-in (hardcoded) logics into subcomponents to generalize the model so that it could be used to support other force structure studies as well.

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APPENDIX A. PLATFORM CAPABILITIES

The capabilities for the various platforms are based on the data sheets compiled in the Project SEA-15 report [1] except for the JMSDF DDH class destroyer and RQ-8 Firescout, which the cited report did not have the data sheet for, and in this case, the open source data is used.

A. JMSDF DDH CLASS DESTROYER

S/N	Parameters	Description
1.	Displacement (tonnes)	13,500 standard; 18,000 full load
2.	Dimensions (ft)	646.3 × 108.3 ×31.8
3.	Main machinery	COGAG; four LM 2500 gas turbines; two shafts
4.	Speed (knts)	30
5.	Range (nm)	6,000 at 20 kt
6.	Missiles	Raytheon Sea Sparrow RIM-162 ESSM; Lockheed Martin Marietta Mk 41 Mod 5 sixteen cell vertical launcher
7.	Guns	Two GE 20 mm/76 Sea Vulcan 20, 2-12.7 mm MGs
8.	Torpedoes:	6-324 mm (2 triple) HOS-303 tubes
9.	Countermeasures: Decoys:	4 Hycor Mk 137 sextuple RBOC chaff launchers.
10.	Electronics Support Measures / Electronic Countermeasures:	NOLQ-3C
11.	Combat Data Systems:	Link 16
12.	Radars	Melco FCS-3; G/H/I-band
13.	Navigation	JRC OPS-20C; I-band.
14.	Sonars	Bow-mounted sonar. OQQ 21.
15.	Organic Aircraft	Three SH-60K plus seven SH-60K or seven MCH-101.

Table 33. Data Sheet for JMSDF DDH (after [18])

B. LPD-17 CLASS AMPHIBIOUS ASSAULT SUPPORT VESSEL

S/N	Parameters	Description
1.	Displacement (tonnes)	24,900
2.	Draft (ft)	23
3.	Endurance (nm)	8,000
4.	Speed (knts)	25
5.	Officers	24
6.	Enlisted	333
7.	Troops	720
8.	Organic Boats	Two LCPL, one RHIB (7m), one utility boat
9.	Well Deck Capability	188ft long x50ft wide x 31ft high Two LCAC, or one LCU 1610 plus 14 EFV
10.	Cargo Capacity (ft^3)	30,000
11.	Vehicle Space (ft^2)	25,000
12.	Water Purification capability (gal/day)	60,000
13.	Helo Capable	Yes
14.	Help Spots	Two CH-53 Spot/ Six extended spots
15.	Organic Aircraft	Two CH-53s, or Four AH/UH-1s, or Four CH-46s, or Two MV-22s, or One AV-8B Harrier
16.	Operating Rooms	Two
17.	Beds	24 Bed Ward
18.	Dental Facilities	Yes
19.	Self Defense Weapons	Two MK-49 RAM, two MK-38 Bushmaster, two MK-26 12.7mm machine guns
20.	Offensive Weapons	N/A
21.	Radar	SPS-48E Air search, SPS-73 Navigation/Surface search
22.	Sonar	N/A
23.	Electronic Warfare / Intel	SLQ-32, SLQ-25A, SRS-1 Joint Services Imagery Processing System-Navy (JSIPS-N)
24.	Communications	SHF,UHF,HF,VHF
25.	Command/Flag Space	N/A

Table 34. Data Sheet for LPD-17 (after [1])

C. JOINT HIGH SPEED VESSEL (JHSV)

S/N	Parameters	Description
1.	Displacement (tonnes)	1463.6
2.	Draft (ft)	11
3.	Endurance (nm)	3,500
4.	Speed (knts)	45
5.	Crew	40
6.	Troops	107+87
7.	Organic Boats	Two RHIB
8.	Well Deck Capability	No
9.	Cargo/Vehicle Capacity (ft^3)	28,740
10.	Helo Capable	Yes
11.	Help Spots	Two (MH-60)
12.	Organic Aircraft	N/A
13.	Operating Rooms	One (foldable operating table)
14.	Beds	N/A
15.	Dental Facilities	N/A
16.	Self Defense Weapons	N/A
17.	Offensive Weapons	Mk 96 Stabilized Weapon System, (25mm Bushmaster Cannon &Mk 19 40mm Grenade Launcher); Mk 45 40mm Grenade Launcher System
18.	Radar Type	Assumed to include equivalent systems as current Mine Warfare surface vessels and Littoral Combat Ships (LCS)
19.	Sonar	
20.	Electronic Warfare / Intel	
21.	Communications	HF/UHF/VHF
22.	Command/Flag Space	Two Conference Room, two Staff Rooms

Table 35. Data Sheet for JHSV (after [1])

D. VISBY CLASS CORVETTE

S/N	Parameters	Description
1.	Displacement (tonnes)	600
2.	Draft (Ft)	7.5
3.	Endurance (nm)	2,300
4.	Speed (knts)	35
5.	Crew	43 (total)
6.	Troops	N/A
7.	Organic Boats	N/A
8.	Well Deck Capability	N/A
9.	Cargo Capacity (ft^3)	N/A
10.	Vehicle Space (ft^2)	N/A
11.	Helo Capable	One
12.	Help Spots	One
13.	Organic Aircraft	N/A
14.	Operating Rooms	N/A
15.	Beds	N/A
16.	Dental Facilities	N/A
17.	Self Defense Weapons	Umkhonto (Air Defense Missile)
18.	Offensive Weapons	Saab Bofors Dynamics RBS 15 Mk2/MK3, Anti-Ship Missile, Saab 40mm Grenade Launchers, Saab Underwater Systems Tp 45 Torpedo, Saab Underwater Systems Tp 45 Torpedo and Bofors 57mm 70 SAK MK3 GPMG
19.	Radar Type	SaabTech CEROS 200 / Fire Control, Saab Sea Giraffe AMB / Air Search, Celsius Tech Pilot I-band Surface Search and CEROS 200 MK3 I/J-band Fire Control Radar
20.	Sonar	Hydra Multi-Sonar Suite
21.	EW / Intel	CS-3701 TRSS, MASS Decoy System
22.	Communications	CETRIS C3
23.	Command/Flag Space	N/A

S/N	Parameters	Description
24.	Special Features (e.g. Mission Modules)	ASW, AS, MCM mission modules

