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**NAVAL
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MONTEREY, CALIFORNIA

THESIS

**NETWORKED LOGISTICS: TURNING THE IRON
MOUNTAIN INTO AN IRON NETWORK**

by

Gregory E. Lynch

June 2019

Thesis Advisor:

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Second Reader:

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**NETWORKED LOGISTICS: TURNING THE IRON MOUNTAIN INTO AN
IRON NETWORK**

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Major, United States Marine Corps
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

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ABSTRACT

The current Marine Corps logistics structure distributes resources from a central point commonly known as the “Iron Mountain” to combat units throughout the battlespace. The Iron Mountain presents a substantial target for adversaries with precision-guided weapons or large-scale attack capabilities. This study explores the effects of replacing the Iron Mountain with a distributed network of mobile logistics support nodes. This “Iron Network” creates a smaller unpredictable target that is harder to locate while still providing logistics support to combat units.

We create a simulation model to explore the factors affecting the resupply capabilities of an Iron Network and Iron Mountain in terms of time for service, unfulfilled requests, and resource requirements. The major findings of the modeling and simulation analysis indicate that this Iron Network structure is possible, but it requires some specific enablers. Asset and supply level visibility across the network are critical for success, as is responsive global logistical support. The best response times occur when vehicle utilization remains below 40%. Given enough vehicles and an accurate picture of the network’s resources, the Iron Network proves to be 79% faster than the Iron Mountain, while using 22% less vehicles and associated fuel and leaving 94% fewer requests unfulfilled.

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LIST OF ACRONYMS AND ABBREVIATIONS

CSS	Combat Service Support
CSSA	Combat Service Support Area
DOE	Design of Experiment
DES	Discrete Event Simulation
E2O	Expeditionary Energy Office
FARP	Forward Arming and Refueling Point
HIMARS	High Mobility Artillery Rocket System
LCE	Logistics Combat Element
LV	Logistics Vehicle
LVSR	Logistics Vehicle System Replacement
MAGTF	Marine Air-Ground Task Force
MOC	Marine Corps Operating Concept
MRE	Meal Ready to Eat
MOE	Measures of Effectiveness
NOLH	Nearly Orthogonal Latin Hypercube

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DISCLAIMER

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

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EXECUTIVE SUMMARY

The Marine Corps Logistics system is structured around a central location where supplies are housed in preparation for distribution to units conducting combat operations. This stockpile of resources is commonly referred to as the Iron Mountain. The adversaries of the United States have more capability today than ever before to threaten the Iron Mountain or make these bases incapable of distributing supplies. This study proposes an alternative structure that takes the resources and capabilities of the Iron Mountain and distributes them across the battlespace in a network of smaller logistical support nodes. This “Iron Network” is meant to leverage nodes that provide resources and then move to new locations in order to decrease predictability, thereby increasing survivability while also improving service efficiency.

This study uses computer simulation and a designed experiment to explore a wide range of possible scenarios. The designed experiment varies 13 factors using a 1025 design point nearly orthogonal Latin hypercube (NOLH) with 20 replications at each point to explore the range of variability. The data was analyzed to determine the key factors leading to the success of this proposed logistics network.

The simulation models two Infantry Companies, a Forward Arming and Refueling Point (FARP), and a missile site as the combat units that receive supply support from three logistics nodes. The logistics nodes vary in size and continually change location after completing a designated number of deliveries. The current system of logistical support uses convoys of multiple vehicles to deliver supplies because this grouping provides increased security and greater capacity to distribute supplies, but this networked system transports supplies with individual vehicle movements. This distributed logistics concept uses the fact that the starting location, the destination, and the frequency of the logistics movements are constantly changing so they derive security by being less predictable and harder for an adversary to target.

This highly dynamic system provides supplies from a wide range of locations, which also means that the Infantry Companies, the FARP, and the missile site do not

always receive their logistical support from the same entity. The closest logistics node with sufficient supplies at the time the request for support is initiated is assigned to provide supplies.

A critical enabling feature for this system is the visibility of assets around the battlefield. Lack of total awareness of resource locations in the current system is not a positive, but it is overcome by always providing resources from a central location. There is no requirement to search for a unit possessing the required items. In a distributed network, it is essential to have full asset visibility because inventory levels and the location of a logistics node determine which entity provides the desired supplies. This cannot be effectively accomplished without total awareness of the location of resources. The assignment of requests to a supporting unit becomes cumbersome and slow without an efficient means of tracking resources, which delays the process of distributing resources to the units that need them. An electronic system that can take, receive, and transmit the constant changes in inventory levels at each logistics node is essential to running a distributed network.

Asset visibility is a requirement but it does not guarantee high levels of support. The distributed logistics model contains many different factors that potentially impact the functionality of a distributed network. They include the frequency of each individual unit requiring supplies, the speed to load and unload vehicles, the possibility of enemy attacks, the possibility of a maintenance issue, the frequency in which the logistics nodes receive external support, how long the logistics node will wait before a partially loaded vehicle to depart, and the number of vehicles utilized by each individual logistics node. These factors are varied to assess how they impact the model performance.

The single biggest factor impacting the speed of delivery and the backlog of requests in the system is the number of vehicles. The distributed network in this scenario needs a minimum of 13 vehicles at each logistics node. If the requests for support from the combat units lead to a backlog of supplies, then the number of vehicles should be adjusted to address the backlog of requests. This will help to keep the network from becoming dangerously stressed and the number of delivery requests from becoming too high. Increasing the number of vehicles also equates to adding personnel to operate the vehicles.

Without planning for the appropriate number of personnel then the number of vehicles is irrelevant.

The distributed logistics model performs best with 13 or more vehicles; 39 or more vehicles spread throughout the designated region. For comparison purposes, a variant of the model simulates a centralized logistical structure (or Iron Mountain) using convoys of 10 vehicles. In this convoy structure model, a minimum of 5 convoys consisting of 50 vehicles is necessary to achieve acceptable performance. The distributed model requires fewer vehicles because it possesses the ability to provide resources to a wide range of locations simultaneously. This is an advantage for the distributed logistics model and leads to a smaller vehicle requirement overall. The results of the experiment follow.

- Asset tracking is critical for the success of a distributed network. All logistics units and the organization that assigns responsibilities must know exactly how many supplies are possessed internally and among their adjacent units. This is critical because the combat units receiving supplies will not always receive support from the same entity. Without an efficient system for tracking supplies and quickly transmitting updates to all relevant parties, this system breaks down.
- The number of functional vehicles is the most important factor in determining the delivery speed and the number of requests that are backed up awaiting delivery. In this simulation, the experiments where the logistics nodes possess 13 or more vehicles indicate the highest likelihood of a rapid delivery and small quantity of requests pending delivery.
- The utilization of the logistics vehicles needs to be at approximately 40%. The common wisdom is that assets should be utilized as close to 100% as possible. This simulation indicates that for experiments where the utilization is above 40%, there is a high likelihood of backlog and slow delivery times. The logistics nodes should maintain sufficient functional vehicles to keep the utilization around 40%.

- The distributed logistics simulation is also compared to a simulation of the current structure of logical support. The current system struggles in an environment where the demands are highly variable, and it experiences substantial delays in distributing supplies and when there are lots of pending requests. The distributed network is able to provide resources faster to a wider range of locations simultaneously.
- To be effective at dynamically providing resources to a wide range of locations simultaneously, a distributed network requires an equally responsive network supporting it. Adjusting the most tactical edge of the logistics chain is insufficient for success. The entire logistics chain must be adapted in order to create a distributed tactical network.

The distributed logistics model in this research only uses ground vehicles for the distribution of supplies from the mobile logistics node to the combat units. The Marine Corps possesses many additional assets for the distribution of supplies, which should be incorporated into the model. A detailed look at the maintenance implications of smaller logistics nodes will greatly aid in evaluating the effectiveness of a distributed network. The use of data farming and simulation is a perfect place to begin studying how the use of unmanned systems and additive manufacturing can improve distribution of supplies.

The adversaries of the United States and technological advancements are changing in future conflicts. Logistical support also needs to change. The Marine Corps needs to find an alternative to the Iron Mountain, and move toward an Iron Network system that is more resilient to enemy attacks while still providing timely and responsive support.

I. INTRODUCTION

The term “Iron Mountain” is used frequently when referring to large-scale military operations. It refers to a location where bulk quantities of resources are stockpiled in preparation for a military operation. The Iron Mountain is incredibly useful because it provides a wide range of supplies to equip a military organization for the widest range of possible operations. However, it tends to be large and immobile which makes it a tremendously enticing target for an adversary. The resources contained in this stockpile are critical to the survival of a military force and directly contribute to the successful accomplishment of their mission. An adversary capable of destroying these supplies or significantly deteriorating the ability to distribute these supplies can bring any military force to an immediate halt. During the wars in Iraq and Afghanistan, the insurgent forces did not possess the capability to conduct an attack on the Iron Mountain. As the United States transitioned to preparations for a near-peer adversary, it has been confronted with a force that does possess the capability to destroy these stockpiles of supplies. This leads to the question: how should a military force position its resources in a manner that is responsive to the demands of combat formations and less vulnerable to enemy attacks?

This study attempts to provide one possible answer to this question. The concept takes the single large stockpile of supplies and spreads it throughout a designated region in a series of smaller mobile logistics nodes. These nodes carry smaller quantities of supplies and are meant to represent targets that are harder to track because they frequently change locations. The smaller nodes conduct smaller movements that do not have the same starting or ending point. These are quick movements where the speed and mobility are the key element of survival rather than presenting a strong defensive posture. The goal is to create a system that is resilient and less susceptible to destruction by a near-peer adversary.

A. MARINE CORPS LOGISTICS

Every unit in the Marine Corps has logistical support personnel. However, the logistics combat element (LCE) is the specific unit within the Marine Air-Ground Task

Force (MAGTF) tasked with providing logistical support. MAGTF units vary in sizes, but their typical structure is depicted in Figure 1.

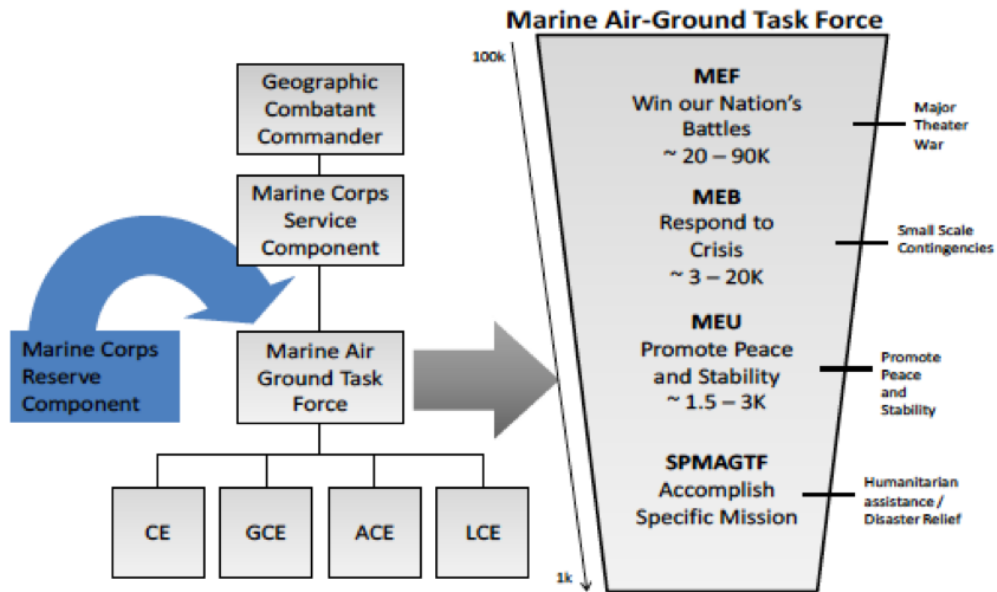


Figure 1. Marine Air-Ground Task Force Command Structure. Source: United States Marine Corps [USMC] (2016b).

The LCE performs the function known as Combat Service Support (CSS) which is the actual activity providing services to a combat formation (USMC MCDP 4 1997a). This encompasses services consisting of Supply, Maintenance, Transportation, General Engineering, Health Services, and General Services. The key functions for this study are the Supply and Transportation functions of logistics which drive how the combat units are provided supplies throughout the course of an operation.

Currently, the entire concept of how the LCE stores and transports logistical supplies is based on establishing a fixed base where sustainment is built up in order to support an operation (USMC MCTP 3-40B 2016b). These fixed or semi-fixed bases are used as a starting point to distribute supplies. This fixed base is commonly known as a Combat Service Support Area (CSSA) which is defined as “the primary combat service support installation established to support MAGTF operations ashore. Normally located

near beach, port, and/or and airfield, it usually contains the command post of the logistics combat element commander and supports other combat service support installations” (USMC 2016b). From the CSSA, logistics support is moved through a variety of different methods to the units conducting the overall mission.

The process for distributing supplies throughout an area of operation generally follows the process outlined in Figure 2.

