NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

IMPROVING MARINE FORCES STORAGE CENTER EFFICIENCY USING WORKFLOW MODELING AND DISCRETE EVENT SIMULATION

by

Kevin J. Ayres

June 2019

Thesis Advisor: Arnold H. Buss
Co-Advisor: Geraldo Ferrer

Research for this thesis was performed at the MOVES Institute.

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.			
1. AGENCY USE ONLY ***(Leave blank)***	**2. REPORT DATE** June 2019	**3. REPORT TYPE AND DATES COVERED** Master's thesis	
4. TITLE AND SUBTITLE IMPROVING MARINE FORCES STORAGE CENTER EFFICIENCY USING WORKFLOW MODELING AND DISCRETE EVENT SIMULATION			**5. FUNDING NUMBERS**
6. AUTHOR(S) Kevin J. Ayres			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING / MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release. Distribution is unlimited.			**12b. DISTRIBUTION CODE** A

13. ABSTRACT (maximum 200 words)

This thesis uses conceptual modeling and discrete event simulation (DES) to assess warehousing efficiency for Marine Forces Storage Center (MFSC), Marine Corps Logistics Command. In April 2018, MFSC took possession of a new warehouse aboard Marine Corps Logistics Base-Albany to consolidate multiple warehousing operations into one warehouse facility to store, issue, receive, and account for military equipment. In August 2018, MFSC began the consolidation process and started moving all military equipment into one single facility. Today, MFSC conducts warehousing in a 57,000-square-foot storage facility, significantly smaller than the 120,000-square-foot facility it operated in previously. First, simulation event graphs illustrate the specific warehouse workflow behaviors and procedures. Simkit, a Java-based simulation package, is used to build a DES to represent the warehouse workflow processes, compute statistical outputs, and assess the warehousing performances based on different input values. This study analyzes the warehouse throughput using different statistical analysis methods, such as simulation experiments and predictive modeling, to reveal the input-output relationships that promote optimal warehouse performance. The warehouse workflow simulation model serves as a proof of concept and verification tool to promote workflow optimization, identify and mitigate bottlenecks in the workflow processes, and assist data driven decision-making to improve operating procedures.

14. SUBJECT TERMS warehousing, work flow, storage, modeling, discrete event simulation, optimization, logistics, supply chain, material handling, Marine Corps Logistics Command, Marine Force Storage Center			**15. NUMBER OF PAGES** 107
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release. Distribution is unlimited.

IMPROVING MARINE FORCES STORAGE CENTER EFFICIENCY USING WORKFLOW MODELING AND DISCRETE EVENT SIMULATION

Kevin J. Ayres
Captain, United States Marine Corps
BS, Jacksonville University, 2013

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MODELING, VIRTUAL ENVIRONMENTS, AND SIMULATION

from the

NAVAL POSTGRADUATE SCHOOL
June 2019

Approved by: Arnold H. Buss
Advisor

Geraldo Ferrer
Co-Advisor

Peter J. Denning
Chair, Department of Computer Science

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

This thesis uses conceptual modeling and discrete event simulation (DES) to assess warehousing efficiency for Marine Forces Storage Center (MFSC), Marine Corps Logistics Command. In April 2018, MFSC took possession of a new warehouse aboard Marine Corps Logistics Base-Albany to consolidate multiple warehousing operations into one warehouse facility to store, issue, receive, and account for military equipment. In August 2018, MFSC began the consolidation process and started moving all military equipment into one single facility. Today, MFSC conducts warehousing in a 57,000-square-foot storage facility, significantly smaller than the 120,000-square-foot facility it operated in previously. First, simulation event graphs illustrate the specific warehouse workflow behaviors and procedures. Simkit, a Java-based simulation package, is used to build a DES to represent the warehouse workflow processes, compute statistical outputs, and assess the warehousing performances based on different input values. This study analyzes the warehouse throughput using different statistical analysis methods, such as simulation experiments and predictive modeling, to reveal the input-output relationships that promote optimal warehouse performance. The warehouse workflow simulation model serves as a proof of concept and verification tool to promote workflow optimization, identify and mitigate bottlenecks in the workflow processes, and assist data driven decision-making to improve operating procedures.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

I would like to thank my NPS advisors who assisted me in this thesis, Dr. Arnold Buss and Dr. Geraldo Ferrer, because their expertise contributed greatly to my overall success. I would like to thank the personnel at Marine Corps Logistics Command-Albany, Mr. Huntley Bodden, LtCol Timothy Egan, Major Daniel Whitt, Major Mark Phelps, and Mr. Elmer Daniels, and all the personnel at the Wilson Warehouse, for their dedication and continuous support throughout this lengthy process. I would also like to thank the MOVES staff and MOVES 399-181 cohort, whose words of encouragement and insights made this all possible.

THIS PAGE INTENTIONALLY LEFT BLANK

DISCLAIMER

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

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

Marine Corps supply and warehousing operations are a hierarchical and structured effort throughout the organization. At each of the different supply levels within the Corps, there are different actions completed to issue, receive, and account for military equipment. The warehousing effort at every supply level within the Corps combine to represent a unified effort that is an essential element to Marine Corps warfighting capabilities. The Marine Corps supply structure and warehousing efforts are aligned with the total force structure of the operating force at every level. At each operating force level, supply and warehousing personnel ensure that military equipment is issued, received, and accounted for in accordance with Marine Corps orders and regulations. Marine Corps Order 4400.201, volumes 1–17, "Management of Property in The Possession of the Marine Corps" promulgates the strategic policy, procedures, and responsibility which govern the management of Marine Corps equipment and property. This order provides "overarching policy and procedures in order to ensure complete and accurate accountability, auditability, and valuation of property in the possession of the Marine Corps" ("Marine Corps Order 4400.201," 2016, p. 1). According to this order, military equipment is any type of general equipment to include weapons systems that can be fielded directly to the Armed Forces to carry out battlefield missions.

The inventory levels of supply are separated into two major levels: wholesale inventory and retail inventory, shown in Figure 1.

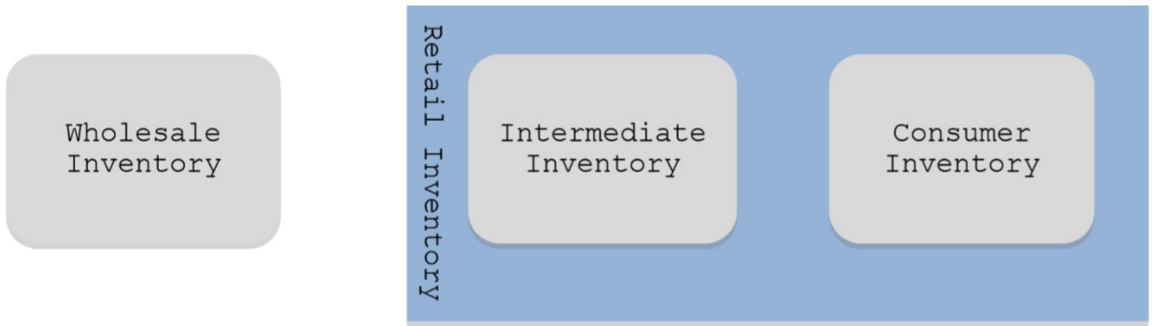


Figure 1. Inventory Levels of Supply. Source: Marine Corps Order 4400.201 (2016).

Wholesale inventory are the resources and assets controlled by the Department of Defense to fulfill inventory demands overseas and in the United States. Wholesale inventory is also referred to as the national inventory for agencies such as the Defense Logistics Agency and General Services Administration to track and control the demand for defense assets and resource down to the unit or consumer levels of supply. Retail inventory encompasses all supplies or materiel stored at the intermediate-level and consumer-level inventory. Intermediate-level inventory is considered retail inventory and is stored at the consumer and wholesale level. The primary purpose of the intermediate-level inventory is to support operating forces within a geographical area whether in the United States or overseas. The consumer-level inventory are assets or resources held by the using unit within the supply chain. The consumer-level inventory serves all internal support function for the using unit to fulfill unit missions and supporting tasks ("Marine Corps Order 4400.201," 2016).

This thesis research examines warehouse operations at the retail inventory levels of supply. This research was initiated by Marine Corps Logistics Command (MARCORLOGCOM), the thesis sponsor. MARCORLOGCOM serves a specific purpose for the Marine Corps that specializes in monitoring the receipt, storage, utilization, transfer, and disposal of military equipment and property. MARCORLOGCOM recently took possession of the Wilson warehouse, a new warehouse facility that will change the workflow processes for receiving and issuing military equipment. This study develops conceptual simulation models and a discrete event simulation model using a Java-based coding software to simulate warehouse operations and evaluate the warehouse performance for both workflow processes. The simulation outputs and statistical methods are used to measure the warehousing throughputs and identify potential bottlenecks in the workflow process. The results for this study use a nearly orthogonal Latin hypercube experimental design and statistical analysis software to test the significance between warehouse resources and warehouse efficiency. The supply and warehousing activities conducted at the wholesale inventory, intermediate-level, or consumer-level supply chains will not be covered in this thesis.

A. HISTORY OF MARCORLOGCOM

The roots of Marine Corps Logistics Command trace back to a supply depot facility based out of a Philadelphia naval base in 1798. For the next 100 years, the supply depot primary responsibility and function was clothing manufacturing for Marines. In 1908, the Marine Corps Supply Activity was established and later supported operational demands during World War I. During war time, the Supply Activity outfitted and equipped thousands of Marines serving overseas. It was not until after World War II, that the Supply Activity's clothing manufacturing capabilities and the procurement of uniforms for all military services shifted to the Defense Personnel Support Center under the Department of Defense. It became very apparent that substantial logistical support is a necessity before and during war time and the Supply Activity could serve a greater purpose for the military service. Shortly after this realization, the mission of the Marine Corps Supply Activity shifted to managing secondary items and repair parts (Marine Corps Logistics Command, 2019). In 1952, the Marine Corps Depot of Supplies was established in Albany, Georgia and further emphasized the realization that logistical support is a necessary requirement. The depot was later renamed the Marine Corps Supply Center Albany (MCLB Albany), which is responsible for the management and control of supplies being stored and issued in the eastern half of the United States (Marine Corps Logistics Command, 2019). By 1976, the Albany depot assumed the responsibilities of inventory control, financial management, procurement, and technical support boosting logistical support operations for the Marine Corps (Marine Corps Logistics Command, 2019).

Then in 1978, MCLB Albany became what it is known today as Marine Corps Logistics Base Albany. The supply and logistics depot became responsible for a large majority of the logistics requirements to sustain Marine Corps weapons systems and equipment. This initiative continued when Marine Corps Materiel Command was also established on the Albany base. This command was notably created to combine the acquisition and sustainment capabilities to provide the most effective functions for logistical support and management of ground weapon systems. In 2003, changes with the Department of Defense governing the acquisition and sustainment of weapons systems and equipment lead to the command and base headquarters merging to establish MARCORLOGCOM (Marine Corps Logistics Command, 2019). The establishment of MARCORLOGCOM unified Marine Corps logistics lines of effort.

B. CURRENT MARCORLOGCOM

Today, MARCORLOGCOM serves as the primary logistics provider for the Marine Corps with extensive logistics functions to support the operating forces worldwide. The specific functions of MARCORLOGCOM include supply, maintenance, storage, distribution, and the propositioning of military resources and assets (Marine Corps Logistics Command, 2009). The command is a modern enterprise, depot-level organization that focuses on sustaining and supporting the logistics demands from two primary customer groups: the warfighter and the acquisition community (Marine Corps Logistics Command, 2009). The warfighters refer to the support to the servicemembers of operating forces, reserve forces, and supporting establishments of the Marine Corps. The acquisition community refer to support provided to other Marine Corps commands such Marine Corps Systems Command who specialize in the procurement of new systems or equipment. The mission of MARCORLOGCOM is essential to sustaining the Marine Corps' mission as a "force in readiness" by providing responsive logistical support to the warfighter.

MARCORLOGCOM capabilities are channeled into "three core competencies: supply, maintenance, and distribution" (Marine Corps Logistics Command, 2009, p. 5). The core competencies represent the values and capabilities provided to the customer, which are "equipment sourcing, acquisition support, logistics services, and prepositioning support" (Marine Corps Logistics Command, 2009, p. 5). The integrated relationships between the competencies and values are what establishes MARCORLOGCOM as a critical integrated logistics provider for the Marine Corps. The integral relationships between core competencies and capabilities by MARCORLOGCOM are further illustrated in Figure 2 from the perspective of the customer. The High Impact Core Value Streams are defined as:

- Equipment Sourcing – Processes that result in the delivery of an end item to the warfighter.
- Acquisition Support – Processes provided to a program manager in support of a weapon system program of record; includes sustainment support.
- Logistics Services – Processes that result in a solution to a specific customer or warfighting need; may be a one-time offering or an ongoing requirement.
- Prepositioning Support – Processes that support the Marine Corps strategic maritime and land-based prepositioning programs. (Marine Corps Logistics Command, 2009)

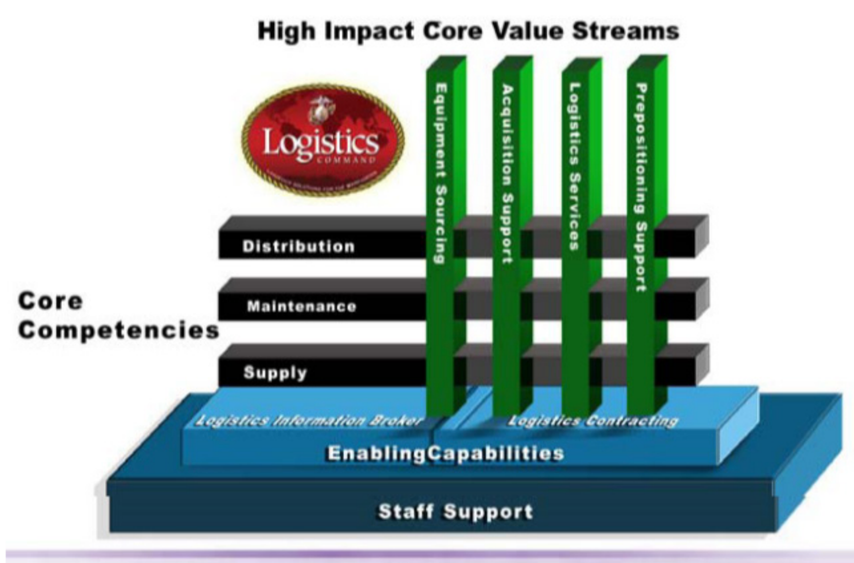


Figure 2. MARCORLOGCOM Core Competencies and High Impact Core Value Streams. Source: Marine Corps Logistics Command (2009).

C. PROBLEM SCOPE

This research assists Marine Forces Storage Center (MFSC) and examines the warehouse workflow processes for the Wilson warehouse. In April 2018, MFSC took possession of the Wilson Warehouse aboard Marine Corps Logistics Base Albany and initiated this study to better understand how warehouse efficiency would be affected. The plan is to consolidate multiple warehousing operations into the new facility to store, issue, receive, and account for weapons, communication, and optical equipment. In August 2018, MFSC began the consolidation process and started moving all small arms, communication equipment and optical equipment into one single facility aboard Marine Corps Logistics Base in Albany, GA.

Prior to the consolidation efforts, warehousing operations for weapons, communication and optical equipment were conducted in separate respective warehouses. The new facility size and layout is configured differently compared to the previous warehouse. The new facility also has additional warehouse resources that will change the workflow processes and streamline warehousing procedures. MFSC leadership wants to understand how the new workflow procedures will affect warehouse performance and what changes may be necessary to improve warehousing efficiency.

According to Marine Corps order 4400.201, "warehouse management functions consists of planning, organizing, directing, coordinating, controlling and evaluating the maximum utilization of storage and warehousing facilities to provide effective and economical use of space to house material in support of military forces" ("Marine Corps Order 4400.201," 2016, p. 3–2). Efficient warehouse management activities also consist of "assuring the most effective, economical use of storage assets; and proper inventory procedures of materiel and supplies within the Marine Corps" ("Marine Corps Order 4400.201," 2016, p. 3–2). However, there are no specific guidelines or step by step procedures to standardize the effective means to execute smarter and efficient warehousing practices. Warehouse facilities and decision makers across the Marine Corps must develop specific best practices and procedures that maximize the physical and technologies capabilities in the warehouse where the work is performed since no warehouse is technically the same. The scope of this study will be to use Marine Corps warehouse management strategy with model and simulation techniques to evaluate the warehouse efficiency for the Wilson Warehouse aboard Marine Corps Logistics Base Albany.

As MFSC resumes operations in the new facility, adherence to Marine Corps policy and directives will be a high point of emphasis and involve operational considerations. The floor plan in the new facility will also have important operational considerations and present several challenges. Warehouse operations for three types military equipment were previously conducted using multiple storage facilities where space was not an issue. Today, MFSC conducts operations in a 57,000-square-foot storage facility and a significant decrease compared to the 120,000-square-foot facility previously used. This thesis will thoroughly address the physical limitations in the new facility and explore resource parameters settings that optimize the simultaneous warehouse processes. The overall workspace shrunk significantly so optimizing the available space and resources will be a primary target to focus on in this research.

1. Thesis Objectives

The objective for this study is to use Simkit, a set of Java packages, to build a discrete event simulation model that represents Wilson warehouse operations. The basis for this research uses the input and feedback from the sponsor to accurately model the warehouse workflow behaviors and address potential bottlenecks in the workflow processes. A site visit to the Wilson warehouse was conducted with the sponsor and warehouse managers to formulate the problem and set the simulation model objectives. First, it is imperative to define and identify the key performance indicators that complement efficient warehouse operations. This effort requires understanding the workflow processes and developing conceptual models to represent the warehouse system behaviors. The models will represent the key events and actions that take place within the warehouse processes. Next, discrete event simulation techniques implement the models into a Java-based simulation application to evaluate the warehouse performance as input values change. The simulation model and statistical analysis reveal the warehouse resources that produce the best warehouse performance. The development of the simulation model uses an iterative modeling approach to identify model requirements and measurable performance throughputs.

The first step includes thoroughly understanding the workflow processes were through observation and feedback from the sponsor. Next, the current warehouse workflow processes were modeled using principles of discrete event simulation. This effort assists MFSC procedural decision-making to achieve optimal workflow performances. To meet this goal, this thesis will focus on creating a discrete representation of warehouse activities using characteristics of the current warehouse workflow procedures to assess the ability to meet operational requirements. The simulation model produces statistical outputs based on variable resources allocations. This research analyzes the warehouse performance using the statistical outputs and conducting several simulation experiments to provide qualitative feedback to the sponsor. The discrete event simulation model will serve as an assistant decision-making tool and proof of concept due to data constraints to identify potential bottlenecks and resources that affect warehouse performance. The simulation outputs will contribute to improve warehousing efficiency and a way forward to verify effective operating procedures.

2. Thesis Impact

This research is an informative study for MFSC and MARCORLOGCOM to identify best practices and evaluate warehouse performance. This research enhances leadership’s ability to make better informed decisions to achieve efficient warehouse processing times. The real warehouse workflow characteristics were used to represent the key events and resources in the simulation model. The warehouse resources variables were changed over several simulation runs and analyzed to determine the optimal warehouse performance. This research highlights the benefits of simulation and the capabilities to streamline future logistical operations for the Marine Corps. MARCORLOGCOM is the highest echelon manger and distributor for Marine Corps military equipment. The command provides depot-level logistical services for all operating units inside and out of the United States. Warehousing efforts at every supply level throughout the Corps provides an essential element to the warfighting capabilities of the unit. Marine Corps logistical processes must continue to modernize and leverage simulation to address complex problems and to ensure effective solutions are implemented. This research exemplifies the use of emerging evaluation methods to address workflow optimization that the Marine Corps should be adopt throughout the organization to enhance mission effectiveness.