Table 36. Data Sheet for Visby (after [1])

E. M-80 STILETTO

S/N	Parameters	Description
1.	Displacement (tonnes)	45
2.	Draft (ft)	Three
3.	Endurance (nm)	500
4.	Speed (knts)	50
5.	Officers	0
6.	Enlisted	Three
7.	Troops	Up to 12
8.	Organic Boats	11m RHIB
9.	Well Deck Capability	N/A
10.	Cargo Capacity (ft^3)	Internal capacity for troops and equipment
11.	Vehicle Space (ft^2)	N/A
12.	Helo Capable	No
13.	Help Spots	N/A
14.	Organic Aircraft	Small UAV capable landing pad
15.	Operating Rooms	N/A
16.	Beds	N/A
17.	Dental Facilities	N/A
18.	Self Defense Weapons	Currently none, however, space provisions have been made for future weapons
19.	Offensive Weapons	Currently none, however, space provisions have been made for future weapons
20.	Radar	Navigation Radar
21.	Sonar	N/A
22.	Electronic Warfare / Intel	Currently none, however, space provisions have been made for future systems

S/N	Parameters	Description
23.	Communications	Space provisions have been made for future systems
24.	Command/Flag Space	N/A

Table 37. Data Sheet for M-80 Stiletto (after [1])

F. CH-53K SEA STALLION

S/N	Parameters	Description
1.	Max Range (nm one way)	454
2.	Cruise Airspeed (kts)	170
3.	Max Airspeed (kts)	190
4.	Speed with external load (kts)	100
5.	Inflight Refueling	Yes
6.	Max Gross Wt (lbs)	84,700
7.	Cargo Lift Capability (lbs)	36,000
8.	External Lift Capability (lbs)	36,000
9.	Normal sling lift (lbs)	27,000
10.	Number of passengers	55
11.	Surface Radar	No
12.	Air Radar	No
13.	SAR/ISAR	No
14.	Airborne Mine Counter-measures	Yes
15.	Forward-Looking Infrared (FLIR)	Yes
16.	Electronic Warfare / Electronics Support Measures	Yes
17.	Sonobouys	No
18.	Dipping Sonar	No

Table 38. Data Sheet for CH-53K Sea Stallion (after [1])

G. SH-60S SEAHAWK

S/N	Parameters	Description
1.	Max Range (nm one way)	200
2.	Cruise Airspeed (kts)	147
3.	Max Airspeed (kts)	180
4.	Speed with external load (kts)	80
5.	Inflight Refueling	No
6.	Max Gross Wt (lbs)	22,000
7.	Cargo Lift Capability (lbs)	8,000
8.	External Lift Capability (lbs)	6,000
9.	Normal sling lift (lbs)	4,500
10.	Number of passengers	12
11.	Surface Radar	No
12.	Air Radar	No
13.	SAR/ISAR	No
14.	Airborne Mine Counter-measures	Yes
15.	Forward-Looking Infrared (FLIR)	Yes
16.	Electronic Warfare / Electronics Support Measures	No
17.	Sonobouys	No
18.	Dipping Sonar	No

Table 39. Data Sheet for SH-60S Seahawk (after [1])

H. RQ-8 FIRESCOUT UAV

S/N	Parameters	Description
1.	Length (m)	6.98
2.	Rotor diameter (m)	8.38
3.	Height (m)	2.87
4.	Weight (kg)	max: 1200 ; empty: 661
5.	Speed (km/h)	231

S/N	Parameters	Description
6.	Ceiling (m)	6,100
7.	Endurance (hours)	Five
8.	Propulsion	Rolls-Royce/Allison 250-C20W turboshaft; 310 kW (420 shp)
9.	Length (m)	6.98

Table 40. Data Sheet for RQ-8 Firescout UAV (after [19])

APPENDIX B. FINAL AIRLIFT MODEL OUTPUT FOR CIVIL SUPPORT MISSION TEST CASES

The following is the output generated by the final airlift model against the three Civil Support mission scenario test cases. Each list describes the sorties flown with details on the aircraft involved, load type and transferred quantity, event timings and the remaining load left after that sortie assignment.

A. MODEL OUTPUT FROM LOW SEVERITY SCENARIO TEST CASE

Assign#	Aircraft#	Load Type#	Transfer Qty	Start Loading Time	Start Sortie Time	Reach Target Time	Leave Target Time	End Sortie Time	Cargo Left	Eqpt Left	Passenger Left
#1	CH53#0	1	2	0	1	4	5	6.76	2232001	4	32
#2	SH60#0	2	12	0	5	7.04	12.04	14.08	2232001	4	20
#3	SH60#1	2	12	0	5	7.04	12.04	14.08	2232001	4	8
#4	CH53#0	1	2	6.76	7.76	10.76	11.76	13.53	2232001	2	8
#5	SH60#0	2	8	14.08	19.08	21.12	26.12	28.16	2232001	2	0
#6	SH60#1	0	4500	14.08	15.08	18.83	19.83	21.87	2227501	2	0
#7	CH53#0	1	2	13.53	14.53	17.53	18.53	20.29	2227501	0	0
#8	CH53#0	0	27000	20.29	21.29	24.29	25.29	27.06	2200501	0	0
#9	SH60#1	0	4500	21.87	22.87	26.62	27.62	29.66	2196001	0	0
#10	SH60#0	0	4500	28.16	29.16	32.91	33.91	35.95	2191501	0	0
#11	CH53#0	0	27000	27.06	28.06	31.06	32.06	33.82	2164501	0	0
#12	SH60#1	0	4500	29.66	30.66	34.41	35.41	37.45	2160001	0	0
#13	CH53#0	0	27000	33.82	34.82	37.82	38.82	40.59	2133001	0	0
#14	SH60#0	0	4500	35.95	36.95	40.7	41.7	43.74	2128501	0	0
#15	SH60#1	0	4500	37.45	38.45	42.2	43.2	45.24	2124001	0	0
#16	CH53#0	0	27000	40.59	41.59	44.59	45.59	47.35	2097001	0	0
#17	SH60#0	0	4500	43.74	44.74	48.49	49.49	51.54	2092501	0	0
#18	SH60#1	0	4500	45.24	46.24	49.99	50.99	53.04	2088001	0	0
#19	CH53#0	0	27000	47.35	48.35	51.35	52.35	54.12	2061001	0	0
#20	SH60#0	0	4500	51.54	52.54	56.29	57.29	59.33	2056501	0	0
#21	SH60#1	0	4500	53.04	54.04	57.79	58.79	60.83	2052001	0	0
#22	CH53#0	0	27000	54.12	55.12	58.12	59.12	60.88	2025001	0	0
#23	SH60#0	0	4500	59.33	60.33	64.08	65.08	67.12	2020501	0	0
#24	SH60#1	0	4500	60.83	61.83	65.58	66.58	68.62	2016001	0	0
#25	CH53#0	0	27000	60.88	61.88	64.88	65.88	67.65	1989001	0	0
#26	SH60#0	0	4500	67.12	68.12	71.87	72.87	74.91	1984501	0	0
#27	SH60#1	0	4500	68.62	69.62	73.37	74.37	76.41	1980001	0	0
#28	CH53#0	0	27000	67.65	68.65	71.65	72.65	74.41	1953001	0	0
#29	SH60#0	0	4500	74.91	75.91	79.66	80.66	82.7	1948501	0	0
#30	CH53#0	0	27000	74.41	75.41	78.41	79.41	81.18	1921501	0	0
#31	SH60#1	0	4500	76.41	77.41	81.16	82.16	84.2	1917001	0	0
#32	CH53#0	0	27000	81.18	82.18	85.18	86.18	87.94	1890001	0	0
#33	SH60#0	0	4500	82.7	83.7	87.45	88.45	90.49	1885501	0	0
#34	SH60#1	0	4500	84.2	85.2	88.95	89.95	91.99	1881001	0	0
#35	CH53#0	0	27000	87.94	88.94	91.94	92.94	94.71	1854001	0	0