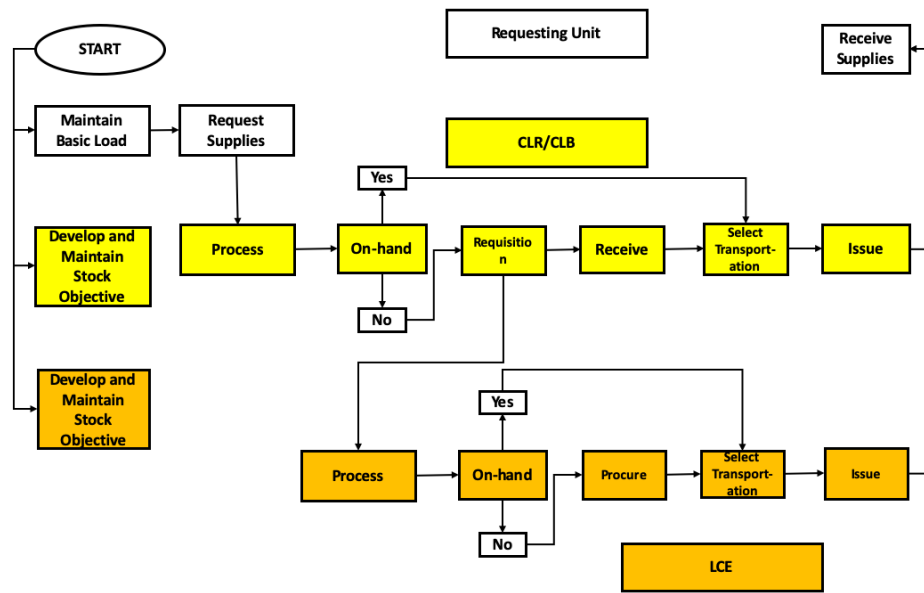


Figure 2. Supply Support during Operations Ashore. Source: USMC (2016b)

Each combat unit will maintain a “Basic Load” of supplies which contains the resources needed to accomplish a specific mission (USMC 2016b). These supplies will sustain them for a period of a few days but will not be enough to support them for a long period of time. The internal logistics support section of a combat unit possesses some capacity for storing supplies and will develop objectives based on their requirements for each type of supply item that they wish to maintain on hand to support the basic load of that unit (USMC 2016b).

When the resources of the combat unit go below the stock objective, they request additional supplies from the LCE unit supporting them. This supporting LCE unit is generally not co-located with the combat unit but is typically at a CSSA in a less dangerous environment. When the LCE receives a request for supplies, they determine if they have the required items. If the items are on hand, they are pulled from the storage and prepared for issue to the combat unit. While this is happening, the LCE unit also determines the most effective means of transporting the requested supplies to the combat unit. Once the LCE prepares the item for issue, they load it on the mode of transportation and deliver it to the combat unit who initiated the request (USMC 2016b).

In the event that the LCE unit does not have a requested item, they will need to submit a request to the LCE unit providing their support in the next higher echelon of the chain of command. This higher level of command will follow a similar process of checking their inventory to see if the requested item is available. If it is not available, this higher-level unit might go through the process of procurement with manufacturers or continue to route the request to the next level of their chain of command. Once the item is available, it can be delivered to the lower echelon LCE unit for distribution to the combat unit; in the case that the item is urgently needed, it might be delivered directly to the combat unit (USMC 2016b).

When transporting supplies, the LCE will use the distribution means that is most effective for the rapid distribution of supplies. This means the LCE can use roads, railways, waterways, pipelines, or the airways to send the requested supplies. However, when operations have moved ashore from the sea and a CSSA is established, supplies are generally moved on roadways or by air using assets that are organic to the MAGTF.

B. DESCRIPTION OF THE PROBLEM

The process currently used by the Marine Corps and throughout the military has proven to be effective across many different operations and campaigns throughout history. The success of this system has been due to the fact that removing logistical support areas, even by a few miles, provided a relatively high level of security. It was difficult for an adversary to move a force large enough to destroy a CSSA to the logistical support areas

without being noticed and intercepted. The United States maintained air superiority in all of the conflicts they fought in the twenty-first century, meaning that threats from air attack were non-existent which further increased the level of security at the CSSA.

The current environment has changed significantly. The Marine Corps Operating Concept (MOC) states, “The Marine Corps is currently not organized, trained, and equipped to meet the demands of a future operating environment characterized by complex terrain, technology proliferation, information warfare, the need to shield and exploit signatures, and an increasingly non-permissive maritime domain” (USMC 2016a). The current adversaries of the United States have equivalent or nearly equivalent capabilities to the United States. This means that the safety of logistical support areas is significantly threatened due to long-range bombers, artillery with increasing lethal ranges, and guided missiles capable of destroying or rendering logistical support areas incapable of performing their function of supporting combat units.

The movement of large quantities of logistical supplies is not instantaneous, so there must be some type of prepositioning of supplies to support combat units; however, the stockpiling of supplies in a semi-fixed location presents a significant target for an adversary. The current adversaries of the United States possess the capability to threaten any CSSA in a fixed location. This means that the military needs a new structure for the housing and distribution of supplies. Technological advancements alone will not solve the logistical problem. A structure is needed which can avoid enemy attacks while still logistical support for formations engaged with the enemy.

C. LITERATURE REVIEW

The MOC outlines a future operating environment that is characterized by highly dynamic forces seeking to quickly maneuver and seek an advantage against an adversary. In this structure, the goal is to avoid linear structures that can be anticipated and exploited. It goes on to say that Marines must “[redesign] our logistics to support distributable forces across a dynamic and fully contested battlespace—because Iron Mountains of supply and lakes of liquid fuels are liabilities and not supportive of maneuver warfare” (USMC 2016a). This research seeks to present and explore a more dynamic structure of logistics that

enhances maneuverability of combat formations and becomes less vulnerable to exploitation of an adversary.

In his article titled “Rethinking Logistics” LtCol Kirk Spangenberg describes many of the problems facing Marine Corps Logistics. A core issue discussed in this article is the trust in the logistics structure (Spangenberg 2017). Operational units want to be prepared for all contingencies so they bring every possible piece of equipment or resource to accomplish a range of missions because they believe the logistics system will not get them the resources they need at the time they need it. This slows down combat units, but the major problem is they do not trust the logistics system to provide them with required resources. In order to counter this perception, the logistical support structure needs to be responsive enough to respond to planned and unplanned needs of the units they support. Spangenberg (2017) mentions several issues and questions whether Artificial Intelligence (AI) or predictive analytics can replace the current focus on ground transportation but does not clearly describe how these technologies replace the methods. Furthermore, he does not describe a new structure of logistics units or describe how they might be used in a new manner. AI and predictive analytics are certainly capable of enhancing logistics, but they do not provide a solution in themselves. The Marines Corps needs to organize their logistics personnel into units that are versatile and more dynamic in nature, and then incorporate these emerging technologies to support these units. These smaller more versatile units are able to quickly adapt to and create a network that is resilient by being unpredictable.

The Navy has studied the problem of a linear logistics structure on a larger scale in an effort to increase their resiliency to adversary attacks. The key issues discussed in the Navy’s study on swarming logistics are enhancing the connectivity between ships and compiling the different resources required by the various naval platforms (Griffin 2018). The report indicates that the reliance on a few key ports where supplies are warehoused increases the vulnerability of the whole network. A decreased reliance on these specific overseas ports leads to an increased need for the connectivity between ships at sea. Without ports to house large stockpiles of supplies, the Navy needs a large number of ships to distribute supplies at sea. These naval ships need to carry a range of supplies in order to support any naval vessel needing supplies. No ship will ever be able to carry every possible

supply required, but supplies can be consolidated in an effort to support the widest possible range of units (Griffin 2018). The Marine Corps problem is related, but not quite the same. Marine Corps ground units possess a high level of interoperability in their platforms and their requirements. The bulk of the supplies required for expeditionary forces are interoperable, and the transfer of supplies can be accomplished with minimal change in the equipment currently used by the Marine Corps.

Any type of logistics network that is distributed in a nonlinear fashion must have distributed control. This is defined as, “There is no single centralized control that governs the holistic naval logistics behavior” (Griffin 2018). Individual logistics commanders must be able to make decisions relevant to their role in the network. This fits very well with the Marine Corps doctrine for the employment of their forces. The Marine Corps defines their philosophy of command by saying,

First and foremost, in order to generate the tempo of operations we desire and to best cope with the uncertainty, disorder, and fluidity of combat, command and control must be decentralized. That is, subordinate commanders must make decisions on their own initiative, based on their understanding of their senior’s intent, rather than passing information up the chain of command and waiting for the decision to be passed down. (USMC 1997b)

Logistics elements have traditionally had the ability to maneuver while in the process of delivering supplies, but not the freedom to adapt their portion of the logistics network while providing sustainment. A change to this dynamic increases the complexity of the network, while providing a level of unpredictability that may make them harder to locate and target by an adversary.

D. THESIS OVERVIEW

The purpose of this study is to propose and model an alternate method of providing logistics sustainment for expeditionary forces. The process of taking supplies from a logistics support unit and transferring them to a combat unit is unchanged. However, in this thesis the Iron Mountain of supplies is distributed to a series of smaller logistical support nodes that frequently move locations throughout the battlefield—transforming the Iron Mountain to an Iron Network. The approach is to model the logistics forces operating

in this manner via simulation, and then to study the simulation model's performance to determine how this system functions compared with an Iron Mountain in the same scenario, whether it is sustainable for a reasonable period of time, and whether it provides some level of resilience to enemy attacks. The Marine Corps Logistics doctrine says, "In times of crisis, when circumstances are changing rapidly and swift adaptation is required, logistics organizations are likely to function in nonstandard ways. Periods in which the system operates in a regular and orderly fashion will alternate with periods in which it is in considerable turmoil" (USMC 1997a). The goal of this thesis is to propose a distributed logistics structure that can provide a level of sustainment equal to or higher than that of current methods, while making the logistics support more resilient to an adversary with equivalent capabilities.

II. BACKGROUND AND METHODOLOGY

This chapter describes a discrete event simulation and provides the background on the Marine Corps units, their sizes and requirements, and the types of supplies used in the Iron Network model. This simulation model is based on that model created for a Naval Postgraduate School thesis studying logistical support utilizing unmanned surface vessels for the Navy (Lin 2018).

A. DISCRETE EVENT SIMULATION

A Discrete Event Simulation (DES) is a modeling system where events take place and then the overall system changes in response to events (Nance 1981, p. 173). A detailed description of DES can be obtained in Law (2015). DES models are generally represented by event graphs. These are pictorial representation of the DES models that show the logic behind how the model functions (Buss 2001). An event graph consists of four key parts:

1. **Parameters:** these are the fixed elements of the model that do not change regardless of the state (Buss 2004).
2. **State Variables:** every state variable “is an element that changes, or at least has the possibility of changing, in the course of a single simulation replication” (Buss 2004).
3. **Events:** the points at which the state of the overall system changes. The events can impact multiple state variables and result in an immediate change to the system. Time does not pass during the event; it only passes between the various events (Buss 2001).
4. **Scheduling Edges:** each edge provides the logic that allows the model to change from one state to another after a designated time delay. (Buss 2004)

B. MODEL CLASSES

This particular DES is built in the programming language Ruby (Matsumoto 2018). Ruby is an object-oriented programming language which means there are a series of entities created, each with different functionality, which will perform actions based on the specific attributes given to the object. The term “class” defines each object and there are several classes used in this model:

- **Location:** this object defines the x and y coordinates of any entity and also computes the distance and bearing to another entity.
- **LOG_NODE:** the logistics node is the entity that provides resupply to the combat units they are supporting. The object can hold a specified number of each type of supply, a specified number of vehicles it can utilize, and a number of resupply deliveries that it provides before it needs to move to a new location. Each logistics node possesses a move number which is a randomly generated number to determine when the logistics node will initiate a move. Each logistics node possesses an attribute that is either true or false to indicate whether the node is in the process of moving. Finally, it possesses a rendezvous location. This is the location where the logistics node will send their vehicles to pick up supplies when they require support. This location changes every time the logistics node moves.
- **LV:** the LV stands for logistics vehicle. A specific type of vehicle has not been defined by this model, but the cargo space for each LV is based on that of the Logistics Vehicle System Replacement (LVSR). Each LV has a specified amount of cargo it can carry, fuel consumption rates while moving and while idle, and the ability to move from one location to another in order to deliver supplies. Additionally, each vehicle possesses a listing to track which requests have been assigned to it to deliver. This listing resets every time the LV completes a movement.

- **Supply_item:** The supply item is the type of item that can be requested by the combat units in the model. Each supply item come with a specific size that corresponds to the amount of space the supply item uses when loaded on the back of a truck.
- **SUP_UNIT:** this is the supported unit or combat unit which will require supplies. The model is does not look into their activities. For the purpose of this model, their function is to consume supplies at a rate based on the unit type. Each unit consumes supplies based on their size but there is variation in the rates of consumption depending on the particular design point.
- **Request:** this is a request for supplies. This object has attributes that specify the type of supply being requested, the quantity, the rendezvous location, and which logistics node is assigned to provide the supplies. Both the supported units and the logistics nodes request supplies.
- **Distributed_log_model:** this is the model that employs the objects within the simulation. The details of the model are covered in the Chapter III.

C. MODEL PARAMETERS

The simulation is designed to represent vehicles, units, and supplies as accurately as possible. The details of how each class and parameter functions are based on Marine Corps publications to reflect their real-life functionality.

1. Supply Items

Each type of supply is individually a different size. In an effort to make a common unit for each type of supply, the amount of space they utilize when loaded on a vehicle is used as a common reference for all types of supply. The bed space on the logistics vehicle is based on the 20-foot bed of the LVSR which can hold approximately 8 pallets of cargo. The pallet space is the common reference for each type of supply. When units order supplies, they get them in pallet loads.

a. Meals Ready to Eat

Meals Ready to Eat (MRE) can be loaded and moved on a single pallet. Each pallet contains 576 MREs (MAGTF Staff Training Program Division [MSTPD] 5.0-3). A maximum of 8 pallets of MREs can be loaded on any logistics vehicle. It is assumed that each Marine in this scenario will consume three MREs per day. This frequency of consumption is used in the initial estimate of how many pallets of MREs each unit consumes per day based on the size of the unit.

b. Fuel

Fuel can be moved in a variety of containers. However, this model utilizes the Flatrack Refueling Capability. This item can hold 2500 gallons of fuel and uses 8 pallet spaces on the back of a LVSR (MSTPD 5.0-3). Each type of unit consumes fuel at a different rate, and each vehicle will consume fuel when loading, unloading, and transiting between points.

c. Water

Water can also be moved in a variety of containers or via pallets of bottled water. Pallets of one liter (1L) bottled water are used in this model. Each pallet contains 1080 1L bottles of water. The water consumption rate per Marine varies based on the climate, but in this scenario the sustained rate in a tropical environment is utilized. At this rate, each Marine requires 6.91 gallons of water per day (MSTPD 5.0-3). This value is utilized in determining the number of pallets each unit requires per day.

d. Ammunition

There are many types of ammunition that the units in this scenario would utilize in practice. In the case of this model, the specific types of ammunition are not modeled. It is only modeled that pallets of ammunition, of varying types, are required by each of the supported units.