3. Thesis Challenges

This study presents several challenges, some of which are inherited from modeling the dynamic behaviors of warehousing and some which were unique to the Wilson warehouse alone. Depot-level warehouse operations can be very difficult to forecast due to variability in operational demand. There are instances where the demand for equipment or need for storage creates a higher tempo in the warehouse operations than normal. One of the most difficult challenges is incorporating real warehousing characteristics and behaviors in the model due to the lack of real or historic data. There are several steps throughout the workflow process where an incredible amount of variability exists in the time it will take to complete the step within the workflow. The time it will take for a warehouse shipment to go from dock to stock or vice-versa can depend entirely on the size of the shipment and available resources. This variability is systemic throughout the entire workflow process and creates the challenge to represent accurate work time and man-hours for a discrete event simulation without accurate data. The lack of data related to work time at and between steps in the workflow process lead to the development of proof of concept model to preserve the fidelity of the model and allow the data requirements into the model once it became available.

This circumstance is problematic for the developing a model that will assist decision-making for real operations. The workflow variability in the simulation model will initially be different from the actual variation for real warehouse operation. However, this does not discredit the use of a discrete event model for this research. The information gathered from key leaders is still provides the key events in the workflow address bottlenecks and assess warehouse performance. The available information by key leaders also provides enough understanding to model the potential concerns in the workflow processes due limited space and resources. This information helps formulate the initial model construct to explore how to maximize warehouse efficiency with the understanding that model fidelity will increase as more data becomes available. The model development techniques remain flexibility to adopt new workflow data and incorporate it into the simulation model to more accurately represents real warehouse operations.

Initially, the research scope included analyzing the space of the new warehouse to determine the best layout that would produce the most time efficient processes. Due to timelines constraints and operational requirements, the warehouse layout was already established based on key leadership input and analysis prior to this study. Initial observations suggest the current warehouse layout takes advantage of decease in storage capacity versus workflow efficiency. The warehouse layout determined to compensate the limited square-foot available in the new facility compared to previous warehouse. The lack of available space also limits the maneuverability for forklift systems in the warehouse. The Wilson warehouse layout limits the forklifts' ability to maneuver everywhere within the warehouse which limits potential adjustments that can be made to improve the workflow performance. This research addresses the spaces limitations and resources within the current workflow processes. The simulation model and statistical analysis in this research identify the variables within the workflow processes that are most related to efficient warehouse performance. Once this is understood, key leadership can use the data-based feedback from model to address the layout and spaces limitations more effectively at specific points within the workflow.

II. BACKGROUND

A. PREVIOUS DISCRETE EVENT SIMULATION STUDIES

1. Discrete Event Simulation used at MARCORLOGCOM

The use of modeling and discrete event simulation are vital tools that have constantly been leveraged by Marine Corps Logistics Command to promote modernization and development of logistics processes. The Marine Corps Maintenance Depot, also located on Marine Corps Logistics Base Albany, and modeling and simulation students have a history of using discrete-event simulation methodology to study and optimize the depot maintenance processes. At the early phases of this study, a comprehensive review is conducted including previous NPS theses, professional studies, and journal articles related to discrete event simulation in supply chain and logistics operations.

The first previous related study using discrete event simulation for the Marine Corps Logistics Command was completed in September 2016 by Major Timothy Curling. The purpose of his thesis was to improve order management policy within subordinate organization Marine Corps Depot Maintenance Command by integrating discrete event simulation and optimization modeling. Specifically, he developed a "proof of concept analytical tool" that optimizes the order management of repair parts, improve order management decision making, and ultimately provide recommendations for reorder policy within the maintenance production process (Curling, 2016, p. V). The discrete event simulation principles and methods used by Major Curling in his thesis will be informative guide and support the development of the warehouse workflow model for this study.

In the methodology phase, Major Curling highlighted the benefits optimization provides to a simulation model. He justified his methodology to connect an optimization model and discrete event simulation using what is known as simulation optimization. His study uses the optimization model to determine the optimal input variables for the discrete simulation model which then produce the most optimal outputs for the simulation. Major Curling uses Figure 3 to illustrate the interactive relationship between an optimization model and discrete event simulation model.

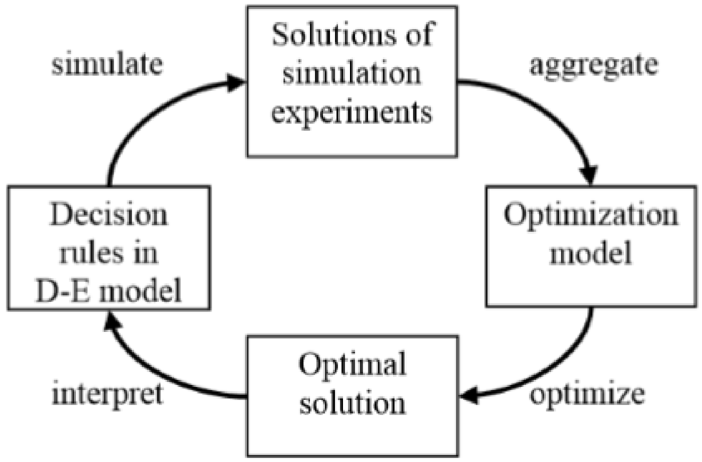


Figure 3. Interaction between Discrete Event Simulation Model and Optimization Model. D-E Means Discrete Event Simulation. Source: Curling (2016).

An important takeaway from his methodology was that optimized inputs boosted the overall performance of the discrete event simulation based on adaptive decision rules obtains from the optimization model. Figure 4 outlines the methodology for his simulation optimization concept development.

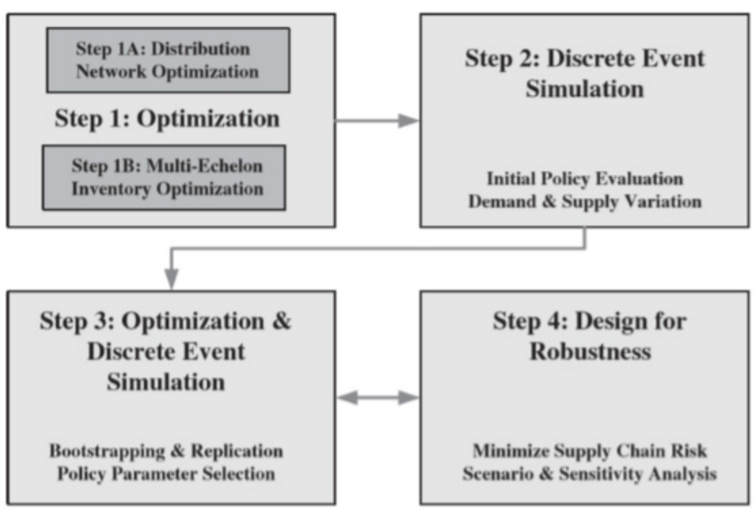


Figure 4. Four-Step Methodology for Simulation Optimization Concept Development. Source: Curling (2016).

The design and development of an order management tool was the primary focus of Major Curling's thesis, not the critical part inventory optimization model alone. Specifically, the optimization model and discrete event simulation operated independently. However, the optimization model and discrete event simulation together resulted in the development an order management tool that contributed to developing effective reorder procedures. The objective of the critical part inventory optimization model is to minimize the chance of parts being out of stock. The optimization model input data and optimal order quantity output data feds into the discrete event simulation as input variables. The discrete event simulation in the study implemented the key events within the maintenance production process and used optimization model outputs to provide the efficient measure for the process. In result, the discrete event simulation computed the five output variables of the system: average principle end item delay in arrival queue, average principle end item delay in assembly queue, average principle end item time in system, average work bay utilization rate, and average production rate (Curling, 2016).

In the implementation phase, the order management tool was developed by using the optimization and discrete event simulation concepts. The milestones Curling used to implement the order management tool were:

1. Critical Part Inventory Optimization Model Development
2. Discrete Event Simulation Development
3. Integration of the Critical Part Inventory Optimization Model and Discrete Event Simulation
4. Testing (Curling, 2016)

The order management tool provided the user with the following output data: delays with the system, utilization rate for work bays, and the overall system production rates. The warehouse workflow simulation model will pursue a different approach than the methodology used by Major Curling and focus on measuring the warehouse operation throughput and cycle time. However, there will be similarities particularly in the use of event graphs to develop the discrete event simulation. Event graphs are an important modeling tool that allow simulation developer to visualize the process to be modeled and simulated. An event graph also is used to illustrate the discrete behaviors of the discrete event simulation which will also be technique utilized in this thesis. Similar challenges Major Curling's faced was obtaining useful data from the maintenance facilities; the same reasonable challenges that will be expected in this study as well. This study uses the insights and techniques by Major Curling to produce a simulation model that represents warehouse operations even with limited information available. In Major Curling's case, he provided recommendations to key leadership for more efficient repair part requisition forecasting with the limited data. His thesis is an example that the development of a discrete event simulation from limited data can still be valuable in providing a proof of concept model to the sponsor and adjustable for new developments that may occur later.

The most recent study using discrete event simulation for the Marine Corps Logistics Command was completed in June 2018 by Captain Michael Blankenbeker. His thesis developed a discrete event model to simulate the depot-level maintenance process for the Marine Corps' Light Armored Vehicle. His study provided the logistic community a tool to make critical decisions to avoid unnecessary delays in the maintenance cycle and promote efficient maintenance cycle times. He also used a discrete event simulation, analysis involving data farming, and statistical analysis to provide qualitative results to the sponsor based on adjusting "resource capacity parameters" (Blankenbeker, 2018, p. V). Specifically, his study demonstrated the potential bottlenecks within the maintenance repair process for the light armored vehicle and assessed work performance when input parameters are adjusted. His overall objective was to reduce the bottlenecks within individual working queues throughout maintenance process using simulation. Based on similarities in the scope and objectives of Captain Blankenbeker's study, this thesis project uses similar modeling approaches and implementation techniques. The potential bottlenecks in the warehouse workflow process are a central focus for this research.

In his methodology phase, discrete event simulation principles and methodology were used to represent the light armored vehicle depot level maintenance process. He used Simkit to develop a robust event driven simulation model vice time stepped. The decision to develop an event-based model was most appropriate to ensure each event taking place in the maintenance process is measured and no event went undetected throughout the simulation. Simkit, developed by Dr. Arnold Buss, was the most ideal application to develop the model of the light armored vehicle maintenance process. In Captain Blankenbeker's thesis, Simkit is used to develop different classes to represent components of the maintenance process. Each class uses methods to represent the different events or task in the maintenance process. The events within the discrete event program are significant since they invoke state transitions and were used to schedule follow-on events. Prior to any coding in Simkit, Captain Blankenbeker's methodology first created event graphs of the system to be later coded in the simulation application. The event graph representations for each class were implemented to help drive the modeling process and ensure all appropriate behaviors were implemented accurately.

In the implementation phase, Captain Blankenbeker began modeling the complex and dynamic depot-level maintenance process for the light armored vehicle. To assist in his objective, Captain Blankenbeker broke down the entirety of the system into manageable classes. This technique facilitated by Simkit allowed checks and verification throughout the implementation process before continuing to complex model development iterations. The use of multiple classes, entities, and servers were all contributing factors of his thesis that made the model development process more complex but efficient in address his research problem. There were several entities developed in the simulation to represent the light armored vehicle and key components of the vehicle that were being passed through the various service stations in maintenance process. His model also used entity servers to represent the team of employees who conducted maintenance on the vehicle components. The seven milestones for Captain Blankenbeker used to guide the simulation development process were:

1. Basic entity, arrival process, server class development
2. Server node aggregation
3. Server complexity
4. Entity complexity
5. Statistics
6. Optimization

7. Refinement (Blankenbeker, 2018)

Captain Blankenbeker's thesis also faced several challenges involving the necessary data requirements to produce accurate arrival times and service times for each class instance. There were also complications in connecting the classes together to appropriately represent the behaviors in the light armored vehicle depot-level maintenance process. After all the class instances were developed, he created the appropriate listeners and adapters to connect the classes. This allowed the entities to transition between each class or event in the simulation. An iteration loop was then implemented to run the simulation time parameter. The loop was set to run the initial conditions at a five-year time period. The iteration loop also allowed the servers to be reset and perform multiple identical independent replications of the maintenance process. The last step in the implementation phase involved developing the code to run the simulation and produce the statistical outputs. The delay in queue was the best statistic to measure and analyze throughout the testing phase. The delay in queue statistic was also the best indicator to determine the performance of the system and reduce bottlenecks as entities are passed from queue to queue of the various service stations.

The techniques and approaches used by Captain Blankenbeker to develop a discrete event simulation for the light armored vehicle maintenance process are certainly noteworthy. There will be fundamental differences in the models and objectives between his thesis research and this research. Ultimately, Captain Blankenbeker implemented a valuable discrete event simulation and adapted to challenges. His thesis illustrates the importance of definitive scope in the model development process and the benefits and complications of a complex model. The warehouse workflow model uses similar approaches and tools to identify the key events and develop the appropriate behaviors to meet the thesis objectives. This thesis research also maintains a level of simplicity to avoid some of the issues experienced by Captain Blankenbeker.

2. Discrete Event Simulation, Logistics, and Supply Chains

"Improving the Rigor of DES in Logistics and Supply Chain Research" by Manuj, Mentzer, and Bowers propose an "eight-step simulation model development process for the design, implementation, and evaluation of logistics and supply chain models" (Manuj, Mentzer, & Bowers, 2009, p. 172). This literature supports the primary approach and methodology for this thesis project and provides critical steps to develop a conceptual model and represent logistics processes through simulation. As previously mentioned, discrete event simulation methodology will used to represent the warehouse operations at the Wilson warehouse facility. The simulation will evaluate the warehouse performance, obtain optimal input variables to reduce bottlenecks, and provide statistical outputs to support decision making. The systematic approach developed in this paper highlights those important standards and provides stronger guidance to development the workflow model that will represent Wilson warehouse operations.

The paper emphasizes and supports using discrete event simulation to assess logistics and supply chain systems. Discrete event simulation is credited as a highly reliable tool because it provides the means to breakdown and understand the imperceptible behaviors of the real logistics process or supply chain system (Manuj et al., 2009). Logistics and supply system processes are paired with simulations so frequently because it provides the visualization and methods to analyze the interrelationships between system components that are too complex to just compute mathematically. The complex nature of logistics and supply chain processes make simulation models an appropriate method to conduct studies and analysis at high level of detail required to better understand the system and make informed decisions.

The simulation model development process is formulated to better understanding the requirements for simulating logistics and supply chains. The simulation model development process is a detailed step-by-step checklist to ensure important simulations requirements are met to produce a high-quality model for logistics and supply chain systems. The simulation model development process is depicted in Figure 5. These steps and guiding principles within this process will be used as it applies to the thesis research to identify simulation requirements for the warehouse workflow model. The eight-step process is concrete methodology to development any model in the supply chain domain and it will certainly serve to be applicable in this thesis to assist decision-making for a complex process.

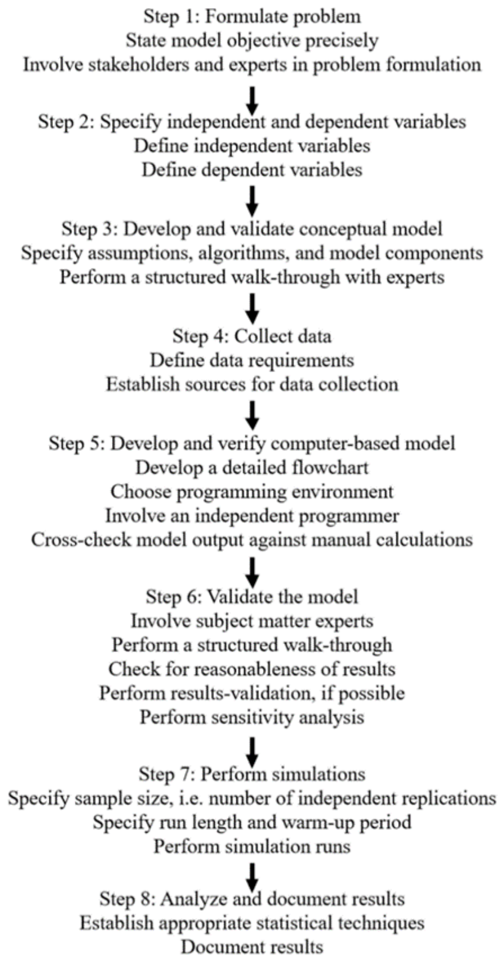


Figure 5. Eight-Step Simulation Model Development Process.
Source: Manuj et al. (2009).

This thesis project will use discrete event simulation methodology to represent the warehouse operations at the Wilson warehouse facility for Marine Corps Logistics Command. Marine Corps Logistics Command manages and performs the highest echelon of materiel distribution and storage for military equipment in the Marine Corps. The activities and functions of this command closely resemble the mission of a commercial warehousing enterprise supply chain. Supply chains are difficult to plan and the main events within them represent the complex nature and dynamic activities that greatly influence supply chain performance. This thesis project will develop a model that represents the appropriate supply chain behaviors and activities for warehouse workflow process for receiving and issuing military equipment. The simulation for this thesis project will evaluate the warehouse system performance using optimal input resource variables to reduce bottlenecks in the warehouse process and provide statistical outputs to support decision making. Discrete event simulation will serve as a reliable and appropriate technique for this thesis based on research supported in the literature by Daniel Hellström and Mats Johnsson.

Before addressing the use of discrete event simulation in supply chain, Hellström and Johnsson concisely define and provide explanation to emphasize their use of a stochastic, dynamic model. The explanations found in (Hellström, 2002) present a creditable frame of reference for discussing a model, a simulation, and simulation classifications types:

- A model is a simplification of a system but contains those components that are identified as relevant to the problem under investigation. Models are used to gain insight or predict future performance of a system.

- A simulation is a descriptive model that is developed to better understand relationships and operations over time as function of policies and parameters. A simulation tells how the design performs and behaves over time when different rules and policies are applied.

- Simulation models are mathematical, and can be classified as being static or dynamic, deterministic or stochastic and continuous or discrete.

- Dynamic simulation models represent systems that change over time.

- Static simulation model represents systems at specific points in time.

- Deterministic models do not contain random variables and have known inputs that result in a unique output.

- Continuous models change their variable continuously over time.

- Stochastic simulation models have random variables, which lead to random outputs.

- Discrete simulation model variables only change a discrete set of points in time. (Hellström, 2002)

In “Using Discrete Event Simulation in Supply Chain Planning,” Hellström and Johnsson assess the use of discrete event simulation as an appropriate technique in supply chain planning. For several reasons, the results in the paper conclude that discrete event simulation is an “effective technique for modeling and analyzing supply chain decisions in the order and material handling processes”(Hellström, 2002, p. 12). First, simulation allows the user to analyze supply chain problems that are considered overly complex to model and solve analytically (Hellström, 2002). It also provides the user with a “holistic view” of the system and insights into the parameters and interrelationships between components in system process (Hellström, 2002, p. 5). Specifically, discrete event simulation provides definitive explanations on how supply chains perform and reasoning for the behaviors at specific times when different performance variables are applied. Hellström also credits simulation as a “well-known technique for investigating time-dependent behaviors in complex and uncertain systems” (Hellström, 2002, p. 5). This technique also allows the user to test the system processes in different scenarios to evaluate a multitude of performances without disrupting the real system. With discrete event simulation, it enables the user to represent the whole supply chain and facilitate the ability to monitor the performance of specific processes such as the inspection procedures and material handling processes. It also facilitates the ability to produce and evaluate “what if” scenarios that would be almost impossible to replicate in the real system without exhausting unnecessary time and resources (Hellström, 2002, p. 6).

Regarding simulation planning and development, Hellström and Johnsson break supply chain planning down into three hierarchical levels depending on the simulation focus, goals, and requirements. Operational planning pertains to evaluating system performance regarding timing and sequence of decisions within the system. Tactical planning is the assessment of resource adjustments and allocations within the system that correspond to system output performances. Strategic planning focuses on resource options that drive system efficiency (Hellström, 2002). The planning level ultimately drives the goals of simulation model and techniques used in the development of simulation.