Assign#	Aircraft#	Load Type#	Transfer Qty	Start Loading Time	Start Sortie Time	Reach Target Time	Leave Target Time	End Sortie Time	Cargo Left	Eqpt Left	Passenger Left
#36	SH60#0	0	4500	90.49	91.49	95.24	96.24	98.28	1849501	0	0
#37	SH60#1	0	4500	91.99	92.99	96.74	97.74	99.78	1845001	0	0
#38	CH53#0	0	27000	94.71	95.71	98.71	99.71	101.47	1818001	0	0
#39	SH60#0	0	4500	98.28	99.28	103.03	104.03	106.07	1813501	0	0
#40	SH60#1	0	4500	99.78	100.78	104.53	105.53	107.57	1809001	0	0
#41	CH53#0	0	27000	101.47	102.47	105.47	106.47	108.24	1782001	0	0
#42	SH60#0	0	4500	106.07	107.07	110.82	111.82	113.86	1777501	0	0
#43	SH60#1	0	4500	107.57	108.57	112.32	113.32	115.36	1773001	0	0
#44	CH53#0	0	27000	108.24	109.24	112.24	113.24	115	1746001	0	0
#45	SH60#0	0	4500	113.86	114.86	118.61	119.61	121.65	1741501	0	0
#46	SH60#1	0	4500	115.36	116.36	120.11	121.11	123.15	1737001	0	0
#47	CH53#0	0	27000	115	116	119	120	121.76	1710001	0	0
#48	SH60#0	0	4500	121.65	122.65	126.4	127.4	129.44	1705501	0	0
#49	CH53#0	0	27000	121.76	122.76	125.76	126.76	128.53	1678501	0	0
#50	SH60#1	0	4500	123.15	124.15	127.9	128.9	130.94	1674001	0	0
#51	SH60#0	0	4500	129.44	130.44	134.19	135.19	137.23	1669501	0	0
#52	CH53#0	0	27000	128.53	129.53	132.53	133.53	135.29	1642501	0	0
#53	SH60#1	0	4500	130.94	131.94	135.69	136.69	138.73	1638001	0	0
#54	CH53#0	0	27000	135.29	136.29	139.29	140.29	142.06	1611001	0	0
#55	SH60#0	0	4500	137.23	138.23	141.98	142.98	145.03	1606501	0	0
#56	SH60#1	0	4500	138.73	139.73	143.48	144.48	146.53	1602001	0	0
#57	CH53#0	0	27000	142.06	143.06	146.06	147.06	148.82	1575001	0	0
#58	SH60#0	0	4500	145.03	146.03	149.78	150.78	152.82	1570501	0	0
#59	SH60#1	0	4500	146.53	147.53	151.28	152.28	154.32	1566001	0	0
#60	CH53#0	0	27000	148.82	149.82	152.82	153.82	155.59	1539001	0	0
#61	SH60#0	0	4500	152.82	153.82	157.57	158.57	160.61	1534501	0	0
#62	SH60#1	0	4500	154.32	155.32	159.07	160.07	162.11	1530001	0	0
#63	CH53#0	0	27000	155.59	156.59	159.59	160.59	162.35	1503001	0	0
#64	SH60#0	0	4500	160.61	161.61	165.36	166.36	168.4	1498501	0	0
#65	SH60#1	0	4500	162.11	163.11	166.86	167.86	169.9	1494001	0	0
#66	CH53#0	0	27000	162.35	163.35	166.35	167.35	169.12	1467001	0	0
#67	SH60#0	0	4500	168.4	169.4	173.15	174.15	176.19	1462501	0	0
#68	SH60#1	0	4500	169.9	170.9	174.65	175.65	177.69	1458001	0	0
#69	CH53#0	0	27000	169.12	170.12	173.12	174.12	175.88	1431001	0	0
#70	SH60#0	0	4500	176.19	177.19	180.94	181.94	183.98	1426501	0	0
#71	CH53#0	0	27000	175.88	176.88	179.88	180.88	182.65	1399501	0	0
#72	SH60#1	0	4500	177.69	178.69	182.44	183.44	185.48	1395001	0	0
#73	CH53#0	0	27000	182.65	183.65	186.65	187.65	189.41	1368001	0	0
#74	SH60#0	0	4500	183.98	184.98	188.73	189.73	191.77	1363501	0	0
#75	SH60#1	0	4500	185.48	186.48	190.23	191.23	193.27	1359001	0	0
#76	CH53#0	0	27000	189.41	190.41	193.41	194.41	196.18	1332001	0	0
#77	SH60#0	0	4500	191.77	192.77	196.52	197.52	199.56	1327501	0	0
#78	SH60#1	0	4500	193.27	194.27	198.02	199.02	201.06	1323001	0	0
#79	CH53#0	0	27000	196.18	197.18	200.18	201.18	202.94	1296001	0	0
#80	SH60#0	0	4500	199.56	200.56	204.31	205.31	207.35	1291501	0	0
#81	SH60#1	0	4500	201.06	202.06	205.81	206.81	208.85	1287001	0	0
#82	CH53#0	0	27000	202.94	203.94	206.94	207.94	209.71	1260001	0	0
#83	SH60#0	0	4500	207.35	208.35	212.1	213.1	215.14	1255501	0	0
#84	SH60#1	0	4500	208.85	209.85	213.6	214.6	216.64	1251001	0	0
#85	CH53#0	0	27000	209.71	210.71	213.71	214.71	216.47	1224001	0	0