2. Supported Units

The supported units are the different units that require logistics support from the logistics nodes.

a. Infantry

The infantry units are based on a standard Marine Corps Infantry Rifle Company. The fuel consumption rate of 100 gallons per day was developed through communication with the Expeditionary Energy Office (E2O) and the utilization of the Military Power and Energy Model (Stone 2019). The scenario contains a total of two infantry companies.

b. FARP

A Forward Arming and Refueling Point (FARP) can vary in size depending on what type of aircraft/missions it is supporting. Due to the fact that there is no standard size of a FARP in the Marine Corps, the author utilized personal experience and estimated the largest size is roughly equivalent to the size of the logistics nodes. This means the water and MRE consumption is roughly equivalent to that of a logistics node, but the fuel consumption is substantially different. In this model, FARPs consume a Flatrack Refueling Container every one to three days. This is an estimated consumption rate based on research into the FARP operations from the Expeditionary Energy Office study of Expeditionary Advanced Base Operations Logistics Supportability Zerr (2018). The assumption made for this simulation is that the FARP is conducting operations over a six-month period so the amount of fuel they provide to a section of aircraft will not change but the frequency at which they support aircraft is smaller. This is due to the system attempting to simulate the sustained rate of operations. The scenario contains one FARP.

c. Missile Site

This unit represents a missile site providing shore based anti-ship missiles. Providing shore-based missiles is a relatively new concept for the Marine Corps, so the number of personnel is based on a platoon from the Army High Mobility Artillery Rocket System (HIMARS) Battalion. The size of the missile sites is estimated to be a platoon size so their consumption of MREs and water is the same as the logistics nodes. Their fuel

consumption was developed with the Military Power and Energy Model, and is set to be one Flatrack Refueling Container every three to nine days (Stone 2019). The simulation contains one missile site.

3. Logistics Nodes

There are three logistics nodes in the Iron Network model. The individual Marines are not specifically modeled but they are represented through the use of the trucks. The Marine Corps requires that each truck has a driver and an assistant driver. Since the trucks are conducting movements in a contested environment, they would likely have a third individual who would operate a crew-served weapon. Each truck is meant to represent a requirement of three personnel. The number of trucks possessed by each logistics node is one of the factors varied during the simulation experiment, which means the size of the logistics nodes vary.

The classes and parameters form the foundation for the model. Chapter III will discuss the events and the logic that drives how they interact with one another.

III. SIMULATION MODEL

This chapter provides a detailed description of the Distributed Logistics Model, the assumptions that were made, and the elements used to develop the state variables.

A. MODEL ASSUMPTIONS

All assets have already arrived at the initiation of the simulation. The simulation begins with a series of assets that have arrived in the area where the simulation takes place. The simulation does not seek to look into the debarkation of assets, but only their function after they arrive at their desired location.

Inventory levels are visible to all players in the simulation. The current military logistics systems do not provide perfect awareness of inventory levels of all units. However, the assumption made is that the logistics units have a mechanism for determining the supply status of their adjacent units. This is essential for a network of this nature because the units are small and will inevitably run low on supplies. If one logistics element cannot provide support, then it must pass the request on to another unit who can provide support.

The units providing support to the logistics nodes do not run out of supplies. There exists a larger logistical network that moves resources into the area of this simulation. However, the goal of this study is not to look into this larger network. As a result, this external network provides resources with a certain delay, but will always have resources to provide.

Vehicles are not restricted by terrain. The simulation does not consider road networks or terrain features as a part of the simulation. The vehicles are always able to take the most direct route to their designated destination.

Maintenance events only cause delays. Maintenance is a serious problem for units as they seek to conduct their mission, which is why it is taken into account during this simulation. However, when there is a maintenance issue, it causes a delay but the vehicles will eventually reach their destination after the appropriate delay.

B. MODEL FORMULATION

1. Model Inputs

These are values that are input at the beginning of each simulation and do not change throughout the course of the simulation. They vary across simulation runs based on the design of experiment.

Time between Requests. (Type: Decimal) A triangular distribution is used to determine the time between requests. It requires inputs of the minimum, maximum, and mode. There are four types of units in the scenario each with four types of supplies. The input values for the minimum, maximum, and mode are used to determine the amount of time to receive requests from the Logistics units, Missile sites, FARP, and Infantry units based on their rate of consumption. This is done by applying a multiplier for each type of unit's consumption rate of each type of supply.

Loading Time. (Type: Decimal) This consists of two inputs used in the Gamma distribution. The time to load combines the staging of supplies in preparation for loading, the physical placement of supplies on the cargo bed of a truck, and the process of securing the pallets of supplies with straps and chains. The first input is the mean time to load a vehicle and the second is the shape parameter for the distribution. This defines the shape for the Gamma Distribution. Depending on the shape parameter, the distribution can be either tightly centered around the mean value or have a wider dispersion around the mean.

Offload Time. (Type: Decimal) This consists of two inputs used in the Gamma distribution. The Offload time represents the time to unchain or unstrap pallets on the back of a truck, remove the cargo from the bed of the truck, and prepare for a return movement. The first input is the mean time to unload a vehicle and the second is the shape parameter for the distribution. This defines the shape for the Gamma Distribution. Depending on the shape parameter, the distribution will either be tightly centered around the mean value or have a wider dispersion around the mean.

Enemy Attack Probability. (Type: Decimal) This is probability of an enemy attack occurring during the movement of a vehicle movement.

Enemy Kill Probability. (Type: Decimal) In the event that an enemy attack occurs, this is the probability the attack results in the destruction of the entire vehicle and all cargo being carried.

Maintenance Event Probability. (Type: Decimal) This is the probability of a maintenance incident that will delay the movement of a vehicle to deliver resources.

External Resupply Time. (Type: Integer) This is the amount of time it takes for a logistics node to receive supplies from the logistics network that is outside of this model.

Maximum Wait Time. (Type: Decimal) This is the maximum amount of time a vehicle will wait with a partially loaded vehicle before departing on a trip to distribute supplies.

Number of Logistics Vehicles. (Type: Integer) This is the number of logistics vehicles possessed by each of the logistics nodes.

Halt Time. (Type: Integer) This is the length of time each experiment will be conducted. All of the experiments were set at 180 days.

2. State Variables

The State Variables are the various attributes that change throughout the course of the simulation.

Request. The request is created to signify that a unit needs supplies. Supported units submit requests according to the distribution assigned to a particular supply item, while logistics nodes initiate requests according to their inventory position.

Request.name. A counter assigns a unique identifier for each logistic request created, and this number is assigned to the request so it can be distinguished from other requests.

Request.time. The time the request was created.

Request.requesting_name. The unit who is requesting the supply items.

Request.supply_item. The type of supply item being requested.

Request.quantity. The quantity of the supply item being requested.

Priority.priority. The priority of the request. This is generally the time at which the request is created, so the first request created gets the highest priority.

Request.rdv_location. The rendezvous location for the delivery or pickup of supplies.

Request.assigned_log_node. This is the logistics node that will provide the requested supplies. At the initiation of the request, no logistics node is designated.

Request.assigned_lv. This is the logistics vehicle that will transport the supplies. At the initiation of the request, there is no logistics vehicle designated.

Requests. This is a priority queue of requests from all assets in the simulation. The requests assigned to each individual logistics node are also tracked in a priority queue.

Log_node_requests. This is a priority queue of all logistics resupply requests. The requests assigned to each individual logistics node are also tracked in a priority queue

LV_available. This is a listing of all logistics vehicles available at a particular logistics node.

Moving_LV. This is a listing of all logistics vehicles which are in the process of conducting a movement to or from a destination.

MC. This is the move counter. This counts the number of deliveries a logistics node has made. It is compared to the move check, and when they are equal it initiates the movement of a logistics node to a new location.

3. Model Events

The events of this Iron Network model are depicted visually through the use of an event graph in Figure 3.

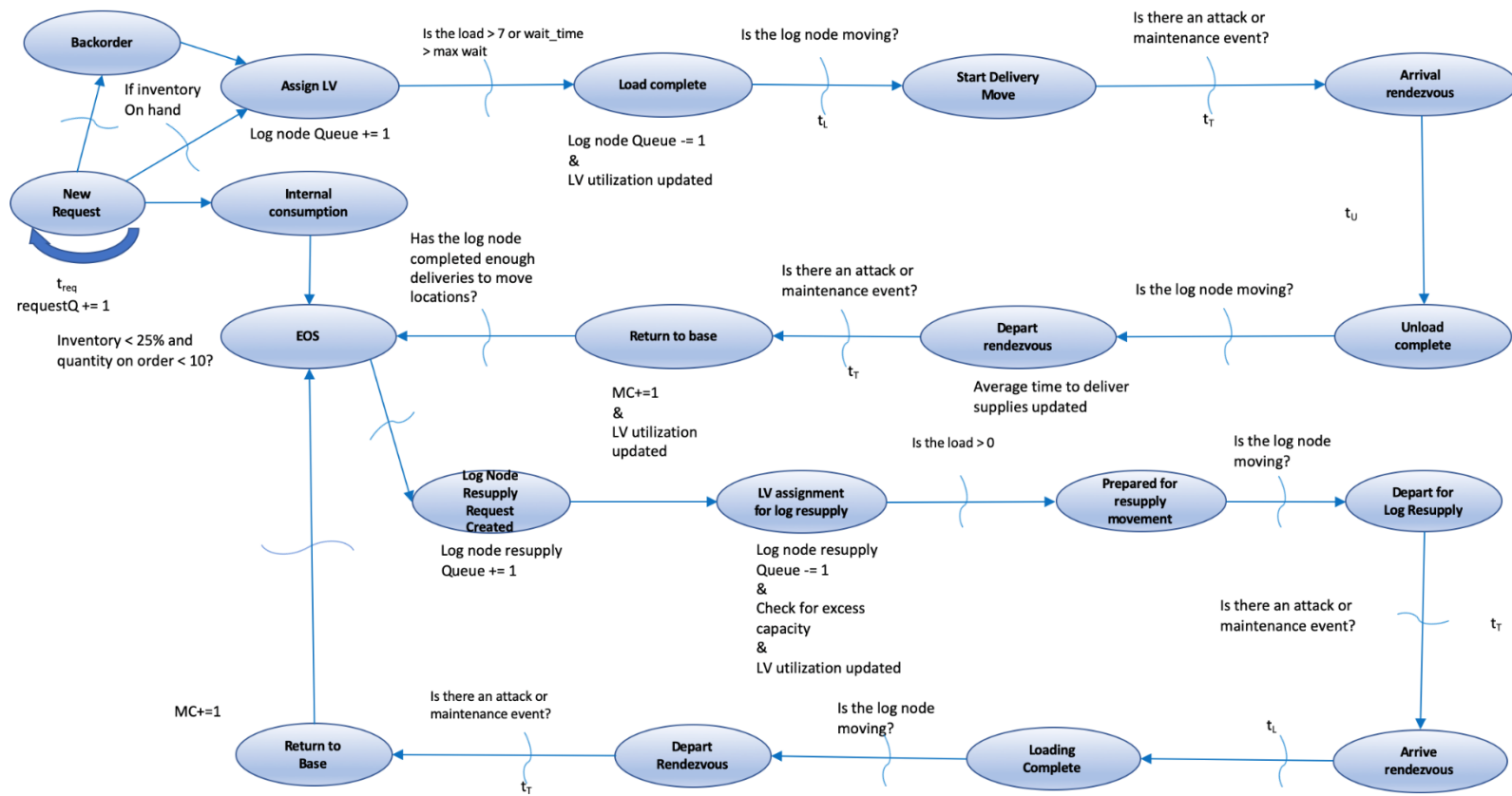


Figure 3. Event Graph for the Distributed Logistics Model

Initialize. During the initialization event (not shown), a series of input parameters are read into the system. After this, the state variables are initialized, and the inputs are used to determine the distributions for the various types of supply items required by each unit. Following this, the supply items and the capacities for each logistics node throughout the model are set. The input parameters are again used to determine the order quantities. Once the order quantities are set, the initial requests are scheduled as well as the first external resupply to the logistics nodes. These vary based on the input parameters. Finally, the time to halt the simulation is scheduled based on the final input.

New Request. The new request event requires two pieces of information to begin: the supply item requested and the unit requesting support. There are several optional parameters that can be specified such as the request identifier, the quantity requested, the rendezvous location, and the time the request was created. If these items are not specified, then they are automatically placed at the default levels. Requests are initiated and then put into the request queue. The next request is scheduled based on the distribution unique to that particular unit and supply item. The event then goes on to identify which logistics node will be tasked with providing the requested supplies. The consumption of resources by a logistics node is tracked in the same way that consumption of resources is tracked by the other units. When it is determined that the request comes from one of the logistics nodes, the internal consumption event is scheduled for that request and it is removed from the request queue.

If the request is not initiated by a logistics node, then the process for selecting which unit will provide support initiates. The program cycles through each logistics node, skipping the ones that are in the process of moving to a new location as well as any nodes that do not have enough inventory for the request, and then determines which, of the remaining logistics nodes, has the closest proximity to the requesting unit. If all of those checks are passed, then a logistics node is assigned, the inventory is subtracted from the total inventory at that logistics node, and the request is put into the request queue for that logistics node. The inventory is subtracted from the total in this event as a representation of those supplies being set aside in preparation for movement.

If no logistics node is assigned after these checks, then the closest of all the logistics nodes is assigned and a backorder event is scheduled for the time when the logistics node is scheduled to receive their next set of supplies.