Hellström and Johnsson also use a case study involving a retail supply chain in the Netherlands to justify the use of simulation for analyzing supply chain processes. This case study is a creditable example within a real-life context used to highlight the effectiveness of discrete event simulation. In this study, discrete event simulation was used to analyze how the supply chain process responds when wireless identification technology was introduced in the process. Discrete event simulation was chosen as a viable technique since the complex problem could not be solved analytically. The order process was the focus of the simulation model but other vital processes such as the material handling process were also evaluated due to the close interaction relationship in the system. Additional performance variables measured in different scenarios were the consumer service, inventory levels and lead times within the system. The simulation assisted the user in analyzing the stochastic and dynamic behaviors of the system. This analytical method was best fit to examine the complex behaviors and performance of the system over time with different inputs.

In conclusion, the result from this study validates the effectiveness of using discrete event simulation for supply chain planning. The discrete event simulation used in this case also proved to be appropriate technique for modeling both operational planning regarding the material handling process and tactical planning regarding the ordering process for different supply chain scenarios (Hellström, 2002). Specifically, the model provided the ability to evaluate the performance and behavioral variability of the material handling process in scenarios when different operational procedures were applied to the system. As a result, the benefits of wireless identification technology were discovered. The ability to analyze the interaction relationships in the system with simulation also revealed the utilization of resource and streamlined more efficient material handling procedures. The simulation provided visualization of the material flow and activities to better understand the system performance and improve the retail supply chain. Overall, effective discrete event simulation techniques provide the means to optimize supply chain processes and represent them with a high level of detail. Discrete event simulation is an effective technique to facilitate effective decision-making for complex supply chain and logistics systems. These findings in this paper will serve as a viable reference to evaluate Wilson warehouse operations.

B. EVALUATING WAREHOUSE PERFORMANCE

1. Warehouse Operations and Assessment

In preparation for this study, it is essential to review warehousing principles for the purpose of industry practices even though the results will benefit military process. The Wilson warehouse being evaluated in this thesis operates very similar to a warehouse for an industry enterprise and Dr. Edward Frazelle highlights several fundamental principles to evaluate warehouse performances.

The first step to effectively evaluate warehouse operations and assess performances is to observe and model the current operations of the warehouse. The model of current operations includes all the events or actions that take place within facility in order to meet the mission of the warehouse. In most cases, these actions involve accurately storing, accounting, receiving and shipping materials or equipment. Additionally, warehouse receiving, and shipping functions will incorporate more elaborate procedures that make up the complete workflow process. For example, a general industrial warehouse workflow receiving process of equipment will involve steps to identify the receipt, inspect the equipment, logging the receipt, identify the appropriate storage location for the equipment and finally the equipment being picked up and stored. A warehouse workflow shipping process follows a similar workflow with exception to a few steps but in reverse order. The key takeaway from observing and modeling current operations is that it inherently reveals a variety of opportunities for process improvement based on performance and time required to complete the processes. This was proven during the site visit to Marine Corps Logistics Base Albany to observe operations at the Wilson warehouse.

Dr. Frazelle introduces the benchmark assessment to assess warehouse operations. A benchmark is a quantitative assessment of one or more performance factors within the warehouse. The process of benchmarking is using the information gathered from the assessment to develop an improvement plan of action for operations (Frazelle, 2002). Dr. Frazelle concludes that the key performances indicators to assess warehouse performance are “productivity, shipping accuracy, inventory accuracy, dock-to-stock time, warehouse order cycle time and storage density” (Frazelle, 2002, p. 45). The composite assessment from the level of performance in each of these areas ultimately determine the performance of the warehouse. To effectively assess performance and implement improvements, Dr. Frazelle emphasizes that warehouse key performance indicators (WKPIs) must be precisely defined, categorized, and quantified accordingly.

Dr. Frazelle categorizes warehouse operations into three performance areas: Warehouse Productivity Performance, Warehouse Quality Performance, and Warehouse Cycle Time Performance. The Warehouse Productivity Performance use two ratios to measure effectiveness-based input and output values. For these performances, the author states,

- Productivity: the ratio of output of a resource to the inputs required to achieve that output.
- Storage density: the ratio of the amount of inventory storage capacity to the square footage in the warehouse (Frazelle, 2002, p. 54).

Productivity is measured by monitoring "the productivity and utilization of the key assets in the warehouse such as labor, space and material handling systems" (Frazelle, 2002, p. 54). Frazelle also summarizes that "storage density that is too high may indicate overcrowded conditions and storage density that is too low may indicate an underutilized facility" (Frazelle, 2002, p. 54). Storage density is measured by monitoring "the percent of available storage locations that are occupied (location utilization)" (Frazelle, 2002, p. 54).

Warehouse Quality Performance indicators break down into the four essential actions within the workflow process and assess accuracy in completing the action. The four key quality indicators for warehouse performance are represented by two indicators for "inbound handling" and two indicators for "outbound handling" respectively (Frazelle, 2002). For these performances, the author states,

- Putaway accuracy: the percent of items putaway correctly.
- Inventory accuracy: the percent of warehouse locations without inventory discrepancies.
- Picking accuracy: the percent of order lines picked without errors.

- Shipping accuracy: the percent of order lines shipped without errors (Frazelle, 2002, p. 54).

Putaway accuracy and inventory accuracy represent the warehouse performance quality for the two inbound handling procedures for equipment. Picking accuracy and shipping accuracy represent the warehouse performance quality for the two outbound handling procedures for equipment. Warehouse Cycle Time Performance is a quantitative measure of time tracked to complete the workflow processes using Dock-to-Stock and Order Cycle Time (Frazelle, 2002). For these performances, the author state,

- Dock-to-Stock Time (DTS): the elapsed time from when a receipt arrives on the warehouse premises until it is ready for picking or shipping

- Warehouse Order Cycle Time (WOCT): the elapsed time for when an order is released to the warehouse floor until it is picked, packed and ready for shipping (Frazelle, 2002, p. 55).

Dr. Frazelle provides the next step of the warehouse assessment process which is to evaluate the performance measures of the warehouse using a "warehouse performance gap analysis" (Frazelle, 2002, p. 55). This step in the warehouse assessment is where the measurable performances from the benchmark are used to assess the utilization of the warehouse and set performance goals. An example of a warehouse performance gap analysis is provided by Dr. Frazelle in Figure 6. Finally, the warehouse performance measures can be combined and quantified into a single performance assessment of the warehouse called a "warehouse performance index" (WPI) (Frazelle, 2002, p. 58). Some of the techniques and approaches by Dr. Frazelle are very informative and assists in the evaluation of the Wilson warehouse. The concept of key quality indicators and performances fell within the scope of this thesis and provided great insights to achieve the thesis objectives.

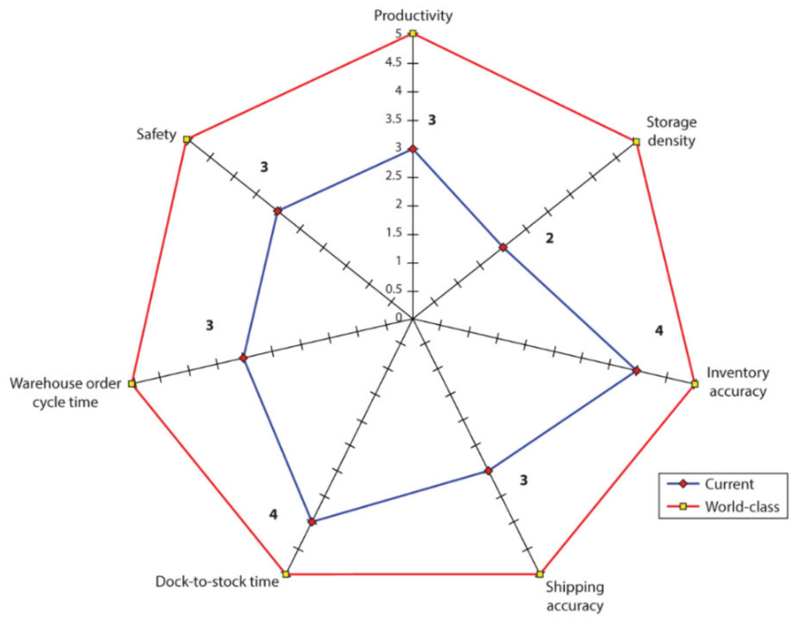


Figure 6. Example Warehouse Performance Gap Analysis. Source: Frazelle (2016).

2. Warehouse Layout and Design

The layout for a warehouse must be efficient, flexible and complement the warehouse workflow and operations. The relationship between warehouse workflow and layout is a key factor to ensure warehouse optimization. According to Dr. Frazelle, efficiency and accuracy are the keys to success in warehousing. Warehouse processes, specifically the ability to effectively receive and issue equipment, are most efficient when an accurate warehouse layout facilitates seamless integration of the processes and material handling systems (Frazelle, 2002). The warehouse layout is determined based on space requirements necessary to complete each process within the warehouse. Dr. Frazelle presents his five-step methodology for warehouse layout which require the following inputs: "the warehouse activity profile, the performance goals for the operations, the definition and configuration of the warehouse processes, and the configuration of all material handling and storage systems" (Frazelle, 2002, p. 189). Warehouse activity profile is the methodical analysis of item and order activity. It is the single most important input that drive the design and layout of the warehouse. The activity profiling process is designed to identify bottlenecks that may occur during the warehouse workflow process. This process also pinpoints opportunities for process improvements to drive the successful development and implementation of a proficient warehouse layout.

A warehouse layout should be based on the interrelationship between processes and the space requirements for each process. According to Dr. Frazelle, “the first step in laying out a warehouse is to determine the overall space requirement for all warehouse processes” (Frazelle, 2002, p. 189). To determine the overall space requirement for warehouse operations, the space requirement for each process must be assessed and determined. Space requirement is broken down into two allocations, the floor space requirement and storage space requirements. A best practice for determining the warehouse floor space requirement is to allocate enough staging space to receive a maximum amount of equipment based on average warehouse receiving activity. The allocation of storage space is more complex since the warehouse must allocate for peak planning considerations (Frazelle, 2002). The duration of peak is the key consideration factor for determining storage space requirements. Dr. Frazelle determines this requirement based on the ratio of peak storage compared to the average storage requirements. He states, “if the duration of peak is short-lived and the ratio of the peak to average ratio is high,” then the warehouse can be expected to accommodate the peak storage (Frazelle, 2002, p. 190) . For long peak durations and the ratio of the peak to average ratio is low, “then the warehouse storage capacity should be sized at or very near the peak requirements” (Frazelle, 2002, p. 190). Dr. Frazelle provides graphical representation of the two scenarios in Figures 6 and 7.

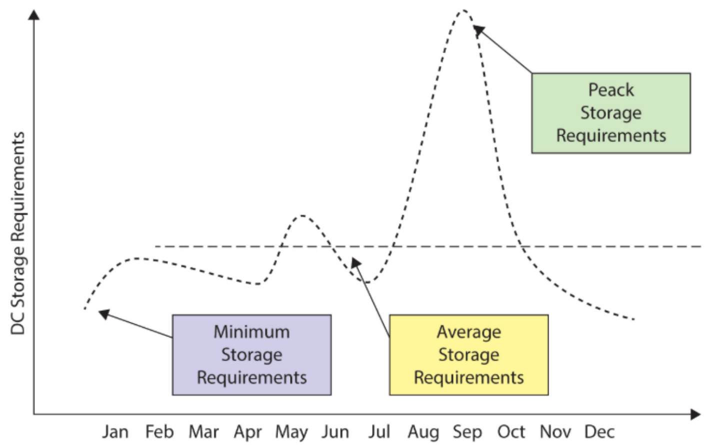


Figure 7. Storage Capacity Requirements with a Short-Lived High Peak-To-Average Storage Ratio. Source: Frazelle (2016).

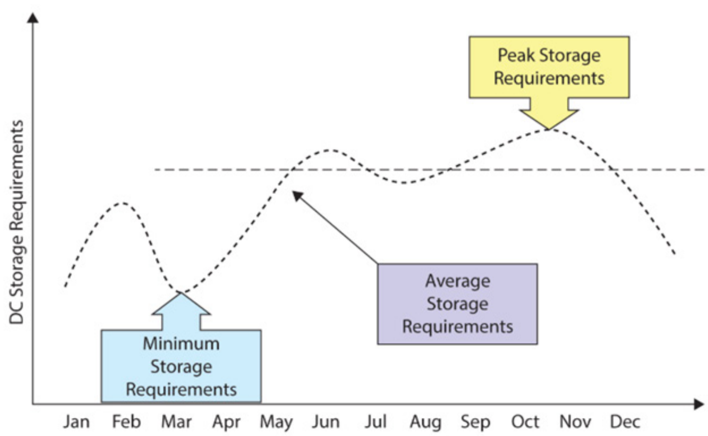


Figure 8. Storage Capacity Requirements over Time with Low Peak-To-Average Storage Ratio. Source: Frazelle (2016).

For material workflow planning, Dr. Frazelle presents three warehouse flow layout designs: U-shape, straight-thru, and modular. The U-shape flow design will be the only layout discussed because it shares the same design and workflow as the Wilson warehouse and falls within the scope of the research. This design layout is unique for its simplicity and symmetrical approach for receiving and shipping material, seen in Figure 9 (Frazelle, 2002).

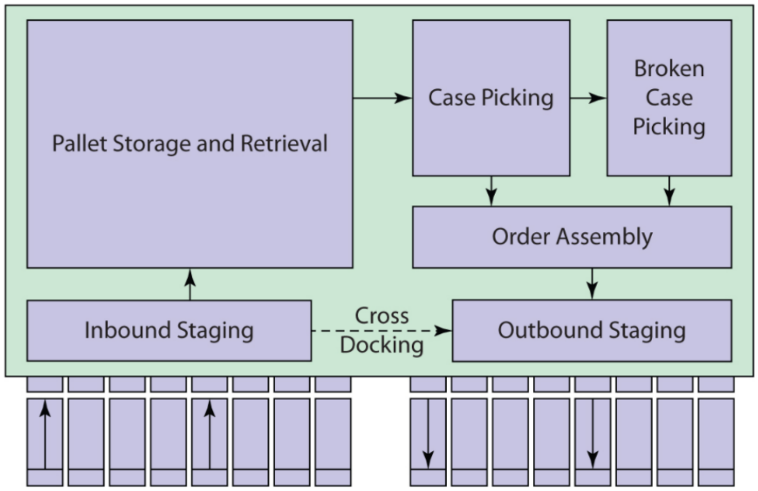


Figure 9. Typical U-Shaped Flow Pattern. Source: Frazelle (2016).

The receiving and shipping docks are located adjacent and on the same side of the building. When equipment is received in the warehouse, receiving material is moved into storage located in the back of the warehouse. For shipping, equipment is picked from storage location and processed towards the shipping dock. The space in the middle of the warehouse is allocated for putaway, cross-docking, material handling and sortation for shipping. Cross-docking is the process when unloading materials goes directly from the receiving dock and processed for shipping without requiring storage actions. A U-shape flow design facilitates several advantages that are primary contribute to the combined utilization of resources. Receiving and shipping processes can share the same dock doors which also facilitates efficient cross-docking and use of warehouse resources. Specifically, putaway and picking trips by material handling systems can easily be combined due to the location of the storage area and dock doors. The Wilson warehouse layout presents several features and advantages of a typical U-shaped flow pattern.

III. METHODOLOGY AND MODELING APPROACH

This chapter provides explanation and justification for the methods and model development techniques used for this study. It outlines the problem framing methodology and conceptual modeling frameworks used to develop the discrete event simulation model as it related to warehouse operations. To guide the development of the simulation model, it is useful to break down the study into collective tasks and parts to better understand of problem and what modeling approaches to take. The methodology required a thoroughly evaluation of the scope and level of detail to incorporated in the model. It is also essential to identify milestones to plan the model development and set achievable thresholds through the model development process. The feedback from the sponsor and warehouse managers throughout the model development were also instrumental for needed clarifications. Lastly, after gathering the problem framing guidance from sponsor and thoroughly understanding of the problem and approaches, the implementation of the warehouse workflow model began.

A. CONCEPTUAL MODELING FOR SIMULATION

The initial priority for this study establishes the conceptual model framework for and identifies the requirements of a conceptual model. According to Robinson, "conceptual modeling is the process of abstracting a model from a real or proposed system" (Robinson, 2008a, p. 278). The guidance and framework provide by Robinson assists in establishing requirements and the model development process for the warehouse simulation model. The most important aspect for the successful design of the simulation model is clearly identifying the model requirements which also includes data requirements and a practical timeframe for development. The timeframe for the development of the model was about ten months from the completion of the site visit. The timeframe was considered ample time to provide a useful simulation model within the scope of the study. The conceptual modeling framework assists in creating a discrete event simulation for modeling operations systems, which directly aligned with the scope of this study. There are two types of conceptual models, a domain-oriented model and design-oriented model (Robinson, 2008a). For the purpose of this study, a domain-oriented model is the primary focus and provides a detail representation of the problem domain, which is the Wilson warehouse operations. The following key principles were established by Robinson for conceptual modeling and used for this study:

- Conceptual modelling is about moving from a problem situation, through model requirements to a definition of what is going to be modelled and how.
- Conceptual modelling is iterative and repetitive, with the model being continually revised throughout a modeling study.
- The conceptual model is a simplified representation of the real system.
- The conceptual model is independent of the model code or software (while model design includes both the conceptual model and the design of the code.
- The perspective of the client and the modeler are both important in conceptual modelling (Robinson, 2008a, p. 281).

During the methodology phase, a conceptual modeling approached is used prior to any coding in Simkit. To assist in this effort, the development of the simulation model is broken down into four key processes stated by Robinson: "conceptual modeling, modeling coding, experimentation, and implementation" (Robinson, 2008a, p. 282). These processes, illustrated in Figure 10, provides an iterative approach to develop the problem situation that feeds into the development of the conceptual model and simulation. The requirements for the simulation model drive the need to improve the problem situation which emphasize its importance to the modeling process. The first step before beginning the development of the model is to clearly understand the problem. This was accomplished through multiple discussions with the sponsor and warehouse managers and a site visit. A clear problem situation allowed better understanding of the simulations requirements and the steps required to produce an accurate model. This concept also provides a holistic view of interrelationships between components of the real system that are simulated.

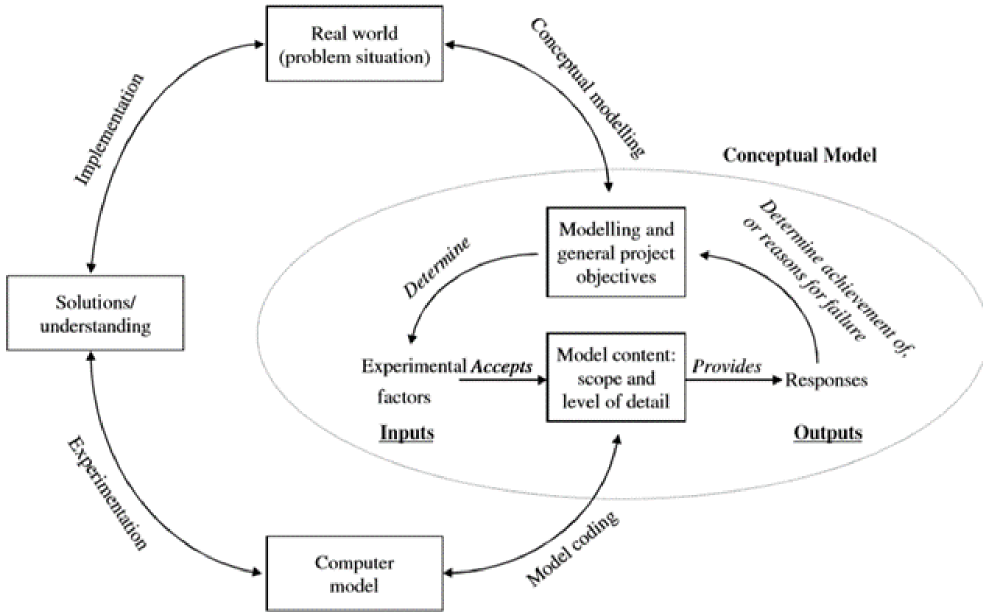


Figure 10. Conceptual Model in the Simulation Project Life cycle.
Source: Robinson (2008).