Assign#	Aircraft#	Load Type#	Transfer Qty	Start Loading Time	Start Sortie Time	Reach Target Time	Leave Target Time	End Sortie Time	Cargo Left	Eqpt Left	Passenger Left
#86	SH60#0	0	4500	215.14	216.14	219.89	220.89	222.93	1219501	0	0
#87	SH60#1	0	4500	216.64	217.64	221.39	222.39	224.43	1215001	0	0
#88	CH53#0	0	27000	216.47	217.47	220.47	221.47	223.24	1188001	0	0
#89	SH60#0	0	4500	222.93	223.93	227.68	228.68	230.72	1183501	0	0
#90	CH53#0	0	27000	223.24	224.24	227.24	228.24	230	1156501	0	0
#91	SH60#1	0	4500	224.43	225.43	229.18	230.18	232.22	1152001	0	0
#92	SH60#0	0	4500	230.72	231.72	235.47	236.47	238.52	1147501	0	0
#93	CH53#0	0	27000	230	231	234	235	236.76	1120501	0	0
#94	SH60#1	0	4500	232.22	233.22	236.97	237.97	240.02	1116001	0	0
#95	CH53#0	0	27000	236.76	237.76	240.76	241.76	243.53	1089001	0	0
#96	SH60#0	0	4500	238.52	239.52	243.27	244.27	246.31	1084501	0	0
#97	SH60#1	0	4500	240.02	241.02	244.77	245.77	247.81	1080001	0	0
#98	CH53#0	0	27000	243.53	244.53	247.53	248.53	250.29	1053001	0	0
#99	SH60#0	0	4500	246.31	247.31	251.06	252.06	254.1	1048501	0	0
#100	SH60#1	0	4500	247.81	248.81	252.56	253.56	255.6	1044001	0	0
#101	CH53#0	0	27000	250.29	251.29	254.29	255.29	257.06	1017001	0	0
#102	SH60#0	0	4500	254.1	255.1	258.85	259.85	261.89	1012501	0	0
#103	SH60#1	0	4500	255.6	256.6	260.35	261.35	263.39	1008001	0	0
#104	CH53#0	0	27000	257.06	258.06	261.06	262.06	263.82	981001	0	0
#105	SH60#0	0	4500	261.89	262.89	266.64	267.64	269.68	976501	0	0
#106	SH60#1	0	4500	263.39	264.39	268.14	269.14	271.18	972001	0	0
#107	CH53#0	0	27000	263.82	264.82	267.82	268.82	270.59	945001	0	0
#108	SH60#0	0	4500	269.68	270.68	274.43	275.43	277.47	940501	0	0
#109	SH60#1	0	4500	271.18	272.18	275.93	276.93	278.97	936001	0	0
#110	CH53#0	0	27000	270.59	271.59	274.59	275.59	277.35	909001	0	0
#111	SH60#0	0	4500	277.47	278.47	282.22	283.22	285.26	904501	0	0
#112	CH53#0	0	27000	277.35	278.35	281.35	282.35	284.12	877501	0	0
#113	SH60#1	0	4500	278.97	279.97	283.72	284.72	286.76	873001	0	0
#114	CH53#0	0	27000	284.12	285.12	288.12	289.12	290.88	846001	0	0
#115	SH60#0	0	4500	285.26	286.26	290.01	291.01	293.05	841501	0	0
#116	SH60#1	0	4500	286.76	287.76	291.51	292.51	294.55	837001	0	0
#117	CH53#0	0	27000	290.88	291.88	294.88	295.88	297.65	810001	0	0
#118	SH60#0	0	4500	293.05	294.05	297.8	298.8	300.84	805501	0	0
#119	SH60#1	0	4500	294.55	295.55	299.3	300.3	302.34	801001	0	0
#120	CH53#0	0	27000	297.65	298.65	301.65	302.65	304.41	774001	0	0
#121	SH60#0	0	4500	300.84	301.84	305.59	306.59	308.63	769501	0	0
#122	SH60#1	0	4500	302.34	303.34	307.09	308.09	310.13	765001	0	0
#123	CH53#0	0	27000	304.41	305.41	308.41	309.41	311.18	738001	0	0
#124	SH60#0	0	4500	308.63	309.63	313.38	314.38	316.42	733501	0	0
#125	SH60#1	0	4500	310.13	311.13	314.88	315.88	317.92	729001	0	0
#126	CH53#0	0	27000	311.18	312.18	315.18	316.18	317.94	702001	0	0
#127	SH60#0	0	4500	316.42	317.42	321.17	322.17	324.21	697501	0	0
#128	SH60#1	0	4500	317.92	318.92	322.67	323.67	325.71	693001	0	0
#129	CH53#0	0	27000	317.94	318.94	321.94	322.94	324.71	666001	0	0
#130	SH60#0	0	4500	324.21	325.21	328.96	329.96	332.01	661501	0	0
#131	SH60#1	0	4500	325.71	326.71	330.46	331.46	333.51	657001	0	0
#132	CH53#0	0	27000	324.71	325.71	328.71	329.71	331.47	630001	0	0
#133	SH60#0	0	4500	332.01	333.01	336.76	337.76	339.8	625501	0	0
#134	CH53#0	0	27000	331.47	332.47	335.47	336.47	338.24	598501	0	0
#135	SH60#1	0	4500	333.51	334.51	338.26	339.26	341.3	594001	0	0