Internal Consumption. This event is meant to account for the consumption of resources by the logistics node. When this event occurs, the quantity of supplies for the request is subtracted from the total inventory at that logistics node, and then an End of Service event is scheduled.

Backorder. This event accounts for the instance that no logistics node has the requisite supplies to support a request. An item is placed on backorder and a delay is initiated until the time when the logistics node receives their next resupply. At this point, the inventory is drawn and the request is put in the queue of the assigned logistics node. At the conclusion, the event to assign a logistics vehicle is scheduled.

Lv_assignment. The assigned logistics node is given as an input for this event. A request is pulled from the appropriate queue and then the model begins cycling through the logistics vehicles available for the logistics node. It first checks to see if there is a vehicle currently assigned to deliver supplies to the same location as the current request and if it has cargo space for the new request. If it does, the request is then assigned to the logistics vehicle with the desired destination. If there is no vehicle going to the requested location, then the first vehicle with no destination is selected. The request is assigned to that vehicle. The request is then removed from the queue.

Following this, a check is conducted on the requests loaded on the selected logistics vehicle. The request that has been loaded and waiting the longest is selected and assigned a temporary variable name of `time_check`. The criteria for the departure of the vehicle is whether the vehicle is full or if the time check is longer than the maximum wait time. The maximum wait time is an input variable. Once these criteria have been met, the load complete event is scheduled with a delay based on the distribution titled ‘onload service distribution.’ This is meant to simulate the time it takes to load the vehicle. This time is also added to the idle time counter which will be used to calculate the fuel consumption at the end of the vehicle’s trip to deliver supplies.

Load Complete. The logistics nodes move periodically so the ‘load complete’ event first checks to see if the logistics node is moving. If the logistics node is moving, then it will schedule the start move event for when the logistics node has completed moving to a new location. If not, then the start move event is immediately scheduled.

Start Delivery Move. All of the movement events follow the same logic to simulate enemy attacks and maintenance incidents. There are three input variables that are used in the movement events. First is the enemy attack variable. This is a number that represents the probability of an enemy attack occurring during this particular movement. Second is the enemy kill variable, which is the probability of the enemy destroying the vehicle during the movement. Third is the probability of a maintenance issue during the movement.

A random number is generated and it is compared to the enemy attack probability. If the random number is greater than one minus the attack probability, then there will be an interaction with the enemy. At this point, a second random number is generated and then checked to see if it is greater than one minus the probability of an enemy kill. If the number is greater than the probability of an enemy kill, the vehicle is completely destroyed. Each of the supplies loaded on the destroyed vehicle are scheduled for a new request and the replacement vehicle event is scheduled to simulate the time where the logistics node is awaiting a replacement for the destroyed vehicle. The delay is ten days before a new vehicle arrives to replace the destroyed vehicle. If the vehicle is not destroyed then an enemy action does occur but it does not prevent the vehicle from reaching its destination. The enemy action itself is not specifically modeled, but is accounted for by a delay to the vehicle reaching its destination.

If the original random number is less than the enemy attack number but greater than one minus the maintenance number, then a maintenance event occurs. The maintenance incident is a delay that slows down the progress of the vehicle proceeding to its destination. If neither the enemy action nor the maintenance incident occurs, the vehicle proceeds to its destination with no delay. The transit time is calculated based on the location of the vehicle, the location of its destination, and the speed of the vehicle. The arrival rendezvous event is scheduled with a delay of the transit time plus any delays from an interaction with the

enemy or maintenance. The transit time and any delays are added to the logistics vehicle moving time which is later used to calculate the fuel consumption by the vehicle.

Replacement Vehicle. This event is very simple and adds a replacement for the destroyed vehicle into the available vehicles.

Arrival rendezvous. The arrival rendezvous event is when the vehicle arrives at its destination. The time to unload the vehicle is determined based on the offload service distribution. This time is added to the vehicles idle time counter and then this offloading time is used as the delay in scheduling the unloading complete event.

Unloading Complete. In the unloading complete event, the first check is to see if the vehicle's logistics node is moving. If it is not, then the depart rendezvous event is scheduled immediately. If the base is moving, the time the logistics node will arrive at its new location is determined, the logistics vehicle's destination is changed to the new logistics node location, and the depart rendezvous is scheduled for the time when the logistics node arrives at its new location.

Depart Rendezvous. In this event, the delivery of supplies is complete so the counter for the number of deliveries is increased by one and the time from the initiation of the request to its delivery is determined for each request that is associated with the vehicle. Then the same logic as in the Start Delivery Move event is used to determine if there is an enemy attack or maintenance event.

Return to Base. When the vehicle has arrived back at its assigned logistics node, the fuel consumption is determined based on the times the vehicle spent idling and moving. The fuel consumption is totaled and then subtracted from the logistics node's fuel inventory. If there is insufficient fuel at the logistics node, then the vehicle is not put back in service until there is fuel on hand. The move counter is increased by one and the logistics vehicle's cargo, idle time, moving time, rendezvous location, and destination are reset in preparation for the next movement. At the end of this event, it is checked to see if the logistics node has made the required number of deliveries to warrant moving the logistics node. If this is true, the Move Log Node event is scheduled. If it is not, the End of Service

event is scheduled. A delay of eight hours is used before the end of service event so simulate the break time for crew operating the vehicles.

End of Service. The end of service happens at the end of a log node movement, a regular resupply movement, a log node resupply movement, and an internal consumption event. The inventory of supplies is checked first. The logistics nodes receive regular resupplies, but if their inventory is getting critically low, there is a check to see if they need to send their own vehicles for a logistics node resupply. The criteria for the logistics node to send its own vehicles to pick up supplies is when the inventory at the logistics node is less than 25% and the quantity of inventory currently in the process of being picked up for the logistics node is low. If this is the case, then a log node resupply event is scheduled.

After the inventory check is complete, there is a check to see if there are pending requests waiting in the log node queue. If there is a backlog of requests, then the LV assignment is scheduled. Additionally, a check is conducted on all of the vehicles that are available for the logistics node. If any vehicles have a full cargo load or have passed the maximum wait time, then the vehicles are scheduled to depart. In this instance, there is a check to see if the movement being conducted is to deliver supplies to a supported unit or to resupply the logistics node. This is done because the type of movement will change the type of event being scheduled: it will be a “load complete event” for a movement for a supported unit or a ‘load log complete’ for a log node resupply event. The delay for both is the onload time.

External Log Support. This event is used to simulate logistics support coming to the logistics nodes from their higher headquarters. The specific details of the units supporting the logistics nodes is not modeled in this simulation, but this event shows that this support does take place in the scenario. This event takes three inputs: the log node receiving the supplies, the supply item, and the quantity. First, the event determines which type of supply item is arriving and adds that quantity to the logistics node inventory. Then, it determines the time to the next resupply based on the input of the resupply time. It then checks to see the current status of that supply item. If the supply status is above 80% of its maximum capacity, then the next external log support event is scheduled but with the quantity requested of zero. The quantity is set to zero to indicate that the logistics node

does not require external support but schedules a time to check again on their supply status. If the logistics node inventory is less than 80% and greater than 70%, then the next external resupply is scheduled for double the standard delivery time for the quantity of the current inventory subtracted from the maximum capacity for that supply item. If the inventory is less than 70%, then the next external support is scheduled for the standard resupply time at the quantity of the current inventory minus the maximum capacity for that supply item.

Log Node Resupply Request. When a logistics node resupply request is initiated, the request is created with inputs of the logistics node requiring support, the supply item, the quantity, and the rendezvous location. The request is then added to the queue for the appropriate node. Then the logistics node resupply logistics vehicle assignment is scheduled.

Log Resupply LV Assign. This event takes the input of the logistics node that needs the supplies. It then pulls first request out of that node's logistics resupply queue. It first checks to see if there is a vehicle with enough space already going to the rendezvous location of that request. If this is the case, then the logistics vehicle already designated for that particular rendezvous location is assigned and the request is removed from the queue.

If no vehicle is going to the desired location, then the first vehicle with no destination is selected and assigned. A key difference between the process for the logistics node resupply and the deliveries for the supported units is that the logistics node resupply requests tend to be larger than the requests for the supported units. In the event that the request is for a quantity greater than one truck's capacity, the truck is loaded to full capacity and the remaining quantity is put into a new request which will be assigned to a different vehicle. Due to the size of the logistics node requests, the vehicles are scheduled for departure as soon as they are loaded. This is accomplished by scheduling the Load Log Complete event. This happens with no delay because the vehicles are departing empty to pick up supplies.

Load Log Complete. In this event, it is determined whether or not the logistics node is moving. If it is moving, the vehicle is scheduled for departure after the logistics node arrives at its new location. If not, then it departs immediately.

Depart for Log Resup. This event is the movement to the rendezvous point for the purpose of picking up supplies. It follows the same logic as the other movements by determining whether there is an enemy attack or maintenance event. If there are delays, then they are added to the movement time. If the vehicle is not destroyed, the arrival rendezvous log resupply event is scheduled with the movement time and any delays added to it.

Arrival Rdv Log Resup. In this event, the logistics vehicle has arrived at its rendezvous point and then the vehicle is loaded with the requested supplies. The loading time is determined from the onloading distribution. This is then used as the delay in scheduling the load log rendezvous event.

Load Log Rdv. The loading of the vehicle has been completed at this point and the vehicle is preparing to return to its home base. It checks to see whether or not the logistics node is moving. If it is, the destination is updated and the vehicle is delayed until the logistics node is done moving. If the logistics node is not moving, then the vehicle starts the return movement immediately.

Depart Log Resup. In this event, the vehicle departs for its home base. It follows the same logic as the other movements by determining whether there is an enemy attack or maintenance event. If there are delays then they are added to the movement time. If the vehicle is not destroyed, the return log resupply event is scheduled with the movement time and any delays added to it.

Return Log Resup. In this event, the vehicle returns to its home base. The fuel consumed during its movement is calculated from the idle time and moving time and then subtracted from the logistics node's inventory of fuel. The supplies delivered by the vehicle are added to the logistics node's inventory, and the counter tracking the quantity of supplies currently on order is decremented. The vehicle's cargo, idle time, moving time, rendezvous location, and destination are reset to be nothing or zero. At this point, a check is conducted to see if the logistics node has conducted the appropriate number of deliveries to warrant moving to a new location. If that is true then the logistics node will schedule the Move Log

Node event with no delay; if not, then it will schedule an End of Service event with a delay to simulate the crew rest time.

Move Log Node. In this event, the logistics node has reached the number of logistics movements to warrant a change in location. The first thing that happens is that the logistics node is set to a moving status. This will prevent any logistics vehicle from starting their movement until the move is complete. The new location is determined by generating two random numbers in the appropriate x and y coordinate range. A move time is determined which is meant to simulate the time it takes the logistics node to pack its things up and prepare for their movement. Then the time to transit to their new location is determined. The move time and the time to transit are added together and they serve as the delay until the End Log Move event is scheduled.

End Log Move. The logistics node has arrived at its new location and the logistics node is removed from a moving status. The quantity of fuel utilized to move from the old location to the new location is calculated for one vehicle. The number of vehicles at the logistics node at the time of the move is multiplied by the quantity of fuel utilized and then the resulting quantity of fuel is subtracted from the fuel inventory. The new log location and time to arrive at the new location are reset. The End of Service event is scheduled and then the log node begins cycling through the logistics vehicles it has available. If any of these vehicles have cargo assigned to them, then the ‘load complete’ or ‘load log complete’ events are scheduled with delays to account for the loading of the vehicles.

C. DESIGN OF EXPERIMENT

A design of experiment (DOE) approach is used because it provides a substantially improved efficiency in testing a wide range of variations of the different factors (Kleijnen, Sanchez, Lucas, and Cioppa 2005). Each combination of input factors is called a design point. The design chosen for this simulation was the Nearly Orthogonal Latin Hypercube (NOLH) which is defined in detail by Cioppa and Lucas (2007). The thirteen factors are varied across the minimum and maximum values described in Table 1. The NOLH design produced 1025 combinations of the 13 input parameters (a base design of 65 design points, and 15 additional stacks). These design points were replicated 20 times for 20,500

experiments of the model. The simulation required approximately 8 hours to run the 20,500 experiments. Each model run simulates 180 days of operation. This is much more efficient than a full factorial design, which would involve 7,843,735,399,500 design points for the 13 factors at the same number of levels as the NOLH.

Table 1. Variation of Factors in NOLH Design

Factor	Minimum Value	Maximum Value	Decimal Places
Time Between Requests (days)			
Min	0.5	1.5	1
Max	2.5	3.5	1
Mode	1.5	2.5	1
Onload Time (days)			
Mean	0.25	0.65	2
Distribution shape	8	10	0
Offload Time (days)			
Mean	0.1	0.5	1
Distribution shape	8	12	0
Other factors			
Enemy Attack Probability	0.01	0.1	2
Enemy Kill Probability	0.01	0.03	2
Maintenance Event Probability	0.05	0.25	2
External Resupply Time (days)	2	10	0
Max Wait Time (days)	0.5	3	1
Number of Logistics Vehicles	8	20	0

IV. ANALYSIS

The goal of this study is to see how the distributed logistics system functions. Five measures of effectiveness are utilized in the analysis of the data; however, many more outputs were collected. A full list of the outputs is shown in the appendix.

A. MEASURES OF EFFECTIVENESS

The goal in developing this simulation was to investigate the feasibility of a distributed logistical network. In this context, success is defined as providing the requested supplies to the units that need them in the shortest amount of time. This view of success drove the development of the measures of effectiveness.

Measure of effectiveness (MOE) 1 is the average number of requests in the queue. The Infantry, Missile, and FARP units have very different requirements and frequencies for submitting requests. A low number of requests in the queue indicates that this system is resilient enough to support the fluctuations of demand. The instances with high numbers of requests in the queue are used to assess the circumstances where the model struggled to meet demand. Further analysis of this measure of effectiveness is conducted to see if there is a common set of circumstances where the network struggled to keep up with demands. A potential extension of the model is to look the different demand profiles and determine the impact to the overall requests in the queue.