Once the problem situation is understood, the problem scope is used to develop the framework to develop the simulation model. The conceptual model consists of four main components: "objective, inputs (experimental factors), outputs (responses), and model content" (Robinson, 2008a, p. 283). These components are also illustrated in Figure 11 to outline the initial framework used to design the warehouse model. According to Robinson, a conceptual model is best defined as:

> A non-software specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions and simplifications of the model (Robinson, 2008a, p. 283).

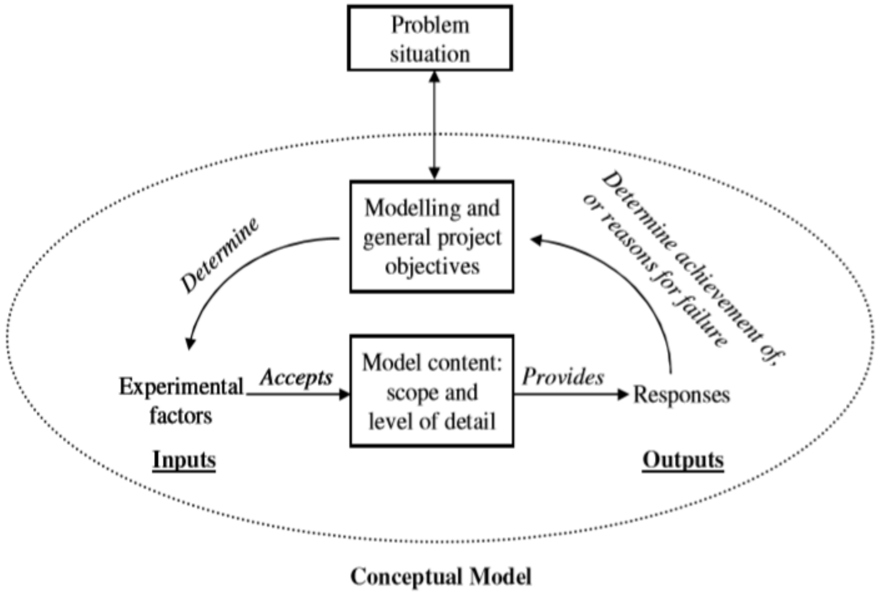


Figure 11. Framework for Designing the Conceptual Model. Source: Robinson (2008).

For the modeling framework, this study follows the five steps established by Robinson for the development of the conceptual model:

1. Understand the problem situation.
2. Determine the modeling and general project objectives.
3. Identify the model outputs (responses).
4. Identify the model inputs (experimental factors).
5. Determine the model content (scope and level of detail, identifying any assumptions and simplifications, [and identify data requirements]). (Robinson, 2008b, p. 291)

Following the modeling framework, the two types of objectives are the modeling objectives and general project objects. The modeling objectives explain the purpose and outcomes for the warehouse simulation model in terms of performance. The general project objectives define the specific attributes of the model. The objectives are identified to avoid issues related to the utility of a model that "includes issues such as ease-of-use, flexibility (i.e., ease with which model changes can be made), run-speed and visual display"

(Robinson, 2008a, p. 286). The inputs or experimental factors are the variables of that can be adjusted to improve the understanding of the problem situation. The input variables are related to the objectives of the model and support whether the objectives have been achieved, or failed, and for what reasons. The outputs or responses are also related to the inputs. Finally, the last step includes determining the model content which depends on the level of accuracy to achieve the model objectives.

The model content involves determining the scope of the model, identifying the model boundaries, recognizing the activities and resources in the real system, and determining the details to include in the model (Robinson, 2008b). This process determined the level of detail included or omitted from the real warehouse workflow process. The level of detail modeled for each activity with the workflow process was ultimately determined based on the significance of the activity to the objectives of the model. The model simplifications and assumptions are also derived by the objectives of model and are identified based on the scope and level of detail of the model. The specific modeling simplifications and assumptions will be discussed in greater detail in Chapter IV. However, it is notable to emphasize that the use of model assumptions supports the lack of data requirements or actual information about the real system. Contextual data such as the warehouse layout was provided to aid in the developing some model characteristics. Collectively, information provided during the site visit was used to develop the simulation model and in cases, where information is unavailable, best alternative simulation methods are used.

1. Simple Models

The conceptual model framework is very elaborate for the purpose of model development, but this detailed methodology is essential to ensure that the model objectives were understood and avoid oversight. The conceptual model framework provides a building block approach to understand the problem and develop the model that best replicates the issues in the real system. The "overarching requirement" for any simulation model are to keep the model simple, meet the objectives, and avoid the development of complex model that is hard to interpret (Robinson, 2008a, p. 286). The goal to develop a simple model adopted for this study and based on five characteristics of a simple model established by Robinson:

1. Simple models can be developed faster

2. Simple models are more flexible

3. Simple models require less data

4. Simple models run faster

5. The results are easier to interpret since the structure of the model is better understood. (Robinson, 2008a, p. 286)

The best modeling principle is to build the simplest model possible to achieve the modeling and simulation objectives (van der Zee, Tako, Robinson, Fishwick, & Rose, 2018). The effectiveness of a simple model is graphically illustrated in Figure 12 to demonstrate the relationship between model accuracy and model complexity (Robinson, 2008a).

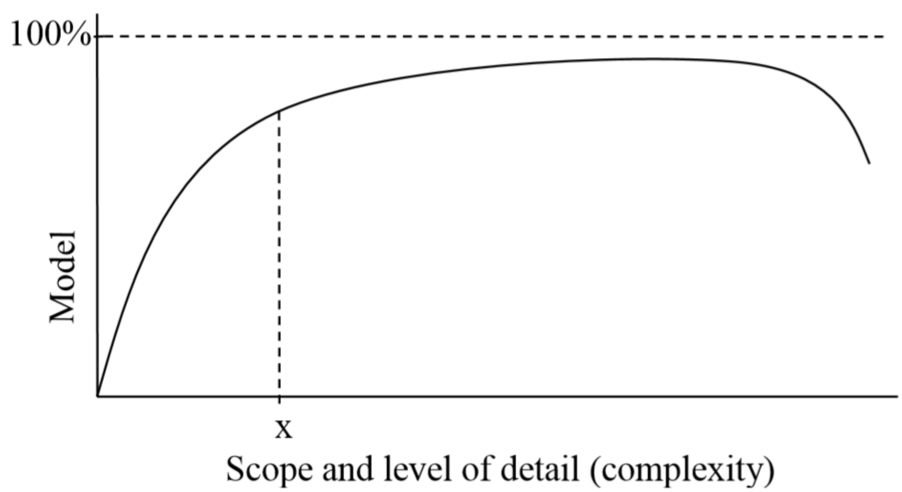


Figure 12. Relationship between Model Accuracy and Model Complexity. Source: Robinson (2008a).

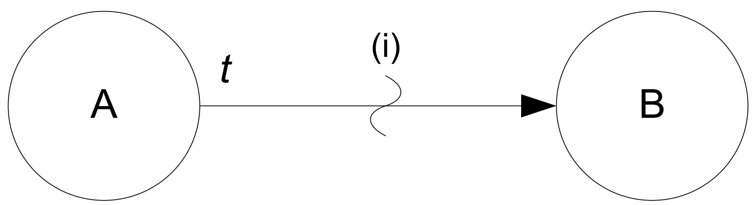
According to Robinson, as the level of complexity increases it is reasonable to expect the accuracy of the model to increase too but never achieve 100% accuracy

(Robinson, 2008a). This graphical representation also emphasizes that too much complexity is detrimental to the accuracy of the model. Specifically, inaccurate results are likely from a model that fail to support the information and data requirements. The model objective and implementation should be driven by the data requirements and supported by available data for the problem set (van der Zee et al., 2018). It is also notable to develop a model that satisfies the objectives to inform the user. Modeling all aspects and information regarding the real system can lead to a model with diminishing returns if its implementation is too complicated. The model framework for this study assists in making the appropriate fundamental decisions to determine what to model and how. There is no standard guidance on developing the perfect conceptual model because the model effectiveness is highly dependent on the scope of problem situation as well as the perception and preferences of the user. However, the methods for this model were thoroughly considered with all viable options to produce a model that ultimately supports the user based on the problem situation.

2. Event Graphs for Simulation Modeling

Event graphs, also known as simulation graphs, are efficient techniques used to provide a graphically representation of the model behaviors and the *Future Event List* logic for a discrete event simulation model. An event graph is extremely useful for discrete modeling because it presents no limitations to guide the develop of the discrete event simulation for any circumstance. An event graph approach is a simple, flexible, and an effective design which make it the “most ideal tool for rapid construction and representation of simulation models” (Buss, 1995, p. 74). Events graphs serve as the conceptual model of the simulation and illustrate all the events and behaviors in the warehouse workflow process that will take place in the simulation before coding.

Event graphs use nodes and edges to represent the key events and scheduling of events for the workflow process. Specifically, each node corresponds to an event, or state transition and each edges corresponds to the scheduling of other events (Buss, 1995). The edges are associated to a boolean condition and time delay to allow an activity or schedule next event when the rule or boolean condition is true. The use of boolean conditions are very effective to represent processes where simultaneous events occur and requires a specific condition to execute the next activity or events. The edges and boolean conditions within the event graph also prioritize the scheduling of events where simultaneous actions within the process occur. This technique ensures that the simulation behaves like the real system and simulates the specific workflow procedures in the process. It is important to note that a priority edges will not always be indicated on the event graph but the coding software for the simulation will support the scheduling prioritizations. This aspect of the event graph methodology can seem trivial, but there are instances where there are multiple edges coming from a single event. For simplicity, Figure 13 shows the fundamental construct and interpretation for an event graph. The time delay (t) is indicated at the tail of the scheduling edge and the boolean condition is positioned in the middle, using state variables in place of (i), above the edge indicated by a wavy line (Buss, 1995).



Whenever Event A occurs, if condition (i) is true after A's state transition, Event B is scheduled to occur t time units later

Figure 13. Fundamental Simulation Graph Construct. Source: Buss (1995).

The initial event in the event graph methodology is represented by an Arrival Process with Run event, illustrated in Figure 14 (Buss, 2001).

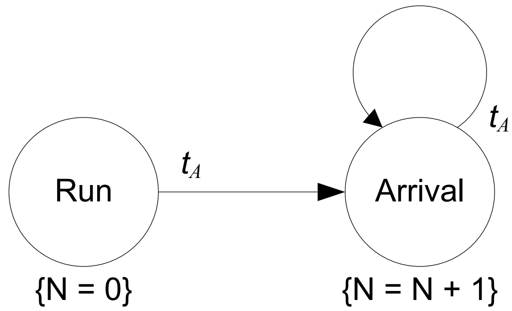


Figure 14. Arrival Process with Run Event. Source: Buss (2001).

The Run event represents the initialize step of the simulation model and where the state variables are set to zero before the Arrival event is scheduled. The state transition that initializes (N) is indicated below the Run Event between the brackets. The direct edge from the Run event to the Arrival event illustrates the Run event scheduling the Arrival Event (t_A) time units later. The (t_A) time delay is a model parameter and represents an interarrival time distribution. The Arrival event illustrates the start of the inbound receiving process and represents shipments arriving of into the warehouse for storage. The (t_A) and the curling edge illustrate the schedule of another Arrival event (t_A) at some time units in the future. The interarrival time (t_A) is a constant, sequence of random time intervals to represent the consist arrival of shipments in the warehouse. The sequence (t_A) can either be a pre-collection of numbers or generated by a probability distribution. The state transition for the Arrival event is the state variable being incremented to account for the cumulative number of arrivals (N), this action is indicated between brackets below the Arrival event. As the construct of the event graph continues, the occurrence of the Arrival event will not only schedule another Arrival event, but it will also attempt to schedule the next event in the simulation model. The same methodology and event graph principles previously mentioned remain consistent throughout the representation of the warehouse workflow model using events, edges, and state transitions.

B. DISCRETE EVENT SIMULATION

Discrete event simulation is the principle modeling technique used to represent the warehouse workflow processes at the Wilson warehouse. This section explains the purpose of a discrete event simulation model. This section also discusses the primary elements of discrete event simulation and the methods incorporated in the simulation model for this thesis. A discrete event simulation is the modeling of events and interactions within a process that represent event driven actions occur over a time period. The key elements in a discrete event simulation model are states, parameters, events, and the scheduling relationships between events (Buss, 2017). The four main elements that drive the development of a discrete event simulation model are summarized by Buss in four steps:

> 1. Define the parameters of the model (the variables that will not change during a single run).
>
> 2. Define the state variables of the model (the variables that will change in piecewise constant state trajectories) and for each state variable specify its initial value.
>
> 3. Define each Event by specifying its state transition and assigning a unique name to the Event.
>
> 4. Define the scheduling relationships between Events. For each Event that could schedule another, give the condition under which it will be scheduled and the amount of time in the future ("delay") the Event will be scheduled to occur. (Buss, 2017, p. 1–6)

1. States and State Variables

A state variable describes the variables in a simulation that have the possibility to change value over the duration of the any simulation run. "The collection of all state variables is called the *state space* and the value of a state variable over time is defined as the *state trajectory*" (Buss, 2017, p. 1–1). The relationship between state value changes over simulation time can be illustrated in a state trajectory graph, shown in Figure 15 (Buss, 2017).

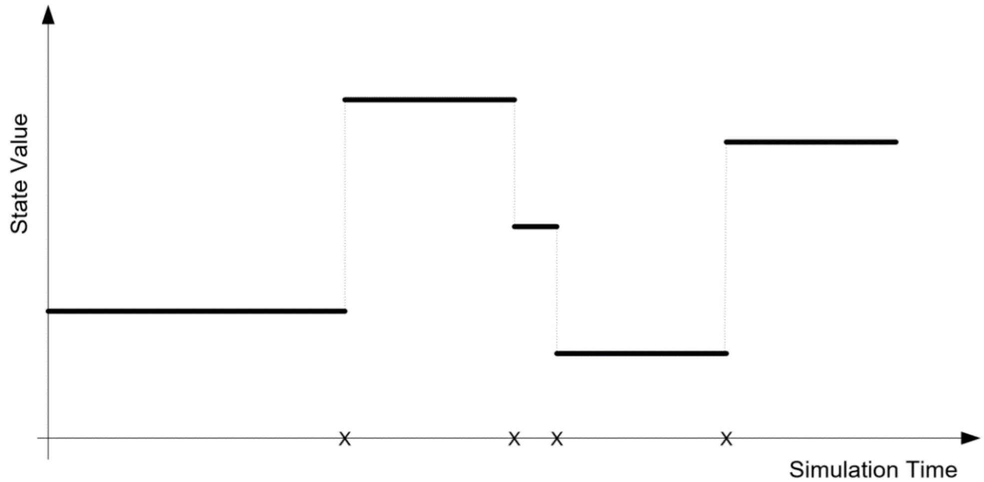


Figure 1-1. A Typical DES State Trajectory

Figure 15. A typical Discrete Event Simulation State Trajectory.
Source: Buss (2017).

The state variable values throughout a simulation run have the possibility to stay constant, increase, or decrease depending the actions and performance of the simulation model. Discrete event simulation favors variables with a piecewise constant state trajectory, but the methodology is still effective and appropriate in modeling state variables that change continuously throughout a process, having little to no limitations in representing complex system activity. The value of the state variables heavily tied to the number of events that scheduled over the duration of a simulation run. State variables are essentially the variables that are expected to change at different points in time, such as number of shipments inspected or racked. Due to the event-driven nature of discrete event simulation, each state transition can be identified with an instantaneous occurrence of an Event (Buss, 2017). The (x) depicted on the horizontal axis in Figure15 shows the occurrence of Events for the state variable. Events are considered the building blocks of a discrete event simulation model and define a state transition in the simulation run. A simulation run consists of a sequence of events where state transition results in state trajectories for each of the state variables (Buss, 2017).

2. Simulation Events

Simulation events represent the key actions in a process that occur at certain points throughout the duration of a simulation run. The Events in the simulation model also facilitate state transitions or a change in state of the overall process. As the building blocks for a simulation model, Events are also used to schedule the next Event in the process and must be defined into to produce a state transition. When an event occurs within the process, the actions executed within the event affect the *state* of the overall process. The events represent the actions taken on a specific object, such as a shipment, as it passes along within in the simulation model. For an event driven simulation, it is essential to understand what event will occur and when throughout the simulation run.

3. Scheduling Relationships and Time Advance

The discrete event simulation is not completed by simply defining the Events within the simulation. Events implemented by themselves will not replicate how the simulation will perform. The performance of the simulation requires the implementation of rules in the form of time delays, scheduling edges, and state variables to describes the actions that are and will take place in the process. The actions in the discrete event simulation represent Events defined by specifying its state transition function and forming *scheduling relationships* between Events (Buss, 2017). The given actions for each Event affect the value of state variables and may cause another Event to be scheduled sometime in the future using a time delay in most cases. A simple example is an Event where a shipment arrives in the warehouse, a second Event might be the shipment being moved to the inspection available for induction into the facility. The first Event (shipment arrival) schedules the second (shipment movement to inspection area) at a time in the future that depends on whether there is available personnel or space to perform the task. As a result of these actions the state variables associated to these Events will be affected in the simulation to account for the change in the number of shipments in the arrival area and reflect the number of shipments that are now in the inspection area. The development of *scheduling relationships* between Events is the driving force of the simulation to represent the execution of actions in the process and evaluate the overall performance over time for a simulation run.

As previously mentioned, discrete event simulation operation is based on event-driven principles to represent the actions within a process or system. The decision to implement a time-step model or discrete model is entirely dependent on the process being modeled and how to best address the problem using simulation. A time-step approach for simulation model can be effective and most appropriate for evaluating small and simple systems and evaluate performance for a sequence of continuous procedures over time. The time interval for this type of simulation is typically fixed and the system is evaluated by observing the events that have been performed during the specific time interval. It is also important to note that in a fixed time-step model, all the events that take place during the time interval are treated as if they occur simultaneously at the end of the interval. However, when the system being modeled is large and complex, a discrete event modeling approach will be most appropriate. There may also be the requirement to measure the performance for each event in the simulation which also make a discrete event approach more favorable. In cases where a time-step simulation method is mistakenly chosen over a discrete event method, it may result to the simulation not detecting the one or more events at the specific time the event occurs. The time-step simulation advances simulation time in a regular, consistent manner, and will only provide a holistic value of the simulation. This simulation approach makes the simulation susceptible to leaving out the most prominent details of the system that could lead to effectively addressing the problems in the process (Alrowaie, 2011). The benefits of using a discrete event modeling approach allow the simulation to advance time based on the occurrence of the event and as the simulation shifts to the next event. The discrete event approach also facilitates the ability to capture and track the time as each event occurs in the simulation. The method of time times advances in a discrete event simulation model is referred as *Next Event* (Buss, 2017). This method advances simulation time in unequal increments as the simulation transitions from the scheduled time of one Event to another. Figure 16 illustrates the Next Event algorithm featured in the simulation for this thesis (Buss, 2017):

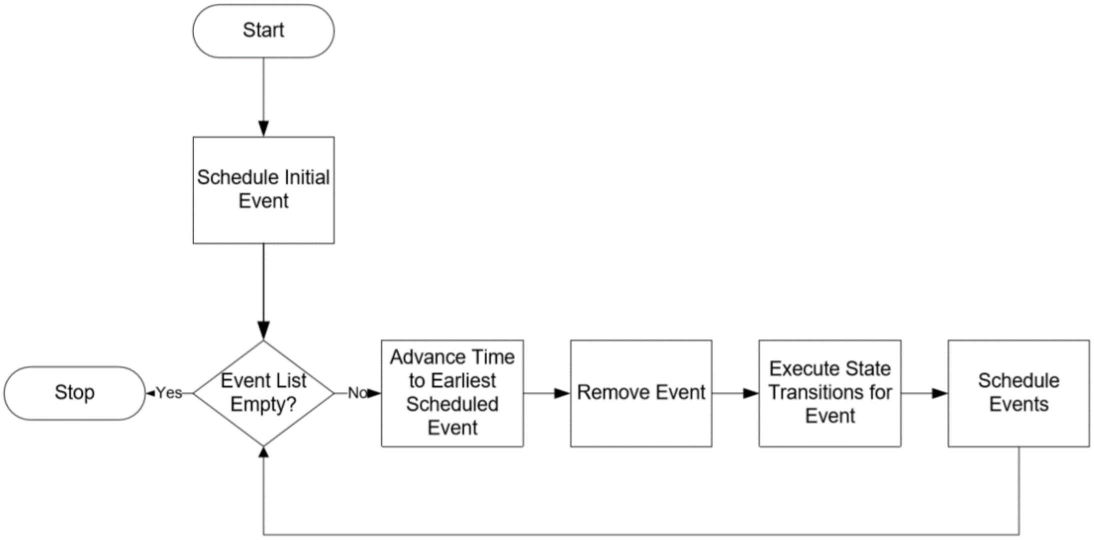


Figure 16. Next Event Algorithm. Source: Buss (2017).