Assign#	Aircraft#	Load Type#	Transfer Qty	Start Loading Time	Start Sortie Time	Reach Target Time	Leave Target Time	End Sortie Time	Cargo Left	Eqpt Left	Passenger Left
#136	CH53#0	0	27000	338.24	339.24	342.24	343.24	345	567001	0	0
#137	SH60#0	0	4500	339.8	340.8	344.55	345.55	347.59	562501	0	0
#138	SH60#1	0	4500	341.3	342.3	346.05	347.05	349.09	558001	0	0
#139	CH53#0	0	27000	345	346	349	350	351.76	531001	0	0
#140	SH60#0	0	4500	347.59	348.59	352.34	353.34	355.38	526501	0	0
#141	SH60#1	0	4500	349.09	350.09	353.84	354.84	356.88	522001	0	0
#142	CH53#0	0	27000	351.76	352.76	355.76	356.76	358.53	495001	0	0
#143	SH60#0	0	4500	355.38	356.38	360.13	361.13	363.17	490501	0	0
#144	SH60#1	0	4500	356.88	357.88	361.63	362.63	364.67	486001	0	0
#145	CH53#0	0	27000	358.53	359.53	362.53	363.53	365.29	459001	0	0
#146	SH60#0	0	4500	363.17	364.17	367.92	368.92	370.96	454501	0	0
#147	SH60#1	0	4500	364.67	365.67	369.42	370.42	372.46	450001	0	0
#148	CH53#0	0	27000	365.29	366.29	369.29	370.29	372.06	423001	0	0
#149	SH60#0	0	4500	370.96	371.96	375.71	376.71	378.75	418501	0	0
#150	SH60#1	0	4500	372.46	373.46	377.21	378.21	380.25	414001	0	0
#151	CH53#0	0	27000	372.06	373.06	376.06	377.06	378.82	387001	0	0
#152	SH60#0	0	4500	378.75	379.75	383.5	384.5	386.54	382501	0	0
#153	CH53#0	0	27000	378.82	379.82	382.82	383.82	385.59	355501	0	0
#154	SH60#1	0	4500	380.25	381.25	385	386	388.04	351001	0	0
#155	SH60#0	0	4500	386.54	387.54	391.29	392.29	394.33	346501	0	0
#156	CH53#0	0	27000	385.59	386.59	389.59	390.59	392.35	319501	0	0
#157	SH60#1	0	4500	388.04	389.04	392.79	393.79	395.83	315001	0	0
#158	CH53#0	0	27000	392.35	393.35	396.35	397.35	399.12	288001	0	0
#159	SH60#0	0	4500	394.33	395.33	399.08	400.08	402.12	283501	0	0
#160	SH60#1	0	4500	395.83	396.83	400.58	401.58	403.62	279001	0	0
#161	CH53#0	0	27000	399.12	400.12	403.12	404.12	405.88	252001	0	0
#162	SH60#0	0	4500	402.12	403.12	406.87	407.87	409.91	247501	0	0
#163	SH60#1	0	4500	403.62	404.62	408.37	409.37	411.41	243001	0	0
#164	CH53#0	0	27000	405.88	406.88	409.88	410.88	412.65	216001	0	0
#165	SH60#0	0	4500	409.91	410.91	414.66	415.66	417.7	211501	0	0
#166	SH60#1	0	4500	411.41	412.41	416.16	417.16	419.2	207001	0	0
#167	CH53#0	0	27000	412.65	413.65	416.65	417.65	419.41	180001	0	0
#168	SH60#0	0	4500	417.7	418.7	422.45	423.45	425.49	175501	0	0
#169	SH60#1	0	4500	419.2	420.2	423.95	424.95	426.99	171001	0	0
#170	CH53#0	0	27000	419.41	420.41	423.41	424.41	426.18	144001	0	0
#171	SH60#0	0	4500	425.49	426.49	430.24	431.24	433.29	139501	0	0
#172	SH60#1	0	4500	426.99	427.99	431.74	432.74	434.79	135001	0	0
#173	CH53#0	0	27000	426.18	427.18	430.18	431.18	432.94	108001	0	0
#174	SH60#0	0	4500	433.29	434.29	438.04	439.04	441.08	103501	0	0
#175	CH53#0	0	27000	432.94	433.94	436.94	437.94	439.71	76501	0	0
#176	SH60#1	0	4500	434.79	435.79	439.54	440.54	442.58	72001	0	0
#177	CH53#0	0	27000	439.71	440.71	443.71	444.71	446.47	45001	0	0
#178	SH60#0	0	4500	441.08	442.08	445.83	446.83	448.87	40501	0	0
#179	SH60#1	0	4500	442.58	443.58	447.33	448.33	450.37	36001	0	0
#180	CH53#0	0	27000	446.47	447.47	450.47	451.47	453.24	9001	0	0
#181	SH60#0	0	4500	448.87	449.87	453.62	454.62	456.66	4501	0	0
#182	SH60#1	0	4500	450.37	451.37	455.12	456.12	458.16	1	0	0
#183	CH53#0	0	1	453.24	454.24	457.24	458.24	460	0	0	0