MOE 2 is the total request turnaround time. The ideal circumstance is that a unit requesting goods receives them in the smallest amount of time possible. Each time a vehicle delivers supplies, the time from the initiation of the request to the delivery is tracked. This helps to determine the circumstances leading to a long delivery time. On many occasions there are undelivered requests in the queue at the time the simulation ended. These unfulfilled request times are averaged and put into a separate output value to determine the time these requests waited in the queue. The time to deliver supplies and the time pending requests took are combined in a weighted average to determine the total request turnaround. Low values are desirable from the supported units' perspective for both the average request turnaround and the average time for the pending requests.

MOE 3 is the number of logistics node resupply requests. These are the instances where supplies were low enough to warrant sending out their organic vehicles to pick up supplies. This is an indirect indicator of how effectively the higher-echelon logistics system operates. The goal is to see whether the effort of the logistics nodes to provide some of their own support has a direct impact on their ability to logistically support the combat units.

MOE 4 is the average logistics vehicle utilization. The utilization is calculated during the simulation by determining the time-weighted average of the amount of time each vehicle spends loading, unloading, and delivering supplies. This is an aggregate number across all of the logistics nodes. The number of vehicles varies depending on the design point, so the aggregate number is divided by the number of vehicles possessed by all three logistics nodes to determine the average individual vehicle utilization.

MOE 5 is the number of requests pending at the end of the simulation run. This MOE flags and provides insight into situations when the system does not perform well. Looking at this measure of effectiveness is helpful to determine the circumstances leading to a failure of the overall system.

B. ANALYSIS OF NETWORKED LOGISTICS SYSTEM

1. MOE Summaries

The analysis begins with histograms of the key measures of effectiveness. The first is for MOE 1, the average number of requests in the queue over the 180 simulated days of operation (Figure 4). Ninety percent of the simulation runs produce an average of less than four average requests in the queue.

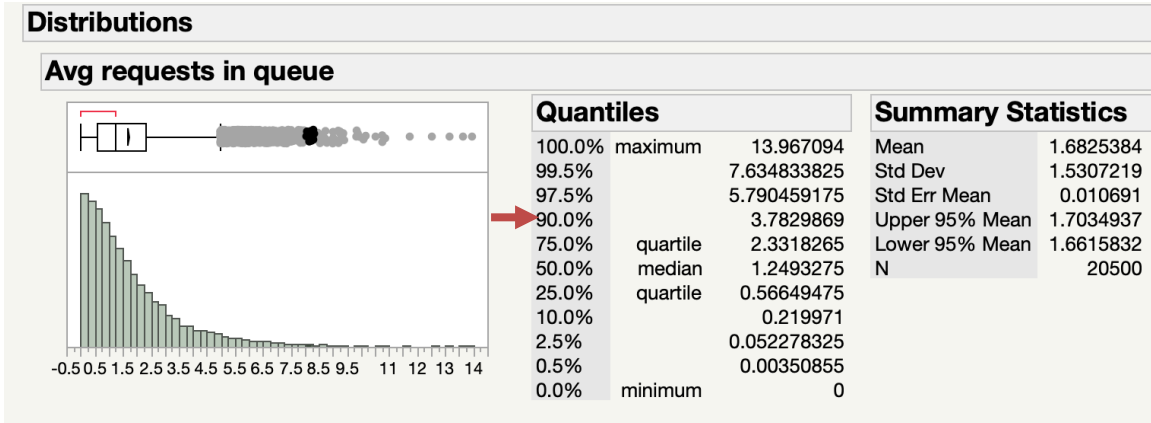


Figure 4. Histogram of the Average Number of Requests in the Queue

For MOE 2, the total amount of time from the initiation of a request to its delivery or the end of the simulation, 90% of the requests required less than three days. However, as Figure 5 shows, a small percentage of the runs yielded much larger averages. In the worst-case scenario, the average delivery time was 50.6 days.

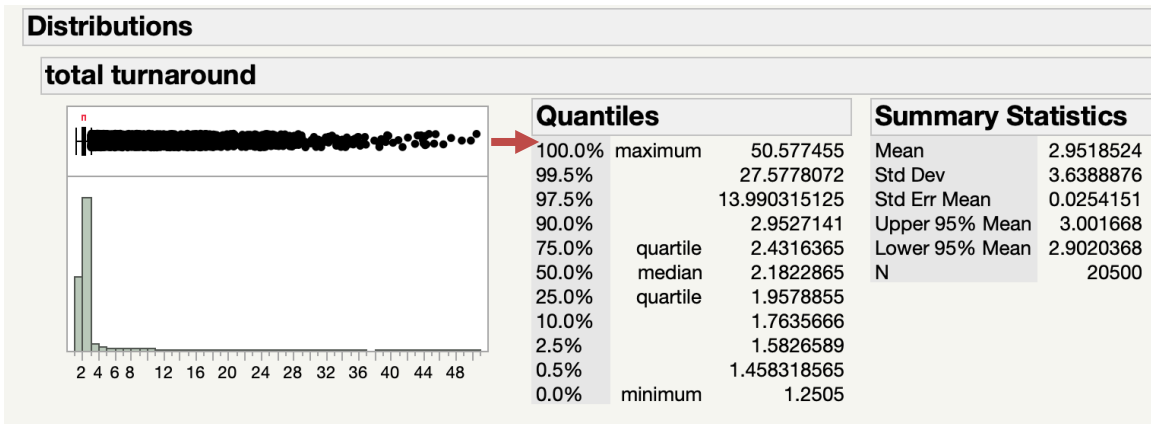


Figure 5. Histogram of the Average Request Turnaround Time

For MOE 3, Figure 6 shows the number of logistics resupply requests which ranges from 189 to 2217 over the course of the 180-day period. The logistics nodes needed to augment the external logistics system on many occasions in order to maintain sufficient supplies levels. The smallest value for this MOE was 189 so there was never a simulation run when the logistics nodes did not have to self-support and go pick up a portion of their

supplies. This pulls vehicles away from transporting supplies to their supported units and potentially slows down the distribution of resources.

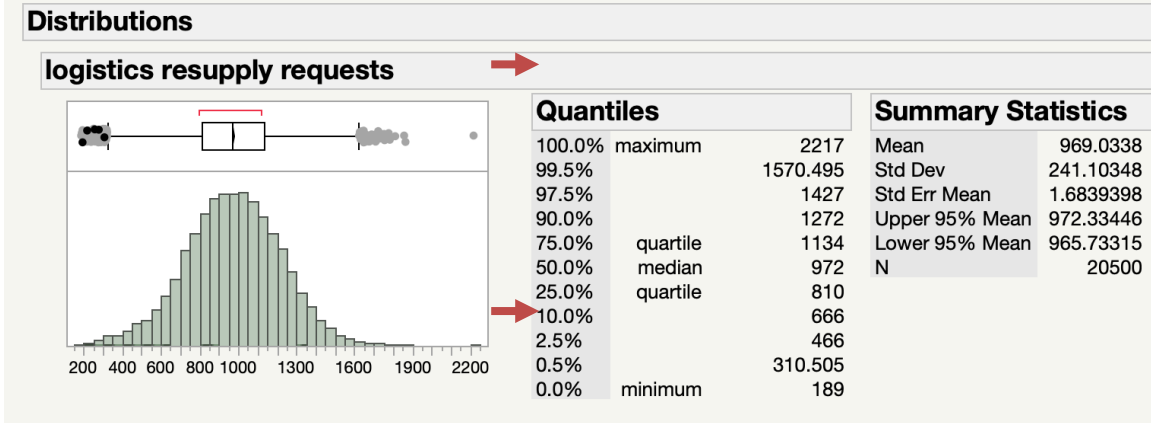


Figure 6. Histogram of the Logistics Resupply Requests

For MOE 4, Figure 7 shows that the Logistics Vehicle utilization for each vehicle ranges from 10.12% to 89.9%.

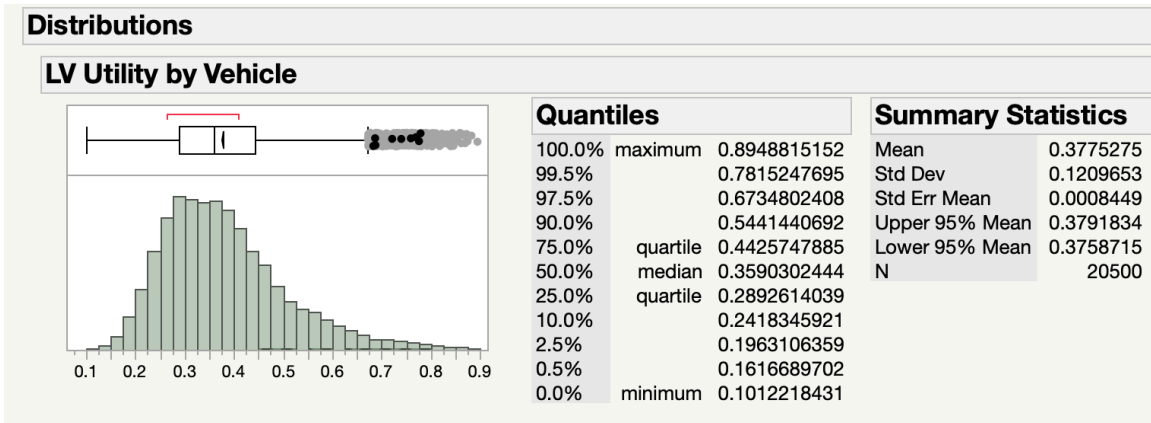


Figure 7. Histogram of Logistics Vehicle Utilization

For MOE 5, Figure 8 shows the distribution of pending requests at the end of the simulation. The histogram shows that 75% of the simulations result in 9 or fewer pending

requests. However, the remaining 25% of the data is significantly larger, with the highest total value being 15,000 requests pending in the queue.

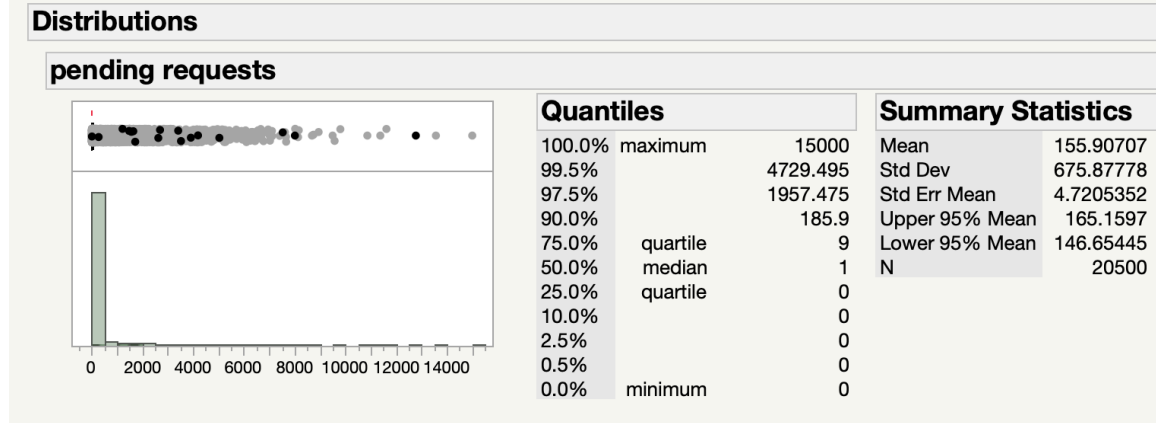


Figure 8. Histogram of Pending Requests

The values of all five MOEs fall within reasonable ranges, with the possible exception of the upper tail of the number of pending requests. There appears to be a great deal of variation, but it is not apparent from Figures 4–8 how much of the variation occurs across design points and how much is solely due to randomness. In accordance with the DOE, each of the 1025 design points were replicated 20 times. Before investigating the variation across design points, the results of each design point are aggregated so each of the 1025 data points is an average of the 20 replications.

It is instructive to look at the different MOEs and determine whether or not they are closely related to one another. Figure 9 shows a scatterplot matrix of the average MOEs from this experiment. Most of the MOEs are positively correlated with one another, but there is still a great deal of variation. This indicates that system performance assessment should not be limited to a single MOE.