4. Future Event List

The concept of the *Future Event List* is most useful tool for verifying the discrete event simulation model is performing accurately, according to the Next Event algorithm. The *Future Event List* identifies when and what event is being performed throughout the simulation run. The contents of the *Future Event List* are called *Event Notices* which contain all the information to process the *Event* (Buss, 2017). The *Event Notices* are essentially time stamps throughout the simulation run that display what event is being scheduled for execution and the scheduled time for the occurrence of the Event. When the simulation starts, the initial event is scheduled and the event notice is placed on the *Future Event List*. As the simulation advances through the first scheduled event, it is removed from *Future Event List* and actions assigned are executed. Then, the simulation will advance to the next scheduled event, place it on the *Future Event List*, and perform the respective assigned actions. This cyclic process will continue until the simulation time is reached or there are no future events to be scheduled for the simulation.

5. Simulation Parameters

A simulation parameter describes the variables in a simulation that do not change value over the duration of the any simulation run. Simulation parameters are the variables that are not expected to change at different points in time, such as number of personnel, forklift systems, or inspection spaces in the process being modeled. Simulation parameter also represent the constraints of the simulation model. Simulation parameter differ from state variables because parameter account the total number of a resource, where state variables represent the amount of the resources at a specific time during the simulation run.

6. Simkit

Simkit is simulation software used to build the discrete event simulation model for this thesis. Simkit is an open source, Java-based application developed by Dr. Arnold Buss at the Naval Postgraduate School to model modern operating systems. Simkit is "platform-independent, written in Java programming language, and will run on any reasonably model operating system" (Buss, 2002, p. 243). The simulation application uses "classes" to implement the components and behaviors of system or process in the discrete event simulation. Simkit is a set of Java packages and was specifically developed to streamline the development of a discrete event simulation using event graphs. Figure 17 provides the translation between the basic elements of an event graph and the implementation into Simkit.

Event Graph	Simkit
Simulation Component	Subclass of SimEntityBase
Event Graph Parameter	Private instance variable, setter and getter
State Variable	Protected instance variable, getter, no setter
Event	‘do’ method
Scheduling Edge	Call to `waitDelay()` in scheduling event’s ‘do’ method
Run Event	`reset()` method to initialize state variables; `doRun()` method to fire PropertyChange events for time-varying state variables
Event scheduled from Run event	Call to `waitDelay()` in `doRun()` method
Event scheduled from any Event	Call to `waitDelay()` in scheduling event’s ‘do’ method
Event cancelled from any Event	Call to interrupt() from canceling event’s ‘do’ method
Priority on Scheduling Edge	`Priority` instance as third argument to `waitDelay()`
Argument(s) on Events	Arguments in corresponding ‘do’ method
Parameter(s) on Edges	Add parameter values/expressions last (in correct order) in `waitDelay()`
Canceling Edge	Call to `interrupt()`

Table 8-1. Event Graph Components and Their Simkit Counterparts

Figure 17. Event Graph Components and Their Simkit Counterparts. Source: Buss (2017).

The development of the discrete event simulation model in this thesis uses Simkit in an integrated developer environment for Java, called NetBeans. The event graphs for the simulation model are not a built-in graphical capability of Simkit or NetBeans. The event graphs are first created using graphical capabilities in Microsoft Visio and used as the framework to implement the discrete event simulation into NetBeans using Simkit. The simulation built in Simkit is a directly reflection of the event graph components and associated simulation components to represent the behaviors of the process or system. The Java classes within Simkit use a combination of methods and functions to represent the objects in the simulation being passed through events of the process being modeled. Simkit can also generate statistical information from each simulation run using its statistical libraries. These capabilities will prove to be instrumental in the analysis used to evaluate the performance of the warehouse workflow process.

C. SITE VISIT AND FINDINGS

A two-day site visit was conducted at Marine Corps Logistics Base in Albany, GA in preparation for this thesis project. The tours of the Wilson warehouse and subsequent meetings with the thesis sponsor facilitated firsthand experience and perspective of the warehouse operations conducted in the new warehouse facility. This valuable opportunity also provided direct communication with leadership and warehouse managers to discuss model expectations and refine the scope of this research. The tours of the Wilson warehouse provided ample time to meet with key warehouse personnel and discuss the specific warehouse functions for the new facility. It also provided lengthy walk-throughs to feature all forklift systems, personnel, and steps involved in the warehouse workflow process. There was also brief discussion and feedback provided by warehouse personnel regarding the warehouse performances they expected to achieve in the new facility. There was optimism that the new modern facility would promote a smooth transition and streamline working conditions for the personnel. This experience also provided familiarity with the new issuing and receiving procedures that would have been difficult to obtain without the direct encounter. The ability to observe both processes in person helped answer specific questions about the workflow and better understanding of the potential bottlenecks that were likely to occur during the complete workflow process. The workflow diagram in Figure 18 was constructed based on the information gathered during the site visit (E. Daniels, personal communication, 10 December 2018):

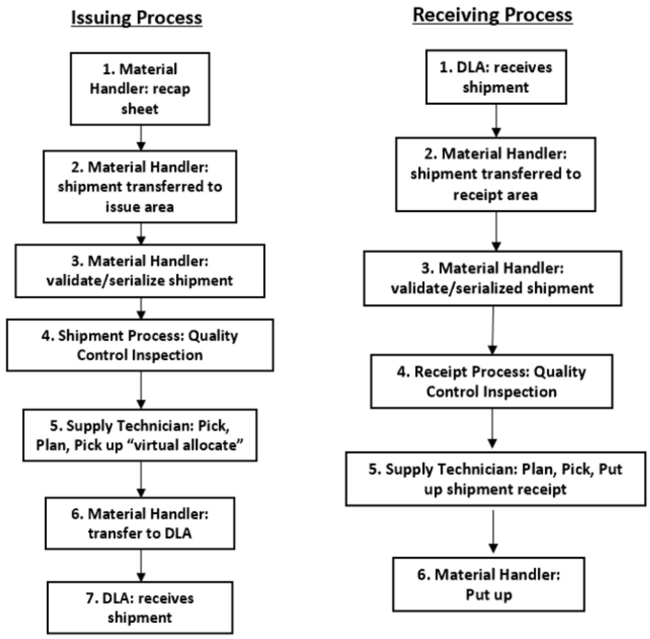


Figure 18. Wilson Warehouse Workflow Diagram for receiving and issuing process. Source: Daniels (2018).

1. Model Intent and Direction

The site visit provided key workflow information and insights to drive the intent and direction of the warehouse model. Based on the workflow diagram and the warehouse floor plan provided in Figure 19, the primary focuses of the model were determined and aligned with the sponsor's expectations. Prior to the site visit, the scope of this thesis research was broad and lacked specific model requirements. Initially, there was many directions this research could pursued which included modeling the warehouse processes, determining the most optimal and performance-driven warehouse layout, and a study of inventory management procedures. All these options were considered based on the assumption that the warehouse was empty and not operational until the completion of this study. However, during the site visit, it was discovered that the warehouse layout had already been determined due to operational timelines and mission requirements. This circumstance left little to no requirement for recommending a new warehouse layout and shifted focus to providing recommendations to improve efficiency and achieve optimal warehouse performance. The following floor plan depicts the Wilson warehouse layout:

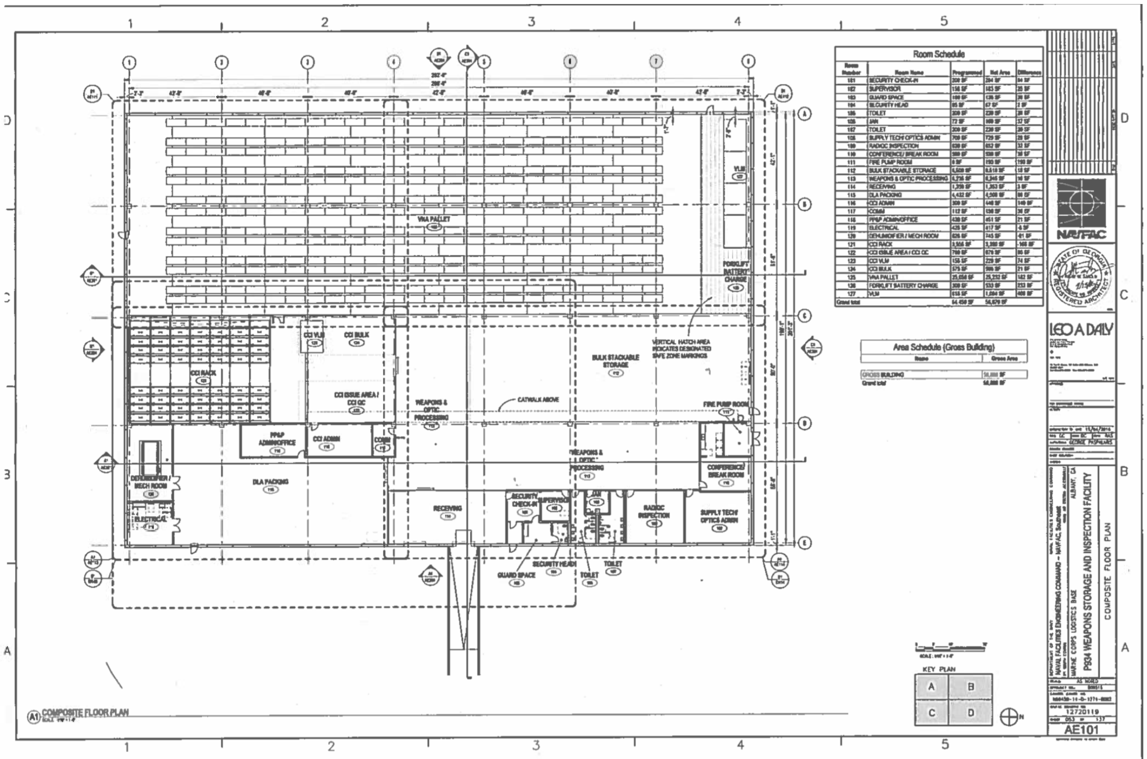


Figure 19. Wilson Warehouse floorplan. Source: Daniels (2018).

The first observation for the new warehouse was the large decrease in area of the new warehouse compared to the previous facility. The Wilson warehouse provides 57,000-square-feet to conduct all the its necessary warehouse functions when included receiving, issuing, and storing military equipment. The previous warehouse facility was 120,000-square-feet to conduct the same warehouse functions so space management became an immediate concern and focus of this study. The second focus involves the use of material handling equipment, the forklift systems, used to conduct the primary actions within the workflow process. The two processes, issuing and receiving, were conducted simultaneously so effective and optimal use of resources such as the forklift systems is an essential goal to achieve efficient warehouse performance. The direction of the warehouse workflow model still focuses on reducing the potential bottlenecks in the workflow processes. The warehouse floor plan shrunk greatly so incorporating this challenge in the model presents possible solutions. The model intent is to demonstrate how different space and resource allocations will affect the warehouse performance. This objective is achieved by modeling the current warehouse workflow processes for issuing and receiving equipment and analyze the performance with different resource parameters using the discrete event simulation model. The actions in the processes involving material handling and space allocation are the focal points of the model and serve as the simulation parameters. The simulation model determines where bottlenecks are occurring in the warehouse processes and demonstrates the ideal parameters that promote the best warehouse performance.

2. Modeling Milestones

The initial efforts in the development process for this thesis focuses on achieving a high level of understanding of warehouse operations and setting the foundation for implementation. At this point, no code was implemented, but event graphs were developed to aid the development of the simulation model. The building block approach helped drive the development of the iterative models and simulation that will used in this thesis research and ensured the appropriate factors and behaviors were represented accurately. It is necessary to break down the development of the simulation model into manageable parts to verify each iteration of the simulation before building more complex iterations of the model. Multiple modeling milestones were established to effectively manage the model progression and promote simple modifications to ensure accuracy. The following five milestones were developed to achieve the objectives of the thesis:

1. Basic warehouse arrival process, pilot model. This milestone provides the initial high-level overview of the warehouse workflow process. This pilot model uses a simple single server concept to illustrate the key actions in the workflow process without many of the real-world complexity of the real system. This stage in the development process serves as the initial foundation to lean from and build upon for a finished product.

2. Warehouse arrival process enhanced, material handling process. This milestone is an extension of the pilot model. This milestone expands the scope of the single server model by incorporating the key aspects in the real-world system to the warehouse model. The scope of this model focuses on the key parameters, variables, and event to represent all steps in the warehouse shipment receiving process. This milestone does not represent the complete workflow process, but model characteristics is increased to simulate the real warehouse system, collect data, and evaluate throughput.

3. Warehouse arrival process with receiving and issue process, material handling process. The main effort for this milestone constructs the backend of the warehouse simulation model. The warehouse issuing process is implemented to the warehouse model to represent simultaneous warehouse activity. Information gathered during the site visit and follow-on communication help establish the last parts of the warehouse workflow simulation model. This milestone incorporates all steps in the warehouse workflow process and effectively captures desired statistics in order to measure warehouse performance and efficiency.

4. Statistical analysis and warehouse performance output. Warehouse performances are calculated and recorded in the simulation outputs for each simulation run. The utilization warehouse resources are also calculated to measure efficiency and identify bottlenecks in the model. The testing of the simulation model focuses on calculating statistical outputs for multiple replications. A nearly orthogonal Latin hypercube experimental design and statistical software produces the desired data using several parameter settings. At this point, simulation time and resources are adjusted to capture warehouse performance at steady state and determine optimal inputs and performances. The statistical analysis software assesses the significance for each input variable on warehouse performance. The outputs from the statistical analysis supports key

decision makers to identify issues and to make better informed workflow decisions.

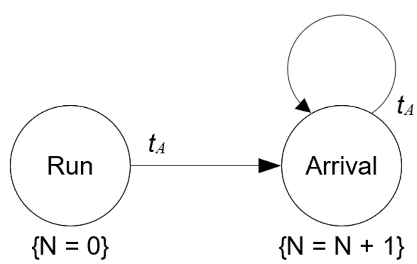
5. Model refinement and recommendations. The objective of this study and the simulation model provides the sponsor with compiled warehouse workflow tool to measure performance and assist decision making. The sponsor can continue modifications and refinements to the model as data and information regarding the warehouse operations changes. This milestone will continue to be ongoing to allow the users to conduct new simulation runs and test the relationship between resources and warehouse performance. Finally, warehouse workflow recommendations are provided to the sponsor based on statistical analysis and findings from the study.

IV. IMPLEMENTATION

The implementation phase begins with gaining a generalized understanding of warehouse operations and the purpose of the warehouse model. This effort involves gradual implementation of the different components of the warehouse workflow model over multiple iterations. The model milestones also serve as an effective guide during this phase to ensure that the model objectives are met, and model development process is smooth.

A. ARRIVAL PROCESS

This warehouse arrival process represents the first step in the warehouse system. This event is the simplest step in the workflow process and illustrated in the model using an arrival process concept. The event graph, shown in Figure 20, illustrates the shipment arriving in the warehouse at various times by using a random generated interarrival time. This component of the warehouse system is very simple and sets the foundation to implement more detail throughout the implementation phase. This step only uses event graphs to represent warehousing behaviors before coding in Simkit.



Parameter

$\{t_A\}$ = sequence of (possibly random) times between the occurrences of the Event.

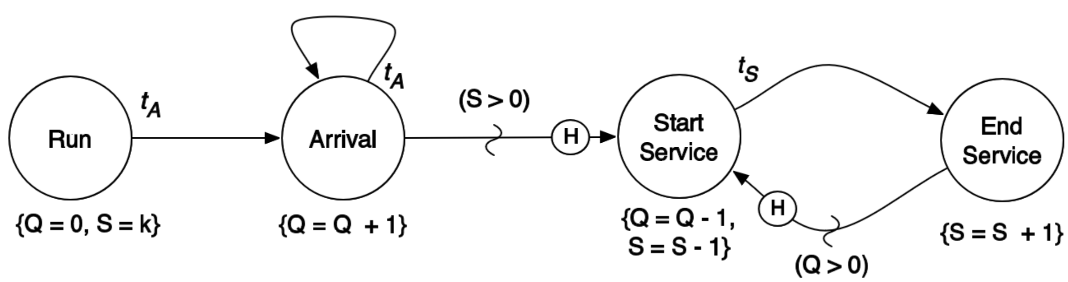
State

N = number of times the Event has occurred. Its initial value is 0.

Figure 20. Arrival Process Event Graph. Source: Buss (2017)

B. WAREHOUSE OPERATIONS CONCEPT

In this step, the warehouse model use event graphs to represent additional warehousing events and behaviors. This approach continues to drive the development of the model and ensure that the appropriate warehousing characteristic are captured in the model. Some events and behaviors are added to represent follow on actions after a shipment arrives in the warehouse. This design also uses an events graph, shown in Figure 21. At this stage in the implementation phase, no code is written in Simkit. To characterize the warehouse behaviors for this portion of the warehouse system, a single server concept is most appropriate and afforded the right amount of detail and simplicity.



Parameters

$\{t_A\}$ = sequence of (possibly random) times between the occurrences of the Event.

k = total number of warehouse resources.

State

Q = number of shipments in the warehouse queue. Its initial value is 0.

S = number of warehouse resources to perform warehousing tasks. Its initial vale is the total of resources (k).

Figure 21. Single Server Concept Event Graph. Source: Buss (2017).

The events in Figure 21 represent a single-server concept where a shipment arrives into the warehouse, services begin, and services end. The event graph captures greater detail of warehouse process by using scheduling edges, conditionals, and time parameters to represent the sequence of events. The next iteration presents the first pilot model for this study and begins coding the warehouse process. The pilot model serves a multi-functional role for this study. The primary objectives of the pilot model are to capture key events within the workflow, identify simulation parameters, and compute initial work performance outputs. The pilot model also serves as a preliminary evaluation to verify the performance of key events and ensure that state transitions behave correctly. The pilot model is the first discrete event simulation for this study implemented in Simkit.

C. THE WAREHOUSE ARRIVAL SIMULATION MODEL

The warehouse arrival simulation model is the first pilot model developed to represent the warehouse workflow process beyond the basic model concepts. The warehouse arrival process is not a complete representation and only illustrates a portion of the complete warehouse system. Additional events, data collection methods, and parameters are implemented in the final warehouse model. However, the first pilot model serves as an initial proof of concept and foundation to build upon.