Table 41. Final Airlift Model Output for Low Severity Scenario Test Case

B. MODEL OUTPUT FROM MEAN SEVERITY SCENARIO TEST CASE

Assign#	Aircraft#	Load Type#	Transfer Qty	Start Loading Time	Start Sortie Time	Reach Target Time	Leave Target Time	End Sortie Time	Cargo Left	Eqpt Left	Passenger Left
#1	CH53#0	1	2	0	1	19	20	30.59	729001	9	72
#2	CH53#1	1	2	0	1	19	20	30.59	729001	7	72
#3	SH60#0	2	12	0	5	17.26	22.26	34.51	729001	7	60
#4	SH60#1	2	12	0	5	17.26	22.26	34.51	729001	7	48
#5	CH53#0	1	2	30.59	31.59	49.59	50.59	61.18	729001	5	48
#6	CH53#1	1	2	30.59	31.59	49.59	50.59	61.18	729001	3	48
#7	SH60#0	2	12	34.51	39.51	51.77	56.77	69.03	729001	3	36
#8	SH60#1	2	12	34.51	39.51	51.77	56.77	69.03	729001	3	24
#9	CH53#0	1	2	61.18	62.18	80.18	81.18	91.76	729001	1	24
#10	CH53#1	1	1	61.18	62.18	80.18	81.18	91.76	729001	0	24
#11	SH60#0	2	12	69.03	74.03	86.29	91.29	103.54	729001	0	12
#12	SH60#1	2	12	69.03	74.03	86.29	91.29	103.54	729001	0	0
#13	CH53#0	0	27000	91.76	92.76	110.76	111.76	122.35	702001	0	0
#14	CH53#1	0	27000	91.76	92.76	110.76	111.76	122.35	675001	0	0
#15	SH60#0	0	4500	103.54	104.54	127.07	128.07	140.32	670501	0	0
#16	SH60#1	0	4500	103.54	104.54	127.07	128.07	140.32	666001	0	0
#17	CH53#0	0	27000	122.35	123.35	141.35	142.35	152.94	639001	0	0
#18	CH53#1	0	27000	122.35	123.35	141.35	142.35	152.94	612001	0	0
#19	SH60#0	0	4500	140.32	141.32	163.84	164.84	177.1	607501	0	0
#20	SH60#1	0	4500	140.32	141.32	163.84	164.84	177.1	603001	0	0
#21	CH53#0	0	27000	152.94	153.94	171.94	172.94	183.53	576001	0	0
#22	CH53#1	0	27000	152.94	153.94	171.94	172.94	183.53	549001	0	0
#23	SH60#0	0	4500	177.1	178.1	200.62	201.62	213.88	544501	0	0
#24	SH60#1	0	4500	177.1	178.1	200.62	201.62	213.88	540001	0	0
#25	CH53#0	0	27000	183.53	184.53	202.53	203.53	214.12	513001	0	0
#26	CH53#1	0	27000	183.53	184.53	202.53	203.53	214.12	486001	0	0
#27	SH60#0	0	4500	213.88	214.88	237.4	238.4	250.66	481501	0	0
#28	SH60#1	0	4500	213.88	214.88	237.4	238.4	250.66	477001	0	0
#29	CH53#0	0	27000	214.12	215.12	233.12	234.12	244.71	450001	0	0
#30	CH53#1	0	27000	214.12	215.12	233.12	234.12	244.71	423001	0	0
#31	SH60#0	0	4500	250.66	251.66	274.18	275.18	287.44	418501	0	0
#32	SH60#1	0	4500	250.66	251.66	274.18	275.18	287.44	414001	0	0
#33	CH53#0	0	27000	244.71	245.71	263.71	264.71	275.29	387001	0	0
#34	CH53#1	0	27000	244.71	245.71	263.71	264.71	275.29	360001	0	0
#35	CH53#0	0	27000	275.29	276.29	294.29	295.29	305.88	333001	0	0
#36	CH53#1	0	27000	275.29	276.29	294.29	295.29	305.88	306001	0	0
#37	SH60#0	0	4500	287.44	288.44	310.96	311.96	324.22	301501	0	0
#38	SH60#1	0	4500	287.44	288.44	310.96	311.96	324.22	297001	0	0
#39	CH53#0	0	27000	305.88	306.88	324.88	325.88	336.47	270001	0	0
#40	CH53#1	0	27000	305.88	306.88	324.88	325.88	336.47	243001	0	0
#41	SH60#0	0	4500	324.22	325.22	347.74	348.74	361	238501	0	0
#42	SH60#1	0	4500	324.22	325.22	347.74	348.74	361	234001	0	0
#43	CH53#0	0	27000	336.47	337.47	355.47	356.47	367.06	207001	0	0
#44	CH53#1	0	27000	336.47	337.47	355.47	356.47	367.06	180001	0	0
#45	SH60#0	0	4500	361	362	384.52	385.52	397.78	175501	0	0
#46	SH60#1	0	4500	361	362	384.52	385.52	397.78	171001	0	0
#47	CH53#0	0	27000	367.06	368.06	386.06	387.06	397.65	144001	0	0
#48	CH53#1	0	27000	367.06	368.06	386.06	387.06	397.65	117001	0	0

Assign#	Aircraft#	Load Type#	Transfer Qty	Start Loading Time	Start Sortie Time	Reach Target Time	Leave Target Time	End Sortie Time	Cargo Left	Eqpt Left	Passenger Left
#49	SH60#0	0	4500	397.78	398.78	421.3	422.3	434.56	112501	0	0
#50	SH60#1	0	4500	397.78	398.78	421.3	422.3	434.56	108001	0	0
#51	CH53#0	0	27000	397.65	398.65	416.65	417.65	428.24	81001	0	0
#52	CH53#1	0	27000	397.65	398.65	416.65	417.65	428.24	54001	0	0
#53	CH53#0	0	27000	428.24	429.24	447.24	448.24	458.82	27001	0	0
#54	CH53#1	0	27000	428.24	429.24	447.24	448.24	458.82	1	0	0
#55	SH60#0	0	1	434.56	435.56	458.08	459.08	471.34	0	0	0