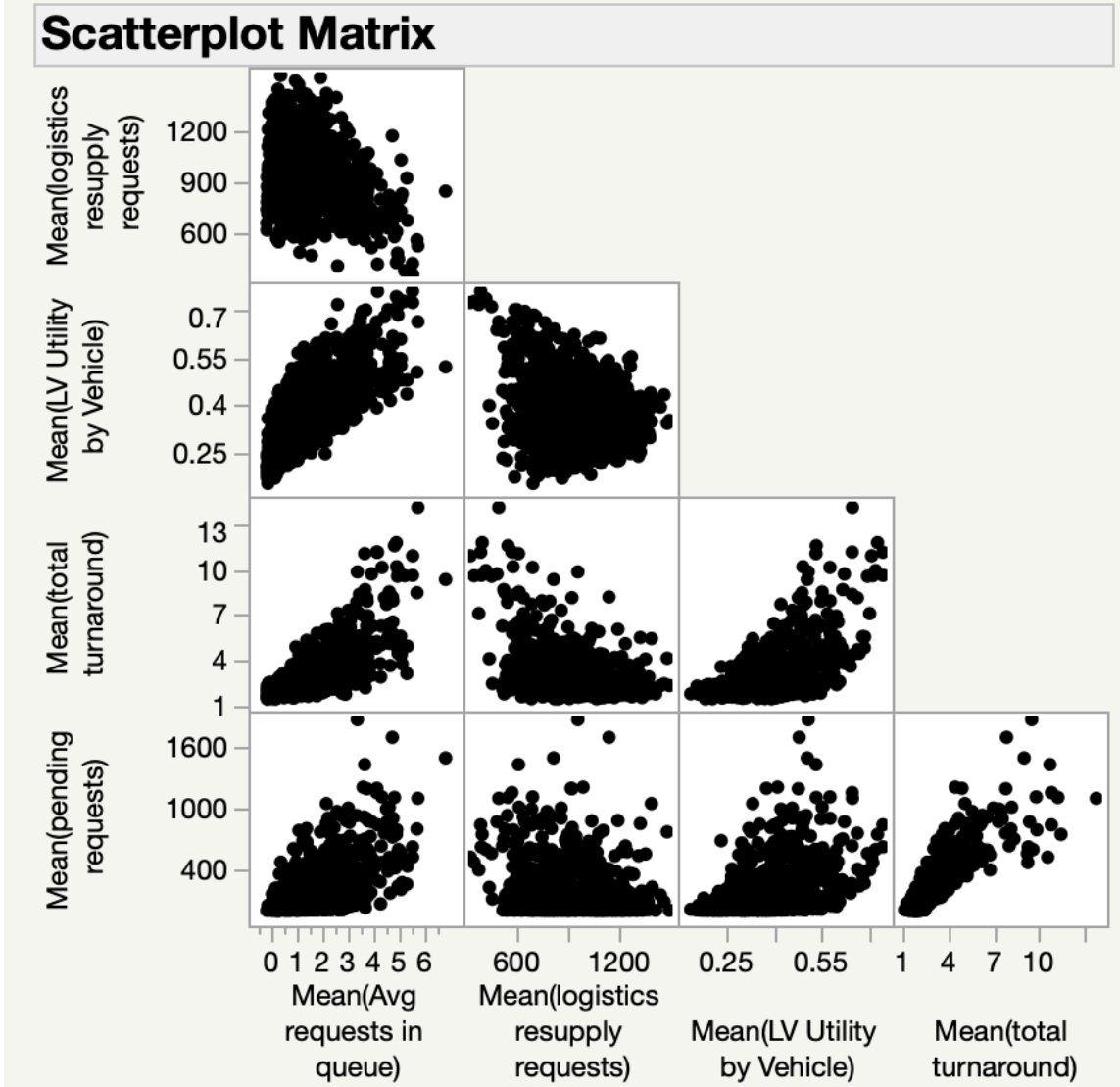


Figure 9. Scatterplot Matrix of MOEs

2. Partition Tree Prediction

The partition tree is useful in identifying factors with a significant impact on the MOEs being evaluated. For each MOE, the effects of the input variables are reviewed to see which are most influential.

The goal of MOE 1 is to have the smallest possible number of requests in the queue on average. The tree in Figure 10 shows that the two factors with the largest impact on MOE 1 are the number of logistics vehicles and the frequency at which the logistics nodes

receive supplies. With the number of logistics vehicles greater than or equal to 16 and an external resupply time of less than five days, the average number of requests in the queue is 0.384 with a standard deviation of 0.30. The first two splits identify number the number of vehicles as the most influential factor and highlight that on the other end of the spectrum, fewer than 13 vehicles and an external resupply time of greater than or equal to 6 days leads to an average number of requests being 3.31 with a standard deviation of 1.08. Ensuring the Iron Network has enough vehicles and is kept supplied can significantly improve its capability to provide service.

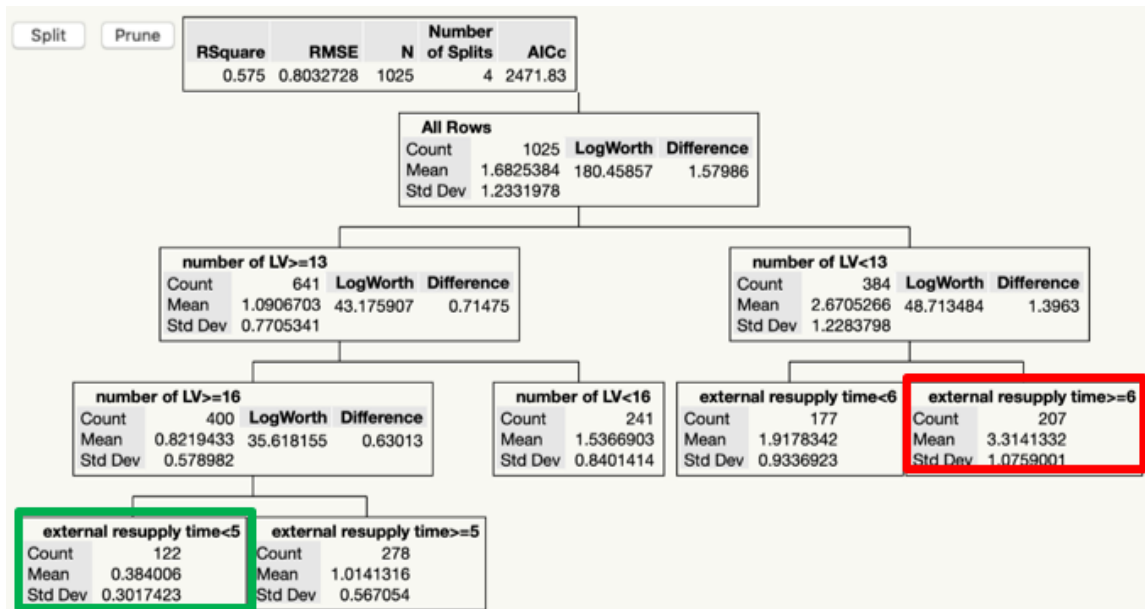


Figure 10. Partition Tree of Average Requests in the Queue

The next MOE is the total request time. For MOE 2, the key factors for decreasing the amount of time to deliver supplies are 12 or more logistics vehicles in this scenario, the probability of an enemy attack less than 0.6, keeping the time to offload the vehicles less than 0.4 days, and the onload time less than a half day. This combination of factors, shown in Figure 11, led to an average delivery time of 1.98 days with a standard deviation of 0.33 days. With fewer vehicles at the disposal of the logistics node, the impact of the enemy becomes much higher. Less than 12 vehicles and the chance of an interaction with the

enemy at 0.06 or above leads to an average delivery time more than double at 4.70 days with a standard deviation of 2.5 days.

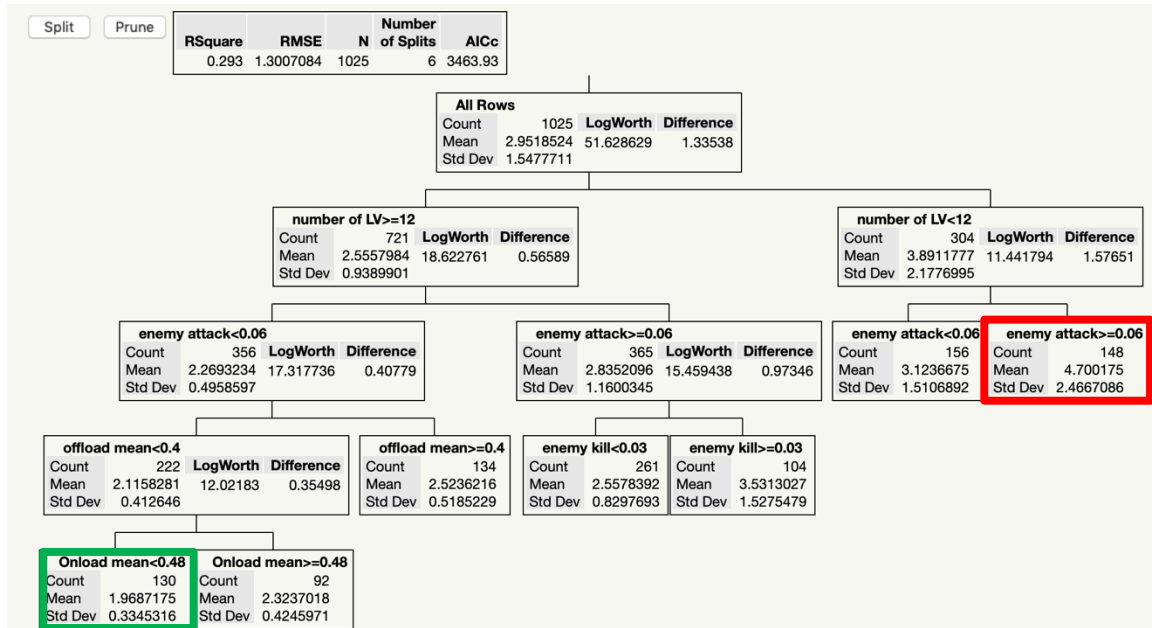


Figure 11. Partition Tree of the Average Time to Deliver Supplies

The number of logistics resupply requests shows important information about setting up this type of system. The biggest factor driving the speed of resupply and keeping the number of requests in the queue low also leads to an increased consumption of supplies at the logistics nodes. This point seems obvious, but it is important because the faster the system distributes supplies the more frequent the need for resupply at the logistics nodes. Figure 12 shows that logistics nodes possessing 16 or more vehicles and an average resupply time of 5 or greater days leads to approximately 1195 resupply requests fulfilled throughout the simulation. This number goes down to 797 requests with less than 10 vehicles. As the logistics nodes become more effective at distributing supplies, the overall system providing support to the logistics nodes needs to become more effective in conjunction.

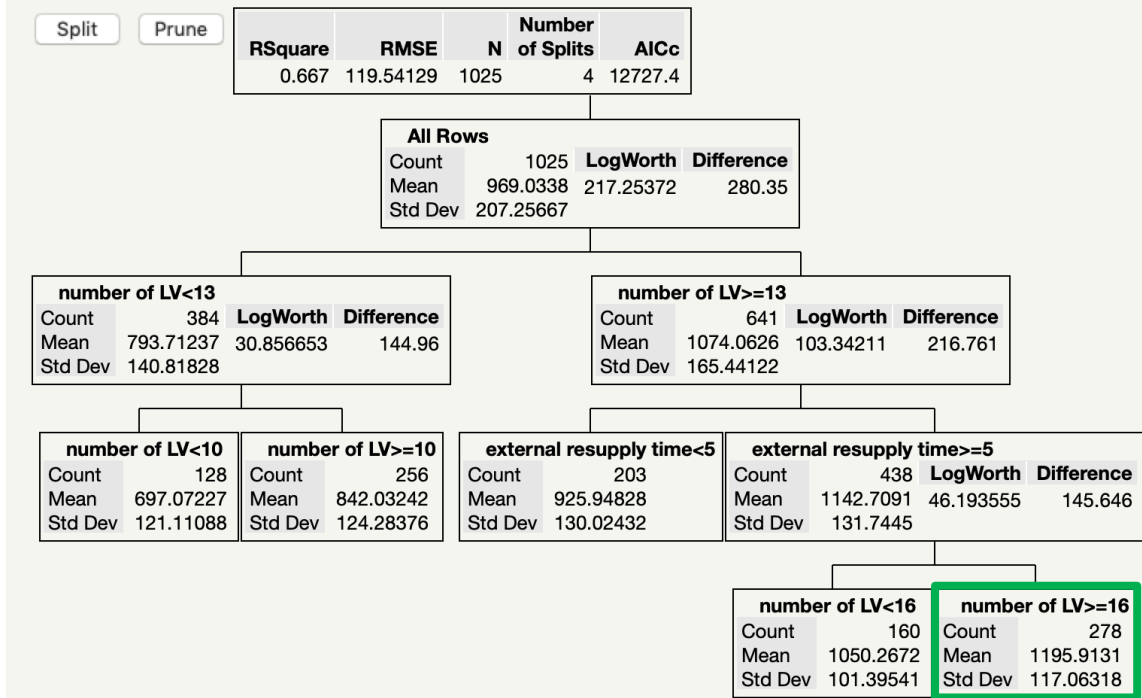


Figure 12. Partition Tree of the Number of Logistics Node Resupply Requests

The partition trees in Figures 10 and 11 indicate that more vehicles lead to fewer requests in the queue and faster delivery times. However, the partition tree in Figure 12 indicates that more vehicles leads to more resupply requests. In Figure 12, the number of logistics node resupply requests are much larger when there are 13 or more logistics vehicles. The external resupply time varies from 2 to 10 days. Figure 13 shows a plot of the average number of requests in the queue depending on the rate of external resupply. As the frequency of resupply gets smaller there tends to be fewer requests in the queue. The Iron Network appears to perform best as the logistics network supporting it gets more

responsive.