The pilot model provides the initial behaviors of simulated warehouse operations. The model also facilitated constructive feedback from the sponsor and advisors to aid future model development efforts. The warehouse arrival process represents the warehouse receiving process which includes the activities that take place once the shipment arrives in the warehouse. This pilot model simulates shipments arrival, inspection, and racking procedures.

1. Arrival Event

The "Arrival" event represents the unloading dock of the warehouse. Arriving shipments are placed in an unloading queue for further actions in the warehouse workflow. In addition, the "Arrival" event still schedules the arrival shipments at random interarrival times. The model records the number of shipments as the shipments arrive in the system.

2. Start Inspection Event

The "Start Inspection" event simulates the movement of the shipment to an available inspection location to be unloaded and receipt for. The number of available inspection spaces is a state variable to track the value of the resource as it changes throughout the simulation. The "total number of inspection spaces" parameter accounts for the workspace concerns occurring within the Wilson warehouse. There is also a conditional put in place to ensure a shipment is scheduled for inspection only when an available inspection location is available. These types of rules effectively simulate the operational norms of the real warehouse system.

When the inspection of the shipment begins, the shipment no longer takes up a spot in the unloading queue, so this state variable is adjusted accordingly as shipments transition through the arrival event. The unloading queue does not have a specified capacity so shipments will continue to enter in the unloading queue at various times. However, the state variable, number of available inspection locations, decreases to account for shipments that are now placed in an available inspection space. During the inspection event, the time expended to inspect the shipment begins at the time the event is scheduled and will end at a random generated time in the future. The time to inspect is another model parameter using a random number generator to represent variability.

3. End Inspection and Start Racking Events

The "End Inspection" event represents the completed inspection of a shipment in the warehouse workflow process. At this point in the process, the items are verified, unloaded and in the possession of the warehouse storage facility. The next workflow event simulated in the model is "racking" or putting up a shipment. The state variable, number of shipments waiting to be put up, is a number tracked by the model. The "Start Racking" event simulates the movement of the shipment from the shipment inspection location and stored in the warehouse. Specific storage locations within the warehouse are not tracked by model. However, the total number of available material handling equipment is tracked and a requirement to rack a shipment. Another conditional is implemented in the model to ensure that material handling equipment is available before the "Start Racking" event is scheduled.

The "Start Racking" event triggers multiple adjustments within the model. The state variables, available inspection spaces, shipment waiting to be put up, and number of available material handling equipment are updated. A conditional is put in place to allow the "Start Racking" event to schedule another inspection when a shipment is in the unloading queue and ready for inspection. This rule represents an occurrence in the simulation that can be expected in the real warehouse process. In addition, the time expended to rack the ship begins and will end using a time random generator.

4. End Racking Event

The “End Racking” event represents a shipment being stored in the warehouse. The number of shipments racked is a state variable and recorded as a statistical output for the simulation. During this event, the number of available of material handling equipment updates and performs the existing task. The “End Racking” event schedules the “Start Racking” when a shipment is waiting to be racked. This circumstance represents seamless and smooth transitions to perform tasks in the simulation that can be expected to occur in the real workflow process.

5. Statistical Data

The statistical data collection for in the pilot model assess early aspects of the warehouse performance and throughput. The simulation also highlights the initial relationship between the quantity of resources and the simulation outputs. The warehouse arrival simulation model computes and collects the following statistics: average number of shipments in the unloading queue, average number of shipments being inspected, average number of shipments waiting to be put up, and the total number of shipments put away.

The initial statistical outputs require further developments to properly track and analyze the advance warehousing behaviors. However, this pilot model paves the way for future model development and provides perspective throughout the implementation phase. This model provide insight to what additional state variables and parameters are required to best represent the actual warehousing behaviors. Overall, this pilot model supports the approach to use discrete event simulation for this study. Simkit is an effective simulation application to evaluate the relationship between warehouse resources and performance outputs. The event graph for the warehouse arrival simulation model is shown in Figure 22.

6. Warehouse Arrival Process Event Graph

Parameters

- q = total number of inspection spaces
- f = total number of material handling equipment
- $\{t_A\}$ = interarrival times
- $\{t_{I\}}$ = inspecting time
- $\{t_{R\}}$ = racking time

State Variables

- I = number of available inspection spaces(q)
- M = number of available material handling equipment (f)
- L = number of shipments in the loading queue (0)
- B = number of shipments waiting to be racked (0)
- R = number of shipments racked (0)

Event Graph

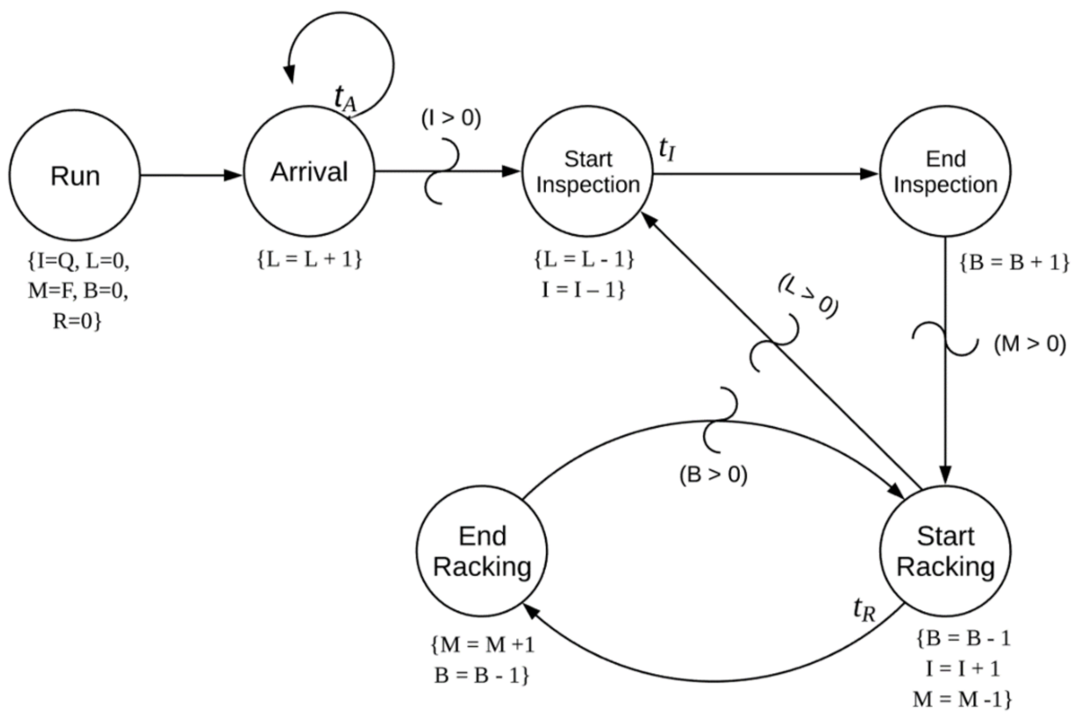


Figure 22. Pilot Model. Warehouse Arrival Process Event Graph.

D. THE MATERIAL HANDLING EQUIPMENT SIMULATION MODEL

The focus of the material handling equipment simulation model demonstrates behaviors within the warehouse process beyond the scope of pilot model. This model incorporates many of the same key events and transitions in the first model, however additional events, parameters and variables are also added. This model uses the feedback from the pilot model to increase the level of detail of procedures in the actual warehouse workflow process. The primary enhancement is to explicitly model material handling using the straight and vertical forklifts.

1. MoveToInspectionArea Event

The "Move to Inspection Area" event, shown in Figure 23, simulates the shipment movement to an available inspection space once it arrives at the warehouse receiving dock. This event demonstrates the realistic situation within the workflow and requires a straight forklift system to perform the event. The "Arrival" event represents a shipment arrival in at the receiving dock only and is incremented appropriately between the two events using the state variable "D" used in the event graph.

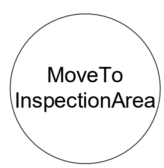


Figure 23. MoveToInspectionArea Event.

2. MoveToRackArea Event

The "Move to Rack Area" event, shown in Figure 24, simulates the shipment movement after it is inspected. The shipment moves from the inspection area to the rack area to be racked. This action demonstrates real behaviors in the workflow and requires the straight forklift system to perform the event. These additional events also allow the simulation to accurately capture the respective state variables if a shipment is waiting for inspections, "I" or racking, "U." The "StartInspection" and "StartRacking" events in the receiving process o are included in the model and behave the same.

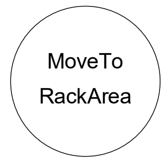


Figure 24. MoveToRackArea Event.

3. ArrivalAtRackArea Event

The "ArrivalAtRackArea" event, shown in Figure 25, simulates the shipment movement from the inspection area to the rack area. Specifically, the "ArrivalAtRackArea" event is confirms the shipment arrival at the rack area location before it schedules "StartRacking." The "ArrivalAtRackArea" event also allows allocated resources such as the straight forklift system to become available to continue future work required in the warehouse workflow process. This actual instance in the real warehouse system ad is represented by the incrementing the state variable, "M" representing the number of available straight forklift systems.

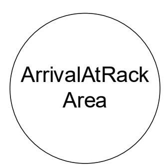


Figure 25. ArrivalAtRackArea Event.

4. Straight and Vertical Forklift Systems

This simulation model features the material handling activity and events specific to warehouse operations at the Wilson Warehouse. In this model, straight forklift systems and vertical forklift systems are added as new parameters in the model. This level of detail is very important to the model because both resources serve distinct purposes within the warehouse workflow process. The straight forklifts move shipments between receiving dock to inspection area and from the inspection area to the racking area. These behaviors are implemented in the model to represent the specific tasks for straight forklift system. The vertical forklifts move shipments from the racking area and store the shipment in a warehouse. The two-forklift system in the model represents the unique procedures performed at the Wilson Warehouse. Additionally, a forklift movement random time generator parameter is added to produce actual variability as tasks are completed. Due to space limitations, the two-forklift system is the most appropriate warehousing method. This model also demonstrates the interactions between events and resources.

The model adds parameters for the total number of straight and vertical forklift systems for warehouse operations. These additional variables allow the model to change the number of a specific resource and assess the separate impact on the warehouse performance. The additional parameters also pair the resource to the event it is intended for in actual operations. This level of detail allows the simulation to assess the performance of individual resources and track potential bottlenecks in the workflow process. Bottlenecks occur when demand for warehouse resources outweighs the resource quantities. Specifically, conditionals are set for events that require movement of a shipment. For example, a shipment can only move to the inspection area, rack area or start racking if the required forklift system is available for work. According to the example depicted in Figure 26, an available inspection space and straight forklift system are required before the shipment can move from the dock area to the inspection area.

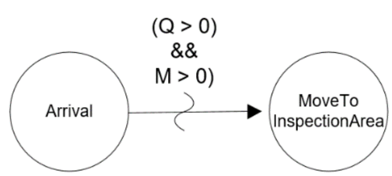


Figure 26. Event Conditional Interaction Example.

The additional events and parameters increase the accuracy of the model. There are still events and behaviors within the warehouse workflow process to incorporate to achieve the desired level of detail for this study. However, this simulation model provides better representation of the warehouse workflow process. The additional detail in the model also facilitate collecting more statistical data to assess the performance of the system. The material handling equipment simulation model tracks and computes the following statistics: current and average number of shipment in the unloading queue(dock area), current and average number of shipments waiting to be inspected, current and average number of shipments waiting to be racked, current and average available straight forklift systems, average utilization for straight forklift systems, current and average available vertical forklift systems, and average utilization for vertical forklift systems. The same statistics are also been used to compute confidence intervals for evaluate warehouse performance over serval time-units and multiple replications. The total and average number of shipments inspected racked are also collected and carried over from the previous iterations.

5. Stress Test and Functional Checks

At this point in the model implementation phase, the simulation contains multiple events, conditionals, and interrelationships that operate collectively to represent the warehouse workflow process. Before moving forward to any additional implementation or statistical analysis, it is necessary to “stress test” the simulation. These checks ensure that the simulation model is behaving correctly. The stress test also ensures that each event is scheduled correctly. It also involves setting initial parameters for the simulation that knowingly produce bad outputs to verify the model still functions accordingly and does not crash. It also verifies that the model behaviors perform accurately when bottlenecks occur in the simulation. This test also verifies the statistical output data is justified. The stress test and check are performed throughout the implementation phases to ensure that the simulation is performing correctly before further developments The event graph for the material handling equipment simulation model is shown in Figure 27.

6. Material Handling Equipment Process Event Graph

Parameters

- q = total number of inspection spaces
- m = total number of straight forklift systems
- a = total number of vertical forklift systems
- $\{t_A\}$ = interarrival times
- $\{t_s\}$ = time to inspect
- $\{t_R\}$ = time to rack
- $\{t_m\}$ = forklift movement time

State Variables

- Q = number of available inspection spaces(q)
- M = number of available straight forklift systems (m)
- A = number of available vertical forklift systems (a)
- U = number of shipments waiting to be racked (0)
- I = number of shipments waiting to be inspected (0)
- D = number of shipments in queue, dock area (0)
- N = number of shipments inspected (0)
- R = number of shipments racked (0)
- T = total number of shipments inspected (0)

Event Graph

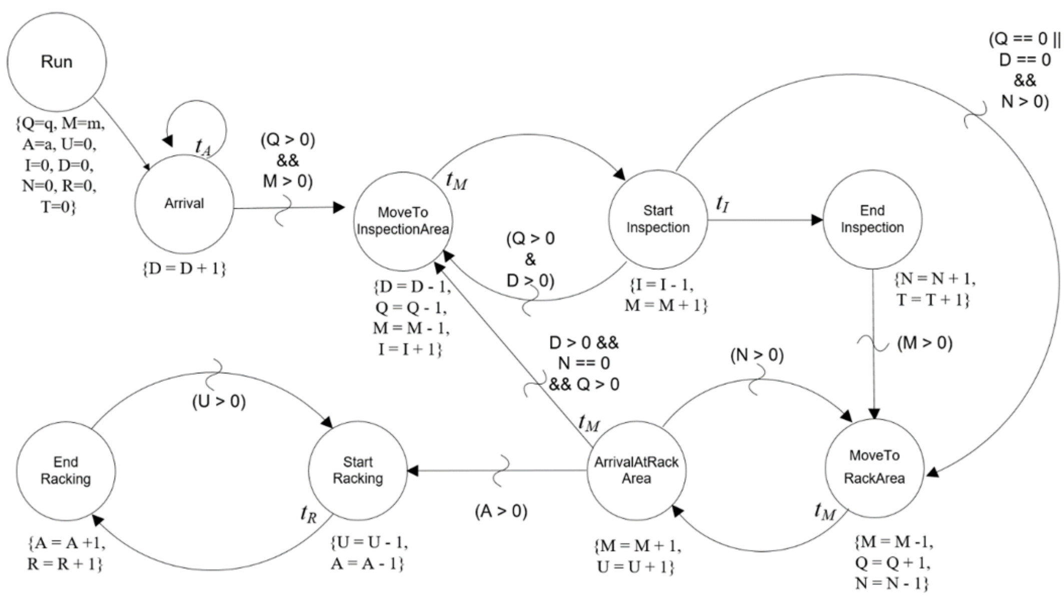


Figure 27. Material Handling Equipment Process Event Graph.

E. MODEL SIMPLIFICATIONS AND ASSUMPTIONS

Model simplifications are instrumental in the development of a model. Simplifications provide clarity during the development of the model by focusing on elements of the system that matter the most and support clearly understanding of the problem (van der Zee, 2017). According to van der Zee, model simplifications reduce the model complexity when large system dynamics are implemented and assist faster model development. Model assumptions are also necessary when "uncertainties or beliefs about the real world" behaviors and delays further model development (Robinson, 2008a, p. 283). In this study, assumptions about the warehouse workflow process are made to offset the lack of data to represent the actual warehouse behaviors. Simplifications and assumptions are vital techniques in the development the model. This technique serves an instrumental purpose when the model objectives, inputs, outputs, and content are established. Simplifications, as its name suggests, simplifies a simulation model "to increase a model's utility and feasibility, while safeguarding its validity and credibility" (van der Zee et al., 2018, p. 4197). These techniques are suitable methods to make implementation efforts easier and to best represent the model behaviors with limited information.

In this study, model simplifications and assumptions are used to simplify the level of detail required and promote accurate representation of the warehousing behaviors. Assumptions and simplifications serve different purposes but are necessary as decisions are made to determine the model content. The model content describes the components and activities represented in the model. Specifically, the content determines the scope of the model and the level of accuracy required in the model. As a result, a high degree of accuracy usually requires a larger model scope and level of detail (Robinson, 2008a).

1. Personnel Behaviors

The first simplification streamlines the personnel specific behaviors in the model to reduce complexity. Also, this level of detail is not a model requirement presented by the sponsor during the problem-framing discussions. According to warehouse managers, the Wilson warehouse has the right amount of personnel to accomplish individual steps with the workflow process, which includes operating the material handling equipment and inspection tasks. Individual performances or human error is not implemented in the model to avoid unduly influence on the simulation outputs. This decision focuses more attention on the parameters that directly impact the warehouse performance. The discussions during the early stages of the model implementation phase emphasizes that all activities and behaviors of the warehouse process could not be captured in this one model. A model with too much information would sacrifice some level the accuracy elsewhere and impacting the model objectives. In this model, the most influential parameters include the material handling equipment, processing times for events, and space resources to effectively evaluate the impact on warehouse efficiency.

2. Time Delays

The next simplification streamlines the representation of work being completed or the movement of resources over time in the model. The representation between time and activities in the simulation is an important aspect to consider during implementation. The model objectives did not require a time delay when an event is scheduled throughout the warehouse workflow process. This decision puts special emphasis on representing the processing time for events influences the overall warehousing efficiency and throughput. Some events transitions throughout the workflow process use a "zero-time" delay to facilitate the scheduling of the next event as soon as conditions were met, without delay. One example of this occurrence is the shipments transition from the dock to the inspection area. For this action to take place realistically, it takes time, an available inspection space, and available forklift system to move the shipment. However, there is no delay in the scheduling of this event and the shipment instantly arrives at an available inspection space if one is available. The primary focus for these events in the warehouse workflow process is the number of available inspection spaces vice the time to move the shipment to the inspection area. Based on the model scope and objectives, the time between shipment arrival and movement to the inspection area does not directly influence the warehouse performance. The zero-time delay is also used once a shipment completes inspection and moves to the rack area. Essentially the model is used to evaluate higher priorities within the workflow process. The zero-time delays reduce the complexity in the model and isolate the impact on the warehouse performance solely based on changes to the parameters defined in the model.

3. Time Distributions

The model uses assumptions for the interarrival time for shipments, inspection times, forklift movement time, and racking times due to lack of data. The model uses random number generators as the model parameters in the place of actual time distributions required in the simulation. The requirement for quality historical data creates a modeling challenge to represent the actual resource performances based on real warehousing data. To lighten this challenge, randomize time generators represent the variability for the events in the model. A random time generator is a practical methodology approach to account for the actual behaviors in the real warehouse process. For simulation modeling circumstances such as these, Robinson suggests using alternatives such as “dropping unimportant components of the model, using random variables to depict parts of the model, or grouping components of the model” (Robinson, 2008a, p. 288).

4. Racking Area

The available space in the rack area has no capacity restrictions in the simulation. Based on the input from warehouse manager, there is not enough evidence to support establishing a state variable or limiting the space available for this event in the model. The logical assumption is that bottlenecks are likely to occur at the rack area in the workflow process when the vertical forklift systems are overworked. However, this instance is not a concern for the Wilson warehouse and these characteristics are therefore not incorporated in the model.

5. Warehouse Shipments

Model simplifications also simplify the representation of shipments for the workflow process to keep the model simple. In the model, a shipment represents several items arriving in the warehouse for inspection and storage, however it treated as one shipment in the model. In future development, the representation of the shipment can involve much more complexity than demonstrated in this model. A shipment is typically made up of multiple containers or equipment types varying in sizes. This level of detail and complexity would also affect the scope of the research and model content. This simplification maintains the focus on the primarily model objectives which do not involve size or handling of specific equipment in the shipment. The size of the shipment is a concern or characteristics required in the model to effectively evaluate warehouse performance. This simplification is also established to minimize unnecessary influence on the simulation outputs.