Table 42. Final Airlift Model Output for Mean Severity Scenario Test Case

C. MODEL OUTPUT FROM HIGH SEVERITY SCENARIO TEST CASE

Assign#	Aircraft#	Load Type#	Transfer Qty	Start Loading Time	Start Sortie Time	Reach Target Time	Leave Target Time	End Sortie Time	Cargo Left	Eqpt Left	Passenger Left
#1	CH53#0	1	2	0	1	34	35	54.41	1318501	14	99
#2	CH53#1	1	2	0	1	34	35	54.41	1318501	12	99
#3	CH53#2	1	2	0	1	34	35	54.41	1318501	10	99
#4	CH53#3	1	2	0	1	34	35	54.41	1318501	8	99
#5	CH53#4	1	2	0	1	34	35	54.41	1318501	6	99
#6	CH53#5	1	2	0	1	34	35	54.41	1318501	4	99
#7	CH53#6	1	2	0	1	34	35	54.41	1318501	2	99
#8	SH60#0	2	12	0	5	27.45	32.45	54.9	1318501	2	87
#9	SH60#1	2	12	0	5	27.45	32.45	54.9	1318501	2	75
#10	CH53#0	1	2	54.41	55.41	88.41	89.41	108.82	1318501	0	75
#11	CH53#1	0	27000	54.41	55.41	88.41	89.41	108.82	1291501	0	75
#12	CH53#2	0	27000	54.41	55.41	88.41	89.41	108.82	1264501	0	75
#13	CH53#3	0	27000	54.41	55.41	88.41	89.41	108.82	1237501	0	75
#14	CH53#4	0	27000	54.41	55.41	88.41	89.41	108.82	1210501	0	75
#15	CH53#5	0	27000	54.41	55.41	88.41	89.41	108.82	1183501	0	75
#16	CH53#6	0	27000	54.41	55.41	88.41	89.41	108.82	1156501	0	75
#17	SH60#0	2	12	54.9	59.9	82.35	87.35	109.8	1156501	0	63
#18	SH60#1	2	12	54.9	59.9	82.35	87.35	109.8	1156501	0	51
#19	CH53#0	0	27000	108.82	109.82	142.82	143.82	163.24	1129501	0	51
#20	CH53#1	0	27000	108.82	109.82	142.82	143.82	163.24	1102501	0	51
#21	CH53#2	0	27000	108.82	109.82	142.82	143.82	163.24	1075501	0	51
#22	CH53#3	0	27000	108.82	109.82	142.82	143.82	163.24	1048501	0	51
#23	CH53#4	0	27000	108.82	109.82	142.82	143.82	163.24	1021501	0	51
#24	CH53#5	0	27000	108.82	109.82	142.82	143.82	163.24	994501	0	51
#25	CH53#6	0	27000	108.82	109.82	142.82	143.82	163.24	967501	0	51
#26	SH60#0	2	12	109.8	114.8	137.24	142.24	164.69	967501	0	39
#27	SH60#1	2	12	109.8	114.8	137.24	142.24	164.69	967501	0	27
#28	CH53#0	0	27000	163.24	164.24	197.24	198.24	217.65	940501	0	27
#29	CH53#1	0	27000	163.24	164.24	197.24	198.24	217.65	913501	0	27
#30	CH53#2	0	27000	163.24	164.24	197.24	198.24	217.65	886501	0	27
#31	CH53#3	0	27000	163.24	164.24	197.24	198.24	217.65	859501	0	27
#32	CH53#4	0	27000	163.24	164.24	197.24	198.24	217.65	832501	0	27
#33	CH53#5	0	27000	163.24	164.24	197.24	198.24	217.65	805501	0	27
#34	CH53#6	0	27000	163.24	164.24	197.24	198.24	217.65	778501	0	27
#35	SH60#0	2	12	164.69	169.69	192.14	197.14	219.59	778501	0	15

Assign#	Aircraft#	Load Type#	Transfer Qty	Start Loading Time	Start Sortie Time	Reach Target Time	Leave Target Time	End Sortie Time	Cargo Left	Eqpt Left	Passenger Left
#36	SH60#1	2	12	164.69	169.69	192.14	197.14	219.59	778501	0	3
#37	CH53#0	0	27000	217.65	218.65	251.65	252.65	272.06	751501	0	3
#38	CH53#1	0	27000	217.65	218.65	251.65	252.65	272.06	724501	0	3
#39	CH53#2	0	27000	217.65	218.65	251.65	252.65	272.06	697501	0	3
#40	CH53#3	0	27000	217.65	218.65	251.65	252.65	272.06	670501	0	3
#41	CH53#4	0	27000	217.65	218.65	251.65	252.65	272.06	643501	0	3
#42	CH53#5	0	27000	217.65	218.65	251.65	252.65	272.06	616501	0	3
#43	CH53#6	0	27000	217.65	218.65	251.65	252.65	272.06	589501	0	3
#44	SH60#0	2	3	219.59	224.59	247.04	252.04	274.49	589501	0	0
#45	SH60#1	0	4500	219.59	220.59	261.84	262.84	285.29	585001	0	0
#46	CH53#0	0	27000	272.06	273.06	306.06	307.06	326.47	558001	0	0
#47	CH53#1	0	27000	272.06	273.06	306.06	307.06	326.47	531001	0	0
#48	CH53#2	0	27000	272.06	273.06	306.06	307.06	326.47	504001	0	0
#49	CH53#3	0	27000	272.06	273.06	306.06	307.06	326.47	477001	0	0
#50	CH53#4	0	27000	272.06	273.06	306.06	307.06	326.47	450001	0	0
#51	CH53#5	0	27000	272.06	273.06	306.06	307.06	326.47	423001	0	0
#52	CH53#6	0	27000	272.06	273.06	306.06	307.06	326.47	396001	0	0
#53	SH60#1	0	4500	285.29	286.29	327.54	328.54	350.99	391501	0	0
#54	SH60#0	0	4500	274.49	275.49	316.74	317.74	340.19	387001	0	0
#55	CH53#0	0	27000	326.47	327.47	360.47	361.47	380.88	360001	0	0
#56	CH53#1	0	27000	326.47	327.47	360.47	361.47	380.88	333001	0	0
#57	CH53#2	0	27000	326.47	327.47	360.47	361.47	380.88	306001	0	0
#58	CH53#3	0	27000	326.47	327.47	360.47	361.47	380.88	279001	0	0
#59	CH53#4	0	27000	326.47	327.47	360.47	361.47	380.88	252001	0	0
#60	CH53#5	0	27000	326.47	327.47	360.47	361.47	380.88	225001	0	0
#61	CH53#6	0	27000	326.47	327.47	360.47	361.47	380.88	198001	0	0
#62	SH60#0	0	4500	340.19	341.19	382.44	383.44	405.89	193501	0	0
#63	SH60#1	0	4500	350.99	351.99	393.24	394.24	416.69	189001	0	0
#64	CH53#0	0	27000	380.88	381.88	414.88	415.88	435.29	162001	0	0
#65	CH53#1	0	27000	380.88	381.88	414.88	415.88	435.29	135001	0	0
#66	CH53#2	0	27000	380.88	381.88	414.88	415.88	435.29	108001	0	0
#67	CH53#3	0	27000	380.88	381.88	414.88	415.88	435.29	81001	0	0
#68	CH53#4	0	27000	380.88	381.88	414.88	415.88	435.29	54001	0	0
#69	CH53#5	0	27000	380.88	381.88	414.88	415.88	435.29	27001	0	0
#70	CH53#6	0	27000	380.88	381.88	414.88	415.88	435.29	1	0	0
#71	SH60#0	0	1	405.89	406.89	448.14	449.14	471.59	0	0	0

Table 43. Final Airlift Model Output for High Severity Scenario Test Case

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APPENDIX C. INPUT PARAMETERS FOR EXPERIMENT #1

Parameters	Value	Remarks
General Parameters		
allocationMode	0	Mode for selecting the load allocation schemes; 0 for ship-level and 1 for fleet-level allocation.
replacementMode	0	Mode for selecting the landing spot reassignment schemes when an assigned aircraft failed; 0 for using replacement mode where landing spot request for replacement aircraft and 1 for reset mode where landing spot return load and seek new assignment
numberReplications	1000	Number of simulation runs.
missionDuration	720	Simulation duration (in mins), which is used for mission duration.
interval	6	Time interval for measuring load delivered over the simulation duration.
variance	0.2	The range to be used for a uniform distribution about a mean value, defined as a factor of that mean value. Uniform distribution is used for all timing random variats except for time-to-failure and time-to-repair.
distance	55	The distance between the ships and the target area for load delivery (in nm).
numberOfShips	3	Number of ships for the task force. The number has to be synchronized with the number of ShipServer instances used for the simulation, which is currently set at 3, i.e., for JMSDF, LPD-17 and JHSV.