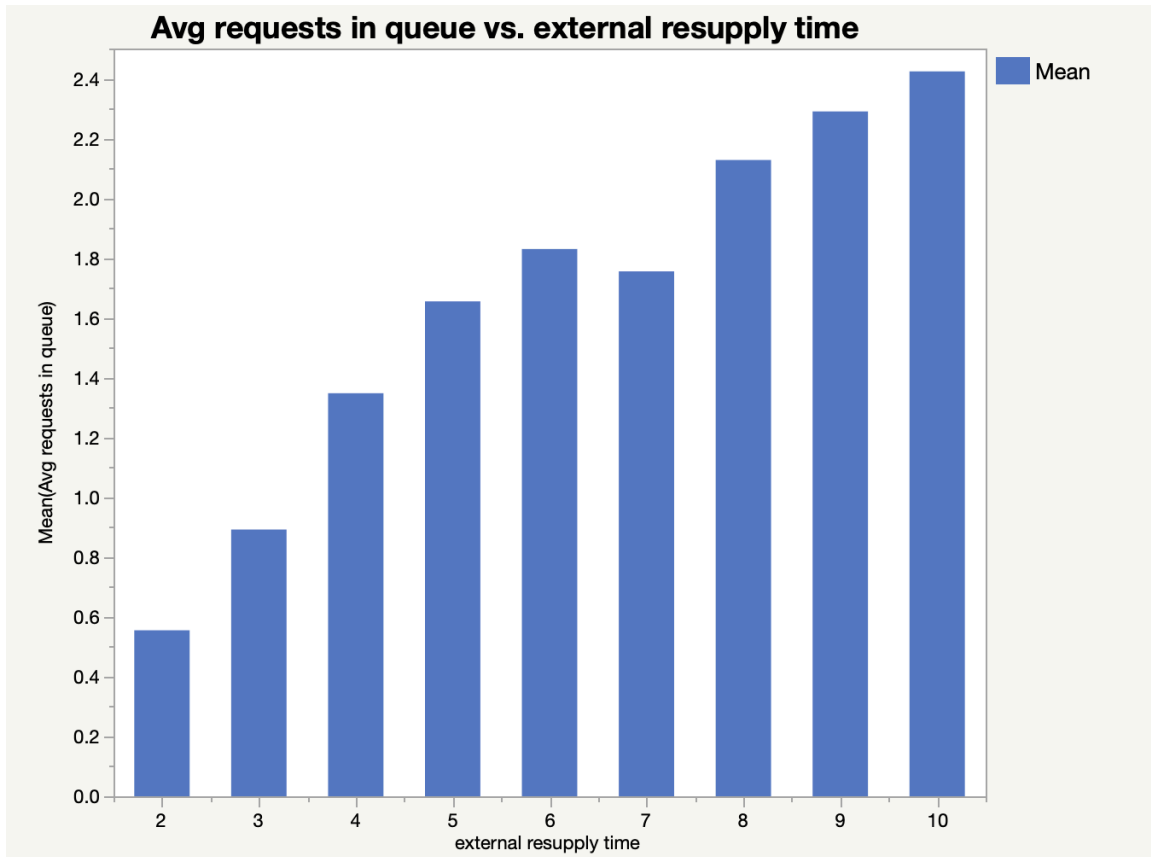


Figure 13. Plot of Average Requests in the Queue and the External Resupply Time

MOE 4 is the utilization of each vehicle. The partition tree in Figure 14 shows the number of vehicles possessed by each logistics node does have a significant impact on the utilization of each vehicle. The time that vehicles wait before departure also plays an important role in the utilization. This data shows that the appropriate wait time is dependent on the number of trucks available. With a larger number of vehicles available, the wait time should be reduced because there is a smaller cost associated with allowing them to depart with a partial load. With a smaller number of vehicles, there is better performance when the logistics nodes establish a longer wait time to ensure they get as much loaded as possible. Implementing this concept will likely produce costs in other areas. Sending vehicles without full loads will increase the fuel consumption as well as the stress on

personnel required to operate them. These issues should be taken into account when planning how to set waiting time thresholds for each logistics node.

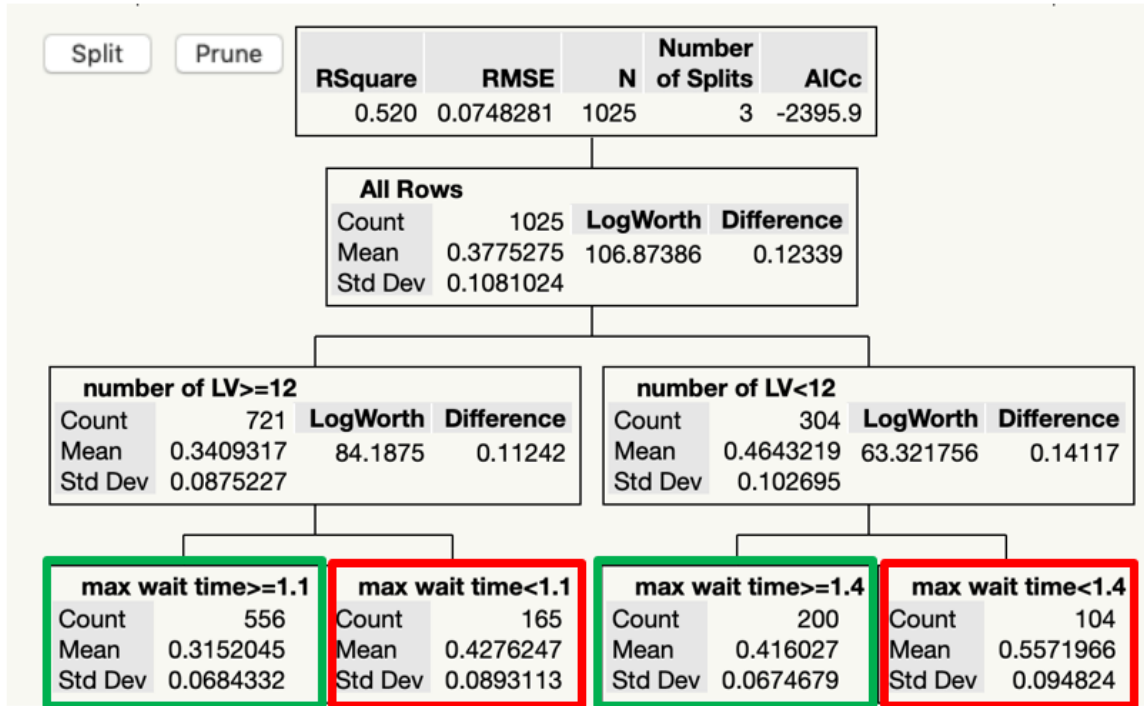


Figure 14. Partition Tree of Logistics Vehicle Utilization

Additionally, when comparing the vehicle utilization to the time it takes to deliver supplies. Figure 15 shows when the utilization is below 40%, the time to deliver supplies is relatively stable at approximately two days; however, when the utilization rate is above 40%, the stability is reduced and the time to deliver supplies increases.

The common wisdom for those unfamiliar with queueing systems is that utilization of assets should be as close to 1.0 as possible, but this is not the case for this model—or for any queueing model seeking to minimize waiting time and customer satisfaction. When the utilization is low, the system remains stable. This is not saying that vehicles should not be utilized; it is saying that slack in the system is the only way of accommodating random arrivals of requests. The greater the unpredictability in the system, the more vehicles are needed to accommodate peak demand and consequently the impact of the lower the average

utilization rate. Excessively high utilization rates also can have a practical cost on the manpower required to operate vehicles continuously and will lead to increased maintenance issues. The planning must be conducted to ensure there are an appropriate number of vehicles for the support requirements, as well as the appropriate number of people to operate them at a reasonable frequency.

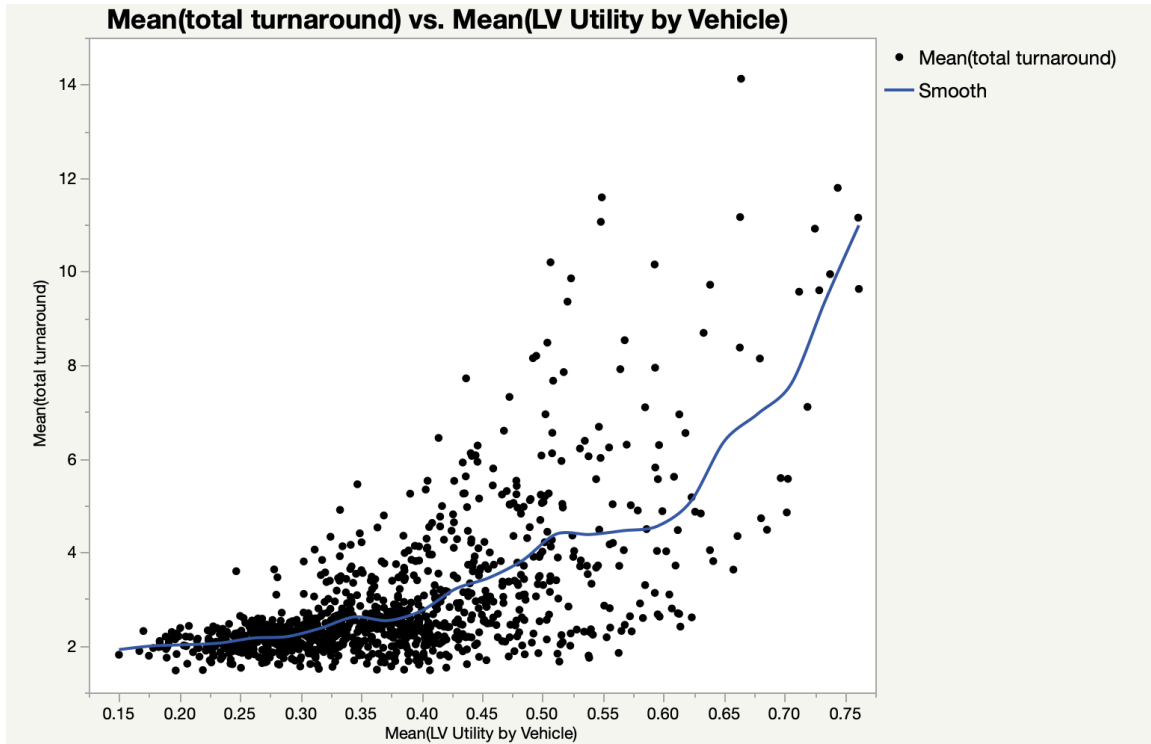


Figure 15. Plot of the Vehicle Utilization and Time to Deliver

Figure 16 shows a partition tree for MOE 5, the number of pending requests in the system at the end of the simulation. This includes the action by the enemy forces as a significant factor in the number of requests that are still remaining. With 12 or more logistics vehicles and a probability of enemy attack less than 0.06, the mean number of pending requests is 37.7. This jumps to a mean of 528.7 when the probability of enemy attack is greater than 0.08 and the probability of an enemy kill is greater than or equal to 0.03. Both of these values for the types of enemy attacks are at the very high end of the

spectrum for the simulation and indicate that the effectiveness of the enemy can drive up the backlog of requests for support.

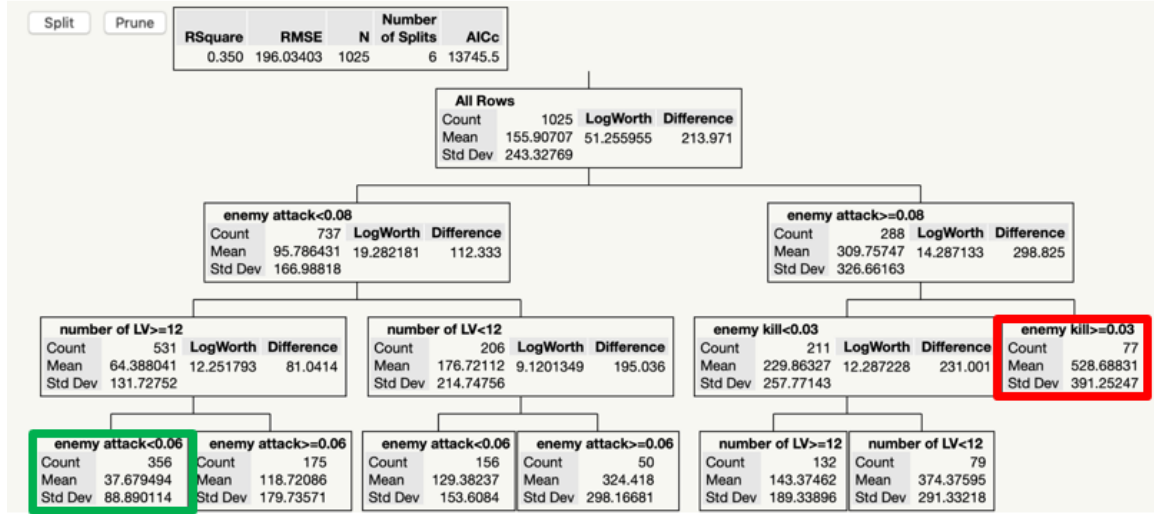


Figure 16. Partition Tree of the Number of Pending Requests

C. COMPARISON OF IRON NETWORK AND IRON MOUNTAIN SUPPORT SYSTEMS

In order to determine how the Iron Network compares to the Iron Mountain, the distributed logistics model was adapted to reflect the current logistical support system. In this comparison convoy structure model, a single supply node sends convoys to distribute supplies throughout the area of operations. In order to adapt the model, several changes were made. The individual logistics vehicles are adapted to represent convoys of 10 vehicles. During the simulation, the number of “convoys,” which are still tracked by the name logistics vehicle in the model, is varied between 3 and 8. The logic for the enemy attacks is also adjusted to reflect a convoy of vehicles versus a single vehicle conducting a movement. In the event of a successful enemy attack, a random number is drawn between 1 and the total number of pallets loaded on the vehicles. The number drawn determines how many pallets of cargo are destroyed during the attack. This quantity of cargo is removed from the inventory on the trucks and then new requests are created for the items lost. The convoy is delayed in its movement but the remaining cargo is eventually delivered

to the destination. This logic is followed with every movement. In the event that the vehicle is returning from delivering supplies and is transiting without cargo, then there will not be a new request created with an enemy attack merely a delay added to time and fuel consumption.

The decision tree in Figure 17 shows the factors that significantly impact the number of requests in the queue for the convoy structure model. The number of supported units requiring supplies and the frequency of their requests remains the same as in the distributed logistics model. What can be seen here is the number of convoys available to provide resources makes a huge difference in the ability to provide support. The best performance for MOE 1 occurs when there are greater than or equal to six convoys, which means a total of sixty vehicles. With four supported units, there needed to be at least two convoys being loaded for movement to keep the number of requests in the queue relatively low. There is a stark difference in performance at five convoys supporting four supported units. The average number of requests in the queue at five or greater convoys is 90 requests. At less than five, there was an average of 712 requests awaiting assignment. In the distributed model, the division which led to an increase in the number of requests awaiting assignment was at 13 vehicles and at this point, the average number of requests went from 1.08 to 2.68. The major reason for this dramatic difference between the two logistical support structures is because the distributed model responds much faster to requests coming from various locations. Each individual vehicle can be assigned a different destination and need not wait as long to have a sufficiently full load to depart. The convoy system has to wait much longer to be available for tasking than the distributed system.