This is also the case for representing racking a shipment in the model. The representation of a complex racking process is outside of the scope and objectives for this study. This could have been viable opportunity to implement specific inventory characteristics of the Wilson warehouse. However, the assessment of the warehouse inventory management procedures could be an entirely separate research project. It is best that the racking event in this model remain simple to preserve focus on the main objectives of the model. Lastly, specific materiel demand or quantity levels are also not within the scope of the study. There is no requirement or data to support incorporating stock shortages behaviors in the model. The assumption is that Wilson warehouse maintains accountability for the items stored in the warehouse for distribution purposes and will only fulfill shipment orders based on the quantity of items on hand.

F. THE WAREHOUSE WORKFLOW MODEL

The warehouse workflow model represents the third milestone and final model iteration of this study. The final model implementation efforts focus on implementing the backend of the simulation which includes the outbound warehousing functions. These functions represent shipments pulled from inventory and processed through the warehouse workflow for issue. So far, the warehouse model represents inbound warehousing functions for storage purposes. The warehouse workflow model establishes the outbound warehousing behaviors of the warehouse operations and establish the interrelationships with the inbound warehousing process to simulate simultaneous processes. The interrelationships in this model demonstrate scheduling consecutive events between processes and the utilization of both forklift systems required in both processes. In this model, work priorities are established to ensure event scheduling priorities are practical and the forklift systems carry out procedures as expected in the real warehouse workflow. Based on the information gathered from the sponsor, issuing shipments takes priority over demand for equipment receiving and storage. This fundamental concept is implemented as a static prioritization throughout the workflow model to demonstrate the accurate behaviors of events and resources. During the implementation of this model, simulation parameters and state variables are refined to ensure that the model tracks and produces the appropriate warehouse outputs. This effort involves adding parameters, state variables, and events to increase of the accuracy of the simulation model and better understand the workflow process. This section will address the changes to the simulation model and behaviors added to implement the warehouse workflow model.

1. ArrivalAtInspectionArea and ArrivalAtRackArea Event

The first event added to the model is the "Arrival at Inspection Area" event. This event accurately captures the forklift movement time between a straight forklift system picking up a shipment from the dock area and delivering it to the inbound inspection area for inspection. This event is not implemented in the previous models and only served as an implied occurrence in the "Start Inspection" event. The additional arrival event allows changes to the forklift movement time without directly interfering the the inspection of the shipment. This event also clarifies when a straight forklift system becomes available to execute other functions in the workflow process. The available asset after the completion of this event is important because the forklift system performs the next work priority in the workflow process. In all cases, the available straight or vertical forklift system executes the next available outbound task before executing any inbound tasks. This behavior is consistent after the completion of an arrival events throughout the model and schedules the next event based on the work priority and the available resource. When a straight forklift system (M) becomes available, it executes the next event where it is required in the issuing process first. The "Start Inspection" event still functions the same as the previous simulation models and schedules the "End Inspection" event after a random inspection time. The "Arrival at Rack Area" event functions the same as well, however it now has the same scheduling priority characteristics as the "Arrival at Inspection Area" event.

2. Demand Event

The "Demand" event represents the first step in the issuing workflow process. This event creates the demand for shipments to be unracked and processed through the warehouse for distribution. The "Demand" event functions like the "Arrival" event in the receiving workflow process, where demands are automatically recreated based on a random interarrival time distribution. This behavior simulates the requirement for outbound activity. There are two state variables in this event to quantify the number of demands in the system. The number of demands (H) indicates the demands to be processed. As a state variable for the simulation, this value changes as demands are fulfilled in the issuing workflow process. The total number of demand (B) is captures the total amount of demands generated during the simulation run. This state variable will not change throughout the simulation run to compare the completed outbound tasks to the total demand. The "Demand" event schedules the "Start Unracking" event when a vertical forklift system (A) is available for work. The number of demands in the system (C) also tracks shipments in the outbound process to compute the time it takes to process the shipment through the outbound process. The same concept is implemented in the issuing process (F) to track the shipments in the system and compute the time is take shipments to be stored.

3. Start UnRacking and End UnRacking Event

The "Start UnRacking" event represents the vertical forklift system removing shipments from storage. This event functions like the "Start Racking" event by scheduling the "End unRacking" event after a random unracking time distribution to indicate work performed. In this model, the "End Racking" event also schedules the "Start UnRacking" event when a demand exists in the system. This scheduling relationship is significant because it demonstrates one of many work priorities implemented in the model to schedule events when a vertical forklift system (A), required for a racking and unracking tasks, becomes available. In this model, when a vertical forklift system is available after unracking or racking a shipment and demands exist, the priority of the simulation is scheduling the "Start UnRacking" event to use the available asset. The "End UnRacking" event schedules the "Start UnRacking" under the same conditions when a demand exists, and a vertical forklift system is available for work. This event schedules the "Start Racking" event if no demand exists and a shipment in the receiving process needs to be racked. This priority concept for the vertical forklift systems is adjustable and can be refined to prioritize racking tasks in the receiving process to alleviate bottlenecks in the receiving process. The "End Unracking" event also utilizes two state variables to track the number of shipments unracked. The number of shipments unracked (X) indicates the shipments is waiting to be moved to the outbound inspection area for inspection. This value changes as the shipments are moved to the outbound inspection area. The total number of shipments unracked or picked (Z) track the total amount of shipments picked during the total simulation run. This state variable will not change and tracks the total output for this specific event. The "End UnRacking" event schedules the "Move to Inspection Area" event to continue the issuing process when a straight forklift system (M) and an available outbound inspection space (K) is available. These two variables are resource requirements to perform the next event.

4. MoveToOutboundInspectionArea and ArrivalAtOutboundInspectionArea event

These two events in the issue process operate the same as the move and arrival events in the receiving workflow process. The "Move to Outbound Inspection Area" represents the task after a shipment is picked up from the unracking area. The racking area and unracking area are the same location in the Wilson warehouse. The straight forklift system moves the shipment from the unracking area to the outbound inspection area for inspection. This event schedules "Arrival at Outbound Inspection Area" event after a random forklift movement time to signify the work performed. When the "Arrival at Outbound Inspection Area" event occurs, a straight forklift system becomes available and the next work priority event requiring the asset is scheduled. The next event scheduled to utilize the available straight forklift system will be based on the same work prioritization concept implemented in the "Arrival at Inspection Area" and "Arrival at Rack Area" events. The "Start Outbound Inspection" and "End Outbound Inspection" events represent the inspection process for outbound shipments which take place over an inspection time interval as well.

5. MoveToPackShip and ArrivalAtPackShip

The “Move to Packaging and Shipping” event occurs after the shipment has completed the outbound inspection process. This event represents the shipments being picked up from the outbound inspection area and transferred to the Defense Logistics Agency for packaging and shipping. The time for this specific task is also uses a forklift movement time interval used in all previous forklift movement tasks. The forklift movement times are used only in the workflow tasks where it is essential to capture this level of detail in the model. This is not a behavior or parameter implemented for every instance in the simulation model to preserve complexity. The “Arrival at Packaging and Shipping” event is the final task of the warehouse workflow process. Once this event occurs, the total number of shipments of shipped (P) is recorded and a straight forklift system becomes available. The “Arrival at Packaging and Shipping” event will follow the same prioritization concept in the previous three arrival events to determine the task the straight forklift task executes next. The straight forklift system tasks are identified as “MoveTo” events. These four events represent the all tasks with the workflow processes that require a straight forklift system. The “Move to Packaging and Shipping” event is the highest priority task when a straight forklift system is available. The next priority will be the “Move to Outbound Inspection Area” event, followed by “Move to Rack Area, and finally “ Move to Inspection Area”.

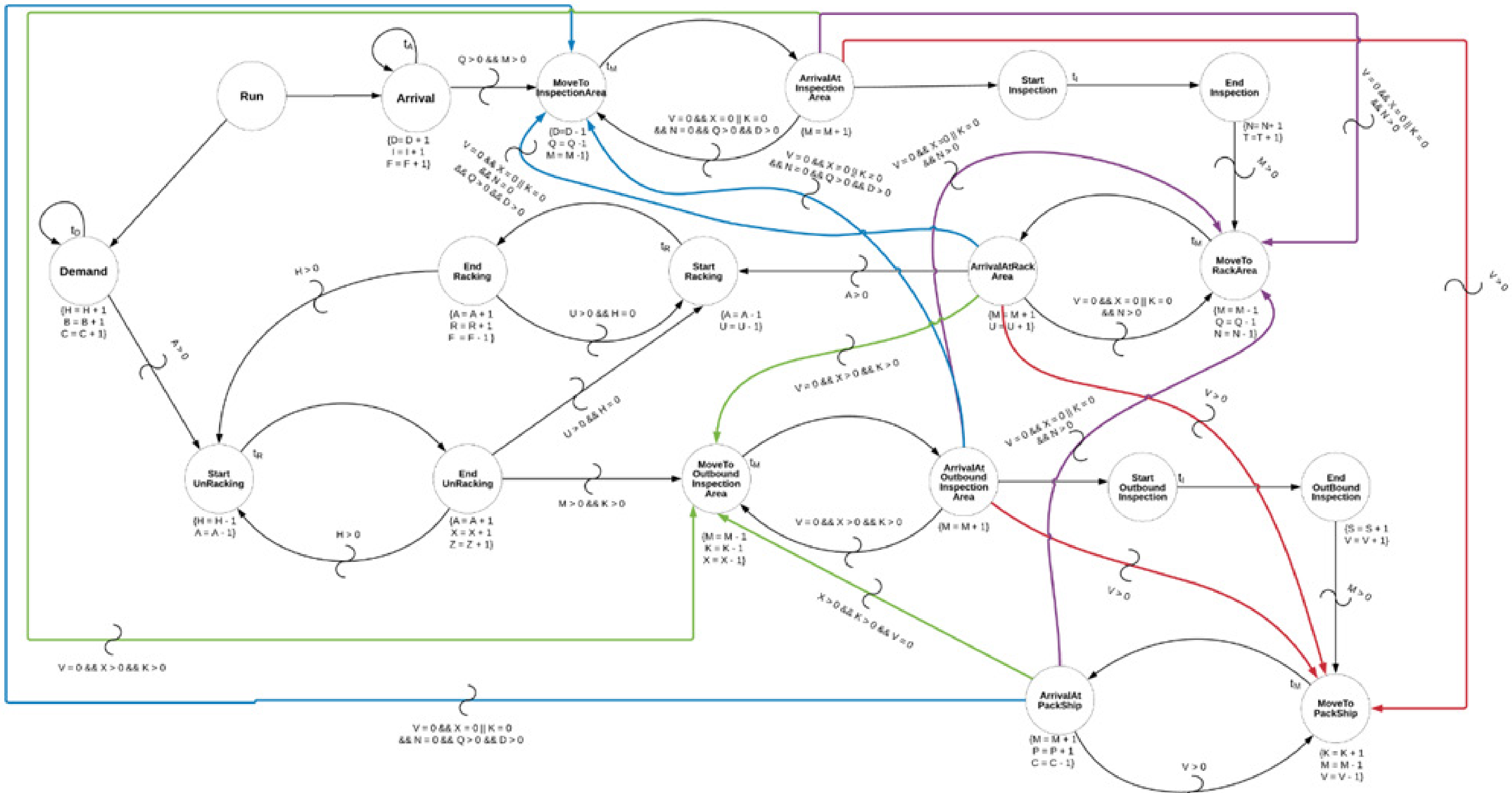
6. Warehouse Workflow Model Event Graph

Parameters

- q = total number of inbound inspection spaces
- k = total number of outbound inspection spaces
- m = total number of straight forklift systems
- a = total number of vertical forklift systems
- $\{t_A\}$ = interarrival times
- $\{t_{D\}}$ = interarrival time for demand
- $\{t_{I\}}$ = time to inspect
- $\{t_{R\}}$ = time to rack and unrack
- $\{t_{M\}}$ = forklift movement time

State Variables

- D = number of shipments in queue, dock area (0)
- Q = number of available inbound inspection spaces(q)
- M = number of available straight forklift systems (m)
- A = number of available vertical forklift systems (a)
- N = number of inbound shipments inspected (0)
- T = total number of inbound shipments inspected (0)
- U = number of shipments waiting to be racked (0)
- R = total number of shipments racked, put away (0)
- I = total number of shipments arrived (0)
- K = number of available outbound inspection spaces (k)
- H = number of shipments to be issued, demands (0)
- B = total number of demands to be issued (0)
- X = number of shipments unracked, and waiting to be moved to inspection (0)
- V = number of outbound shipments inspected (0)
- S = total number of outbound shipments inspected (0)
- Z = total number of shipments unracked, picked (0)
- P = total number of shipments delivered to packing/shipping (0)
- C = number of demands in the system, shipments to be issued (0)
- F = number of inbound shipments in the system (0)



The work priority for the straight forklift have color coded scheduling edges to specify the next scheduled event once the resource becomes available. The red scheduling edge indicates the first work priority, when **V > 0**. The green scheduling edge indicates the second work priority, when **V = 0 && X > 0 && K > 0**. The purple scheduling edge indications the third work priority, when **V = 0 && X = 0 || K = 0 && N > 0** and the blue scheduling edge indicates the fourth and final work priority, when **V = 0 && X = 0 || K = 0 && N = 0 && Q > 0 && D > 0**.

Figure 28. Warehouse Workflow Model Event Graph.

THIS PAGE INTENTIONALLY LEFT BLANK

V. RESULTS

The testing and statistical analysis of the warehouse workflow model was conducted in three stages. The first stage of testing implements statistical functions to measure the warehousing throughputs for the complete workflow process. There are several outputs computed by the simulation to evaluate the performance of various warehouse tasks conducted throughout the workflow process. However, the average time in system for inbound shipments and average time in system for outbound shipments are used to test and evaluate the warehouse processes from start to finish. An inbound shipment consists of the equipment arriving in the warehouse for storage, and an outbound shipment represents the equipment being processed out of the warehouse for distribution. The second stage of testing and analysis consists of conducting an excursion analysis as an initial exploratory method to assess the warehouse workflow performance based on small, one-at-a time changes to the inputs. The inputs for the warehouse model are the total number of straight forklift systems, the total number vertical forklift systems, the total number of inbound inspection spaces, and the total number of outbound inspection spaces. The utilization of these are also computed by the simulation model to provide additional feedback, so the analyst can better understand the performance of the system and identify where potential bottlenecks may be occurring. The third stage of testing uses a data farming approach (Sanchez, Sanchez, & Wan, 2018). The purpose of this stage of testing uses a design of experiment techniques to evaluate warehouse system and determine the inputs that statistically have the greatest impact on efficient warehouse operations. The data requirement still presents the biggest challenge to provide the most accurate and realistic representation of the warehouse operations for the Wilson warehouse. However, this challenge does not prevent the model from providing insights as a proof of concept based on the real warehousing procedures.

A. SIMULATION MODEL OUTPUTS

The run class of the simulation model is designed to run the model for a set of independent replications over a set number of time units determined by the user. For the purpose of this analysis, the simulation model is set to run 30 independent replications over 10,000 time units. These figures were chosen as practical baseline to ensure the simulation output assessment represents warehouse workflow performance at steady state with a high level of confidence to actual workflow conditions. The performance data below represents all computed performance outputs produced by the warehouse workflow model with a 95% confidence interval, based on 30 replications over 10,000 time units.

1. Receive Process Performance Breakdown

   - 95% CI for total number of shipments arriving
   - 95% CI for number of available inspection spaces
   - 95% CI for number of shipments in dock area
   - 95% CI for number of shipments waiting to be racked
   - 95% CI for total number of inbound shipments inspected
   - 95% CI for total number of inbound shipments racked

2. Resource Availability Breakdown

   - 95% CI for number of available straight forklifts
   - 95% CI for number of available vertical forklifts
   - Issue Process Performance Breakdown
   - 95% CI for number of shipments demands waiting to be Issued
   - 95% CI for number of available outbound inspection spaces
   - 95% CI for number of shipments waiting for outbound inspection
   - 95% CI for total demand for issue
   - 95% CI for total number of outbound shipments inspected
   - 95% CI for total number of outbound shipments unracked
   - 95% CI for total number of shipments delivered to DLA

3. Utilization of Input Variable Resources

- 95% CI for utilization of inbound inspection spaces
- 95% CI for utilization of outbound inspection spaces
- 95% CI for utilization of straight forklift systems
- 95% CI for utilization of vertical forklift systems

4. Warehouse Performance Time in System

- 95% CI for average time in system for inbound shipments
- 95% CI for average time in system for demands outbound shipments

B. EXCURSION ANALYSIS

The average time in system statistic evaluates the overall performance of the inbound and outbound warehouse processes. The average time in system statistic also captures the dock-to-stock time to storage equipment and the stock-to-dock time to process equipment for distribution. In other words, the average time in system statistic assesses the overall performance of the warehouse system from start to finish. The other statistical outputs provide the underlying behaviors of the system that explain the performance of individual tasks within the workflow process. These additional statistical outputs assist the user to better understand the "how" and "why" the system is performing by breaking out specific performance data. The excursion analysis serves as an informal method used to quickly reveal how the warehouse workflow process performs with different value for some inputs.

The excursion analysis conducts three independent simulation experiments using practical input values for the baseline. The input values for the baseline simulation run are selected to produce satisfactory warehouse performance outputs, but not great performance. The objective of this analysis is to evaluate the effects of the warehouse performance when an input is incremented by one value. The average time in system for inbound and outbound shipments are the primary two outputs used in this analysis to assess the change in performance. The conditions for the first simulation experiment ran the simulation for 30 replications at 10,000 time units with three straight forklift systems, 4 vertical forklift systems, 6 inbound inspection spaces, and 6 outbound inspection spaces: this is called Baseline Run (3,4,6,6). The average time in system (mean) and standard error was recorded for the baseline run, then the simulation was run four more times, with each of the inputs incremented by one value before each simulation run. The same process was conducted for two additional baselines, Baseline (5,4,4,4) and Baseline (6,4,5,5). The results for the three simulation experiments are shown in Figure 29, 30, and 31. The largest improvement is in the vertical forklift system (step 3) and the results also conclude the next improvement is in the outbound inspection space (step 5). According to the results from the excursion analysis, the vertical forklift systems and outbound inspection spaces are the parameters that have the greatest impact on warehouse average time in system statistics. Specifically, the addition vertical forklift adds approximately 12 times more productivity in the inbound workflow process, while also reducing the average time in system for shipments in the outbound workflow process.

	Avg Time in System (Inbound)	Std Err (Inbound)	Avg Time in System (Outbound)	Std Err (Outbound)
Conditions				
Step 1. Baseline Run (3,4,6,6)	101.58	14.85	9.37	0.06
Step 2. Baseline +1 Straight Forklift	127.29	23.65	9.29	0.08
Step 3. Baseline +1 Vertical Forklift	10.05	0.11	8.61	0.07
Step 4. Baseline +1 Inbound Space	121.53	22.83	9.29	0.06
Step 5. Baseline +1 Outbound Space	127.14	25.21	9.24	0.06

Figure 29. Excursion Baseline Run (3,4,6,6).

	Avg Time In System (Inbound)	Std Err (Inbound)	Avg Time In System (Outbound)	Std Err (Outbound)
Conditions				
Step 1. Baseline Run (5,4,4,4)	133.77	23.69	11.01	0.13
Step 2. Baseline +1 Straight Forklift	114.97	22.38	11.15	0.16
Step 3. Baseline +1 Vertical Forklift	11.66	0.24	10.20	0.13
Step 4. Baseline +1 Inbound Space	123.98	22.03	11.06	0.14
Step 5. Baseline +1 Outbound Space	113.08	21.29	9.60	0.08

Figure 30. Excursion Baseline Run (5,4,4,4).