Table 44. Input Parameters for Experiment #1

Parameters	Value			Remarks
numberOfLoadTypes	3			Number of load types to be transferred, i.e., cargo, equipment and passenger. The number has to be set as 3 because of the logics hard-coded to optimize the load location.
numberOfAircraftTypes	2			Number of aircraft type for the task force, i.e., CH-53 and SH-60. The number has to be set as 2 because of the logics hard-coded to optimize the load location.
maxSupportLandingSpotFleet	3			Maximum number of landing spots that the fleet can allocate for support tasks (i.e., repair/refuel) at any one time.
waitTime	5			Expected arrival time difference that a ship is willing to wait in order to get a better aircraft match (optimized) for the remaining load onboard the ship, i.e., based on the unassigned aircraft in the holding list.
Ship-related Parameters	**JMSDF**	**LPD17**	**JHSV**	
minLoadingLandingSpotShip[]	2	1	1	Minimum number of landing spots that must be available at any one time for direct airlift operation support (i.e., for load preparation and loading activities only).
Number of Landing Spots	4	2	1	Total number of landing spots for the ship
Number of Logistics Crew	4	2	1	Total number of logistics crew for the ship
load[0]	638,200	6	24	The quantity of cargo load type onboard the ship that needs to be transferred (in lbs).

Table 45. Input Parameters for Experiment #1 (Continued)

Parameters	**Value**			**Remarks**
load[1]	400,000	6	36	The quantity of equipment load type onboard the ship that needs to be transferred (in sets).
load[2]	200,000	4	39	The number of passengers load type onboard the ship that needs to be transferred (in pax).
deckTransferTime[0]	15	15	15	The preparation meantime needed for cargo load type for the ship (in mins).
deckTransferTime[1]	15	15	15	The preparation meantime needed for equipment load type for the ship (in mins).
deckTransferTime[2]	5	5	5	The preparation meantime needed for passengers load type for the ship (in mins).
hookUpTimeCH53[0]	1	1	1	The CH-53 loading meantime needed for cargo load type for the ship (in mins).
hookUpTimeCH53[1]	1	1	1	The CH-53 loading meantime needed for equipment load type for the ship (in mins).
hookUpTimeCH53[2]	5	5	5	The CH-53 loading meantime needed for passengers load type for the ship (in mins).
hookUpTimeSH60[0]	1	1	1	The SH60 loading meantime needed for cargo load type for the ship (in mins).
hookUpTimeSH60[1]	1	1	1	The SH60 loading meantime needed for equipment load type for the ship (in mins).

Table 46. Input Parameters for Experiment #1 (Continued)

Parameters	Value			Remarks
hookUpTimeSH60[2]	5	5	5	The SH60 loading meantime needed for passengers load type for the ship (in mins).
Aircraft-related Parameters	**CH-53**	**SH-60**		
Quantity	7	2		The quantity for the aircraft type.
maxDistanceYY	454	500		The maximum distance that the aircraft can travel in between refuels (in nm).
minBufferTimeYY	20	20		Minimum buffer time (in mins) that an aircraft must be able to hold in the air upon returning to ship used for refueling consideration
minBufferFactorYY	0.1	0.1		Minimum buffer factor based on travelling distance that an aircraft must cater for a sortie used for refueling consideration
Capacity[0]	27,000	4,500		Aircraft capacity for cargo (in lbs).
Capacity[1]	2	0		Aircraft capacity for equipment (in sets)
Capacity[2]	55	12		Aircraft capacity for passenger (in pax)
Speed[0][0]	100	80		Aircraft speed from ship to target area transporting cargo (in knts). Use for computing delivery time random variate based on distance defined and using uniform distribution.

Table 47. Input Parameters for Experiment #1 (Continued)

Parameters	Value		Remarks
Speed[1][0]	170	147	Aircraft speed from ship to target area transporting equipment (in knts). Use for computing delivery time random variate based on distance defined and using uniform distribution.
Speed[2][0]	170	147	Aircraft speed from ship to target area transporting passengers (in knts). Use for computing delivery time random variate based on distance defined and using uniform distribution.
Speed[0][1]	170	147	Aircraft speed from target area to ship after off-loading cargo (in knts). Use for computing delivery time random variate based on distance defined and using uniform distribution.
Speed[1][1]	170	147	Aircraft speed from target area to ship after off-loading equipment (in knts). Use for computing delivery time random variate based on distance defined and using uniform distribution.
Speed[2][1]	170	147	Aircraft speed from target area to ship after off-loading passengers (in knts). Use for computing delivery time random variate based on distance defined and using uniform distribution.
meanHookOffTime[0]	1	1	Meantime for loading up cargo (in mins). Actual loading time is a random varaiate based on uniform distribution.

Table 48. Input Parameters for Experiment #1 (Continued)

Parameters	Value		Remarks
meanHookOffTime[1]	1	1	Meantime for loading up equipment (in mins). Actual loading time is a random varaiate based on uniform distribution.
meanHookOffTime[2]	5	5	Meantime for loading up passengers (in mins). Actual loading time is a random varaiate based on uniform distribution.
meanRefuelTime	5	5	Meantime for refueling (in mins). Actual refuel time is a random varaiate based on uniform distribution.
timeToRepair	60	60	Meantime between failure (in mins). Actual failure time is a random varaiate based on exponential distribution.
timeToFaiure	1200	1200	Meantime to repair (in mins). Actual repair time is a random varaiate based on exponential distribution.

Table 49. Input Parameters for Experiment #1 (Continued)

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