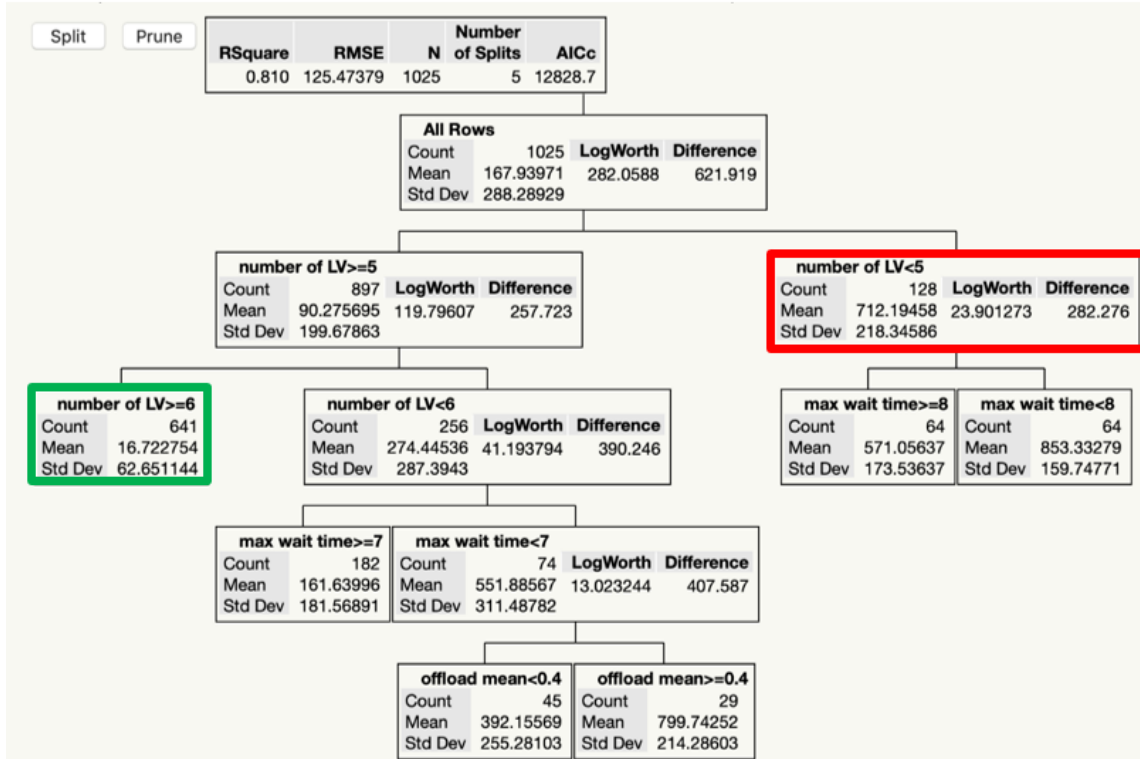


Figure 17. Average Requests in Queue for Convoy Structure

The partition tree for MOE 2, the average amount of time to respond to requests, shows the same trend (Figure 17). In Figure 18, the dividing line is five or more convoys between a 9.3 day turnaround time and a 51 day turnaround for support requests. Even in the best circumstances for the Iron Mountain, the Iron Network is able to provide resources to its supported units at a much faster pace than the convoy model with a reduced number of vehicles and fuel requirements.

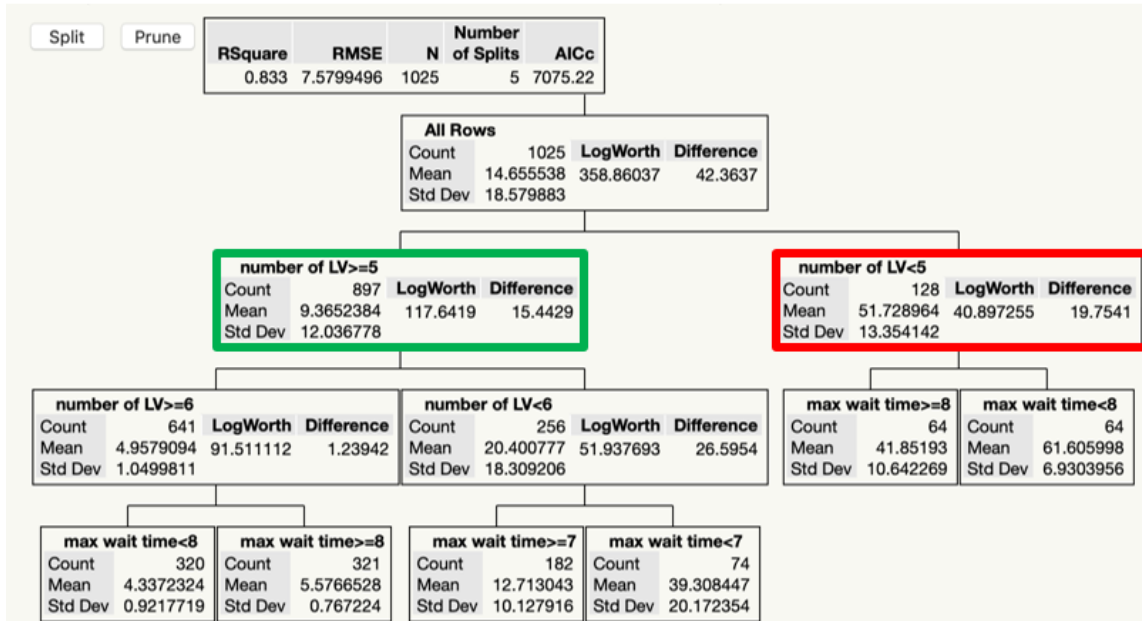


Figure 18. Partition Tree for the Average Convoy Request Turnaround

D. POTENTIAL EXTENSIONS OF THE MODEL

This model took a look at logistics support by relying solely on ground vehicles to provide supplies from the logistics nodes to the supported units. There may be many other resources capable of providing support. This involves manned and unmanned aircraft, watercraft, or contracted support. The addition of these assets in future research will provide a more realistic and accurate depiction of the functionality of a distributed logistical system. However, based on the research and analysis in this work, the results will likely translate to these other systems and situations well.

As technology continues to improve, there are emerging technologies that are being discussed and developed in support of the distribution of supplies. Autonomous vehicles, both air and ground, have the potential to greatly enhance the distribution of supplies with little additional cost in terms of personnel. These vehicles, in addition to the other vehicles in the simulation, all have a maintenance cost. This model accounted for maintenance as a delay but did not take a detailed look at the maintenance implications for this system. The addition of a detailed look at maintenance leads to an increased requirement for parts. Additive manufacturing is a possibility for procuring parts for conducting maintenance

without a significant delay for procurement. Sanchez, Lynch, Luhrs, and McDonald (2019) describe how these might be incorporated into this distributed logistics model. The object-oriented nature of this simulation model should facilitate adding many of these enhancements.

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V. CONCLUSIONS AND FUTURE WORK

As the Marine Corps transitions to operations where they are likely to be conducting highly distributed operations, the structure of the logistics system needs to adapt as well. This study looks at a tactical piece of this logistics system, and presents some insights to provide a starting point in creating a more dynamic and adaptable system.

A. CONCLUSIONS

The critical enabler for a distributed “Iron Network” logistics system is the visibility of assets around the battlefield. Currently the lack of total awareness of resource locations in the current system is not a positive, but it can be overcome because resupply is provided by a single source. There is no requirement to search for a unit with the required items. In a distributed network, there must be a much more effective means of tracking resources. The requests for support frequently go to different entities and this is determined based on the supply status of the logistics unit and delivery capability. This cannot be effectively accomplished without total awareness of the location of resources. With this enabler in place however, great efficiencies and improvements in service can be achieved.

This study explores a simulation model of an expeditionary operations scenario involving two Infantry Companies, a FARP, and a missile site which are supported by three logistics nodes. The proposed employment involves logistics nodes that are mobile and provide deliveries using individual vehicles. This is a highly dynamic system which seeks to provide supplies from a wide range of locations. If there is not complete or nearly complete visibility of resources then the system becomes bogged down with efforts to find a logistics provider who can provide support. This delays getting resources to the people who need them. An electronic system which can retain, receive, and transmit the constant change in circumstances at each logistics node is essential to running this network.

A data farming approach is used to assess the impact of 13 factors on five measures of effectiveness for the distributed logistics system. The single biggest factor impacting the speed of delivery and the backlog of requests in the system is the number of vehicles. The data indicates that a structure of this type should have a minimum of 13 vehicles at each

logistics node. If the demands from the supported units are greater, then raising the allocated number of vehicles is the most likely adjustment to relieve the stress on the system. This will help to keep the network from becoming dangerously backlogged and delivery request turnaround times from becoming too high. Increasing the number of vehicles also equates to adding personnel to operate the vehicles. Without planning for the appropriate number of personnel, as assumed in this study, the number of vehicles is less meaningful.

Thirteen vehicles at each of three logistics nodes is the number of vehicles where the performance was best in this scenario. That equates to a total of 39 vehicles spread throughout the Iron Network. In the Iron Mountain model, a minimum 5 convoys consisting of 50 vehicles was necessary to see similar performance. The ability to provide resources to a wide range of locations simultaneously is an advantage for the Iron Network model and leads to a smaller vehicle requirement overall.

An effective distributed network will require an equally effective system supporting it. If the logistics network with the most direct interaction with the warfighter changes, then the network that supports it must change as well. The Iron Network performed well even in an environment where there was a high requirement for different supplies across a large battlespace. The current model with a central logistics node and large convoys carrying bulk supplies did not perform well by comparison in this environment. In a highly distributed environment, adjusting only a portion of the logistics chain will proved to be ineffective. The whole chain must adapt in order to provide the required support.

B. FUTURE WORK

This research focuses specifically on the distribution of assets through the use of ground vehicles. This is an important aspect of military logistics, but emerging technologies have the potential to greatly enhance the feasibility and supportability of the Iron Network. The incorporation of unmanned aerial vehicles and unmanned ground vehicles may dramatically enhance the effectiveness of this system, while increasing the survivability and lowering costs. This is an area that should be investigated in future studies.

Maintenance is a critical piece of any operation. This study took a very superficial approach to maintenance. If this aspect of combat operations can be incorporated into the model in a more detailed manner, it may enhance the credibility of the results and provide additional insights for that domain of logistics.

In conjunction with unmanned systems, additive manufacturing has the potential to dramatically improve the ability to acquire and distribute parts and supplies in an austere environment. This technology has the potential to dramatically change the nature of military operations. This simulation could easily be expanded to investigate a wide range of methods to incorporate additive manufacturing into this network.

C. SUMMARY

This study assesses the performance of a distributed logistical network in a contested environment. It focuses on the use of mobile logistics nodes and ground vehicles for the distribution of assets throughout a region in an Iron Network construct vice the traditional Iron Mountain logistics site. The use of simulation and data farming provides a mechanism for evaluating a wide range of different scenarios for a proposed network of this nature. In doing this, it provides a method of adjudicating different factors of the construct and determining which provides the best starting point for adapting the current logistical structure. The results indicate that a set of mobile logistics nodes of appropriate size can provide sustained logistics support throughout a larger battlespace with improved request response time, and less resources than the traditional Iron Mountain. This is one possible configuration of logistics assets, but there are many possible ways to design this system in terms of the number of logistics nodes per supported unit, size of the nodes, and types of supported units. Distributing systems in a manner that leads to less of a reliance on an Iron Mountain is necessary for the future of operations. This “Iron Network” may provide better results and should be investigated further to improve the ability of the Marine Corps to support its future combat formations.

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APPENDIX. MODEL OUTPUTS

AvgNumRequestsInQueue. This is the average number of requests that are backed up while awaiting vehicles or supplies.

AvgNumLogRequestsInQueue. This is the average number of logistics resupply requests that are backed up while awaiting vehicles or supplies.

AvgNumAlphaRequestsInQueue. This is the average number of requests that are backed up while awaiting vehicles or supplies at the Alpha Logistics Node.

AvgNumAlphaLogRequestsInQueue. This is the average number of logistics requests that are backed up while awaiting vehicles or supplies at the Alpha Logistics Node.

AvgNumBravoRequestsInQueue. This is the average number of requests that are backed up while awaiting vehicles or supplies at the Bravo Logistics Node.

AvgNumBravoLogRequestsInQueue. This is the average number of logistics requests that are backed up while awaiting vehicles or supplies at the Bravo Logistics Node.

AvgNumCharlieRequestsInQueue. This is the average number of requests that are backed up while awaiting vehicles or supplies at the Charlie Logistics Node.

AvgNumCharlieLogRequestsInQueue. This is the average number of logistics requests that are backed up while awaiting vehicles or supplies at the Charlie Logistics Node.

Log_move_counter. This counts the number of logistics node moves.

Internal_requests. This is a count of the consumption from within the logistics node.

Logrequestnum. This is the number of logistics node resupply requests.

AvgLVUtil. This is a time-weighted average of the number of logistics vehicles being utilized at any one time.

AvgRequestTurnaround. This is the average amount of time it takes to deliver requests.

Numberofdeliveredrequest. This is the number of requests that are delivered. It combines the requests delivered to a supported unit and those for obtaining supplies for a logistics node.

PendingRequests. This is the number of requests that are waiting to be delivered at the conclusion of the simulation.

AvgpendingrequestwaitTime. In the event the simulation ends and there are pending requests waiting to be delivered, this is the average amount of time the pending requests have been waiting.

RequestNum. This is the total number of internal consumption requests and requests to provide logistics to a supported unit.

TotalRequestTurnaround. This is a weighted average that combines the average turnaround time for delivered requests with the average wait time for pending requests. It is a lower bound on the average request turnaround time for requests initiated during the simulation run.

InfantryReq. This is the total number of requests from the two infantry companies in the simulation.

FARPReq. This is the total number of requests from the FARP unit.

MissileReq. This is the total number of requests from the missile unit.

One additional measure, the individual logistics vehicle utilization, is created from the outputs. This is computed by taking the AvgLVUtil and dividing it by the total number of vehicles possessed by all three logistics nodes.

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