	Avg Time in System (Inbound)	Std Err (Inbound)	Avg Time in System (Outbound)	Std Err (Outbound)
Conditions				
Step 1. Baseline Run (6,4,5,5)	131.70	28.43	9.52	0.08
Step 2. Baseline +1 Straight Forklift	118.98	24.15	9.59	0.08
Step 3. Baseline +1 Vertical Forklift	10.25	0.12	8.84	0.06
Step 4. Baseline +1 Inbound Space	132.10	26.78	9.55	0.08
Step 5. Baseline +1 Outbound Space	128.52	27.77	9.27	0.07

Figure 31. Excursion Baseline Run (6,4,5,5).

C. SIMULATION DESIGN EXPERIMENTS

The third stage of testing and analysis of the warehouse workflow model involves a simulation experiment using a 4-factor nearly orthogonal Latin hypercube (NOLH). Design experiments provide a formal and creditable method to investigate the relationship between the input factors and the output data for the simulation model. Predictive modeling techniques are then used to further describe the input-output relationship. The experimental design tool was provided by the NPS Simulation Experiments and Efficient Designs (SEED) Center for Data Farming (Sanchez, 2011). The NOLH experimental design tool was created using a Microsoft Excel spreadsheet. The spreadsheet provides the framework to set the maximum and minimum levels for the factors analyzed in the simulation experiment. In this case, the four factors for the warehouse workflow model are used. The number of forklift systems range from three to seven, and. The number of inbound and outbound inspection spaces range from four to eight. These ranges of values are consistent with the inputs used in the excursion analysis and are practical values for the real warehouse system. The experimental design tool provides an NOLH with 257 different combinations of input values, also called design points to be run in the simulation model. This design provides a good coverage of different configurations for the warehouse system without testing every possible design point in the input space.

1. Multiple Regression Analysis

The average time in system for inbound and outbound shipment were recorded for 257 design points, based on 30 replications for 10,000 time units. Next, the outputs were imported into JMP statistical analysis software (JMP Pro Version 14.0.0, 2018) for analysis purposes. The output data was analyzed using a Multiple regression by considering all main effects, quadratic effects, and two-way interactions, and then removing all non-significant terms to come up a simple model of the input-output relationships. The results reveal that the total number of vertical forklift systems is the key driver of the average time in system for inbound shipments, according to the sorted parameter estimates in Figure 32. The actual by predicted plot for the inbound process is shown in Figure 33 and summary of fit in Figure 34, also indicates the model has a R-Square value of 0.81, meaning the simulation model explains 81% percent of the total variability in the average in system inbound shipments. This is a very high correlation.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio		Prob>|t|
Vertical Forklifts	-429.4589	18.00679	-23.85		<.0001*
(Vertical Forklifts-5.00778)*(Vertical Forklifts-5.00778)	339.17636	14.70011	23.07		<.0001*

Figure 32. Sorted Parameter Estimates for Average Time in System Inbound.

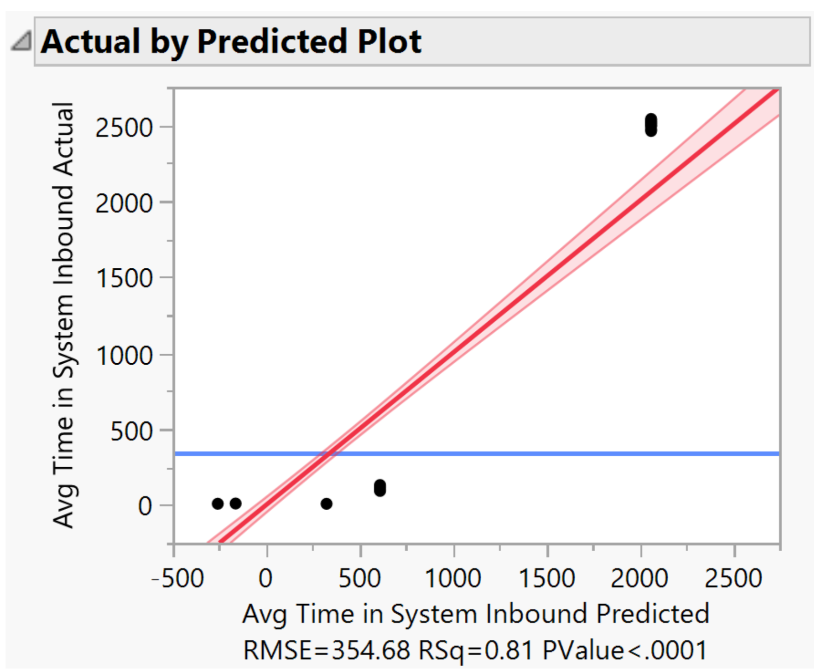


Figure 33. Average time in System Inbound Actual by Predicted Plot.

Summary of Fit

RSquare	0.81291
RSquare Adj	0.811437
Root Mean Square Error	354.6847
Mean of Response	345.4829
Observations (or Sum Wgts)	257

Figure 34. Summary of Fit for Average Time in System Inbound.

The statistical analysis for the average time in system for outbound shipments reveals that the two significant factors are the number of vertical forklift systems and the number of outbound inspection spaces. According to the sorted parameter estimates in Figure 35, both inputs are statistically significant and predictors of the warehouse performance for outbound shipments. The actual by predicted plot for the outbound process shown in Figure 36 and summary of fit in Figure 37, show a R-Square value of 0.96 that indicates a very strong relationship.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Vertical Forklifts	-0.506971	0.00905	-56.02	<.0001*
Outbound Inspection Spaces	-0.360374	0.00905	-39.82	<.0001*
(Outbound Inspection Spaces-6.00778)*(Outbound Inspection Spaces-6.00778)	0.216271	0.00739	29.26	<.0001*
(Vertical Forklifts-5.00778)*(Vertical Forklifts-5.00778)	0.1674285	0.007391	22.65	<.0001*

Figure 35. Sorted Parameter Estimates for Average Time in System Outbound.

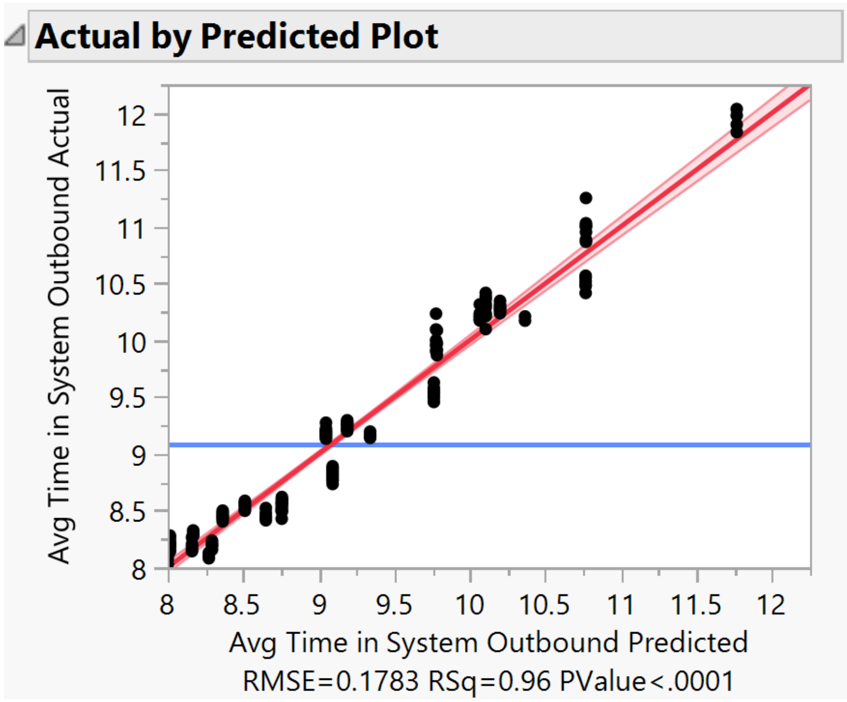


Figure 36. Average time in System Outbound Actual by Predicted Plot.

Summary of Fit

RSquare	0.960132
RSquare Adj	0.959499
Root Mean Square Error	0.178266
Mean of Response	9.084304
Observations (or Sum Wgts)	257

Figure 37. Summary of Fit for Average Time in System Outbound.

Despite to the very high R-square values in the two regression models, the warehouse performance is highly variable.

2. Partition Tree Analysis

A nonparametric modeling approach called a partition tree is also conducted as an alternative to multiple regression. This statistical method uses a partition algorithm in the JMP analysis software to choose optimum input splits and predict the output values (JMP Pro Version 14.0.0, 2018). The analysis uses recursive partitioning to display the relationships between the input values and the average time in system for inbound and outbound shipments. The splits are applied to the data until the R-square value stabilizes and the desired fit of the data is reached for the minimal observed sample size selected (JMP Pro Version 14.0.0, 2018). The decision tree diagram in Figure 38 and 39 illustrates the input-output relationship that corresponds to the best average time in system inbound and outbound performance, respectively. The decision tree for the average time in system inbound indicates that the vertical forklift system is the primary predictor, yielding an R-square value of 1.0 with only two splits. According to the decision tree, the best performance is achieved when the number of vertical forklift systems is at least five. It is also worth pointing out that the average time in system is predicted to be extremely high, at about 2504 time units, for inbound shipments when three vertical forklifts are used. Then, the average time in system drops significantly, to about 112 time units, when four forklifts are used. The decision tree for the average time in system outbound also indicates that the number of vertical forklifts systems and the number of outbound inspection spaces are the primary predictors, yielding an R-square value of 0.72 with only three splits. According to the decision tree, the best performance is achieved when the number of vertical forklift systems is at least five and the number of outbound inspection spaces is at least six. Both models represent a very strong relationship between the input values and output performance.

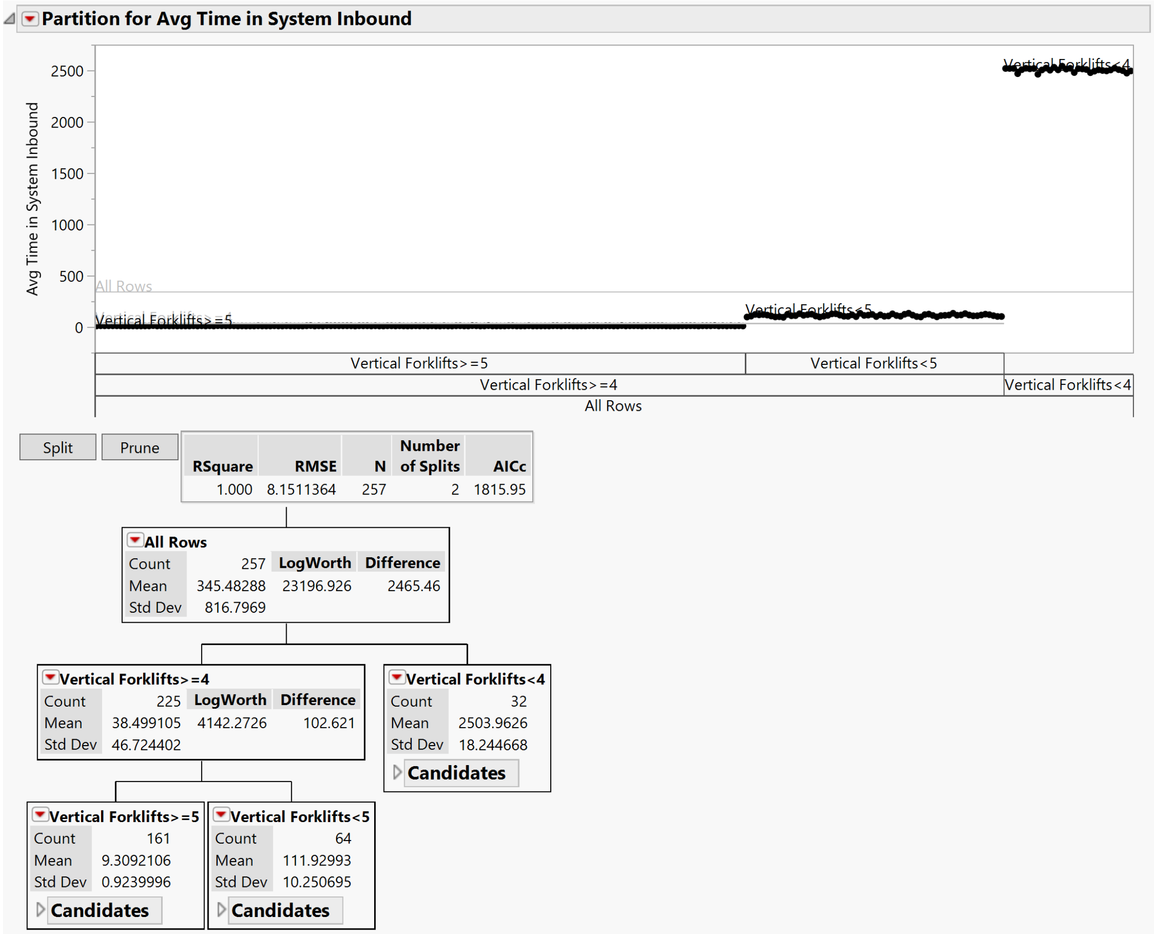


Figure 38. Decision Tree Partition for the Average Time in System Inbound.

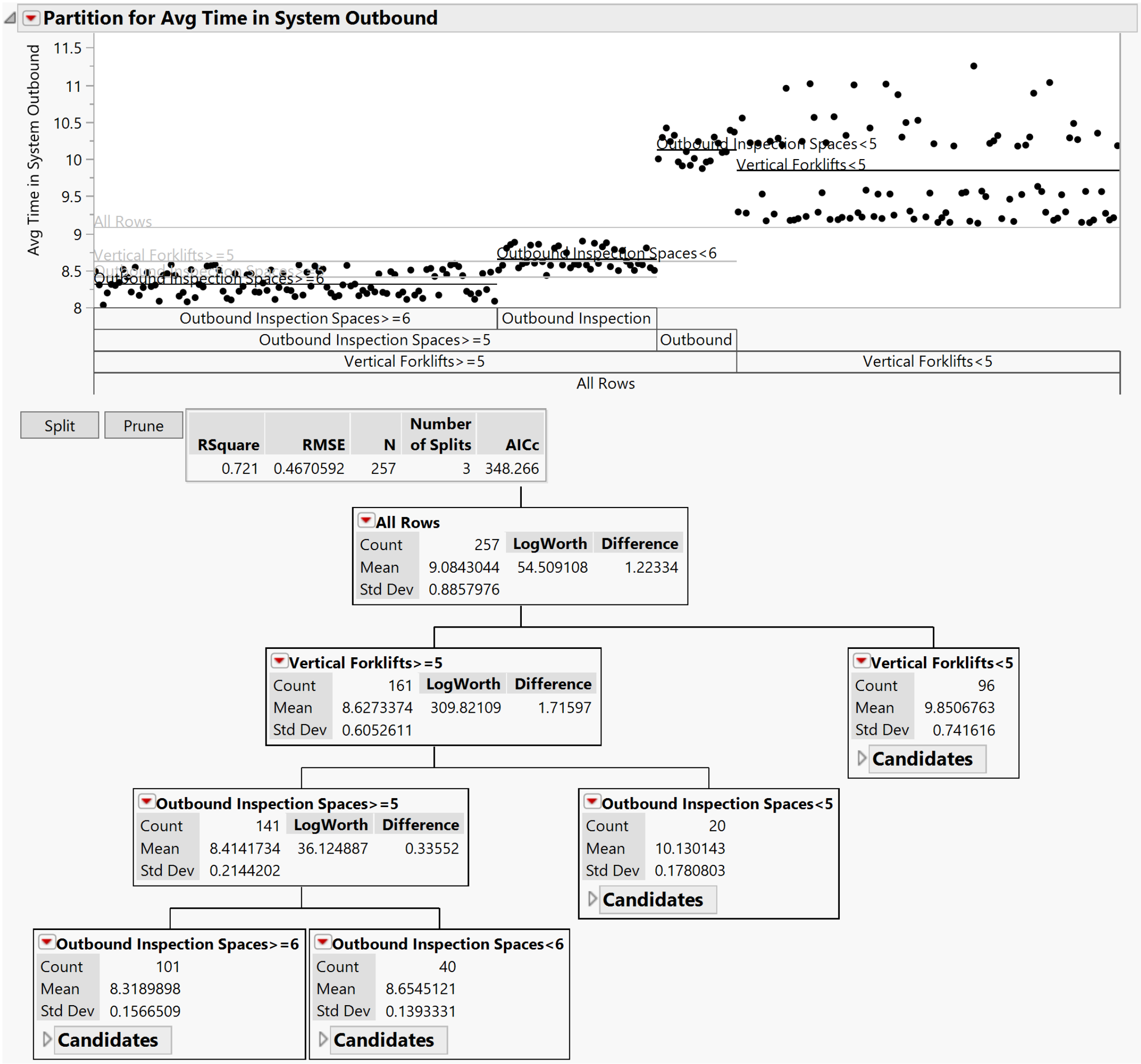


Figure 39. Decision Tree Partition for the Average Time in System Outbound.

D. CONCLUSIONS

The results from this study conclude that to improve warehouse efficiency, MFSC should focus on the quantity and throughput of the vertical forklift systems. The quantity and throughput of the other warehouse resources should be considered because oversight in these areas could ultimately impact the warehouse efficiency in the most extreme cases. The statistical analysis supports that the total number of vertical forklift systems in both workflow processes is the best predictor for warehouse efficiency and produces the largest improvement to the average time in system statistics. In addition to the vertical forklift systems, the outbound inspection spaces are also predictors to determine warehouse workflow performance. Finally, the warehouse performance data was sorted to obtain the best workflow scenario for the simulation model. The best warehouse performance, shown in Figure 40, represents the most optimal inputs that produce efficient resource utilization and outputs based on targeted performance criteria.

Total Number of Straight Forklift Systems: 4
Straight Forklift System Utilization: 33.4%
Criteria Specification: greater than or equal to 30%

Total Number of Vertical Forklift Systems: 6
Vertical Forklift System Utilization: 66.7%
Criteria Specification: greater than or equal to 60% and less than 80%

Total Number of Inbound Inspection Spaces: 5
Inbound Inspection Space Utilization: 60.2%
Criteria Specification: greater than or equal to 60%

Total Number of Outbound Inspection Spaces: 5
Outbound Inspection Space Utilization: 60.1%
Criteria Specification: greater than or equal to 60%

Average Time in System Inbound: 8.8-time units
Criteria Specification: less than 9.0-time units

Average Time in System Outbound: 8.6-time units
Criteria Specification: less than 9.0-time units

Figure 40. Optimal Simulation Inputs and Outputs.

VI. FUTURE WORK

The future work for this study emphasizes the collection of quality historical data from the warehouse workflow processes. The historical data from real warehouse operations is a requirement to update to the current time distribution settings for the warehouse workflow simulation model. These parameters are essential elements that control the function of workflow processes and impact the performance of the warehouse resources. Without historical data that reflects the actual time distributions, an inaccurate representation of the warehouse system and less meaningful statistical analysis will result. The lack of data was a critical challenge to study and a common trend from previous NPS studies that must be corrected. The use of random number generation was an acceptable method to represent the variability of the actual time distributions. This method produces results consistent for proof of concept purposes, but the use of accurate data is a necessity to achieve model verification, validation, and accreditation. To achieve this goal, the warehouse workflow simulation model requires collecting data to calculate time distributions for the arrival expectancy of shipments for storage, the demand expectancy for shipments for shipping, equipment inspection times for the inbound and outbound process, racking and unracking times, and forklift movement times.

The characteristics of the model is another area has the potential for future work. Like any model, more complexity and behaviors can be improved in attempt to increase fidelity. It is also notable to point out that more detail in the model will not guarantee better results. Models are designed to achieve specific goal and will obtain not represent every aspect of a real system. There is always details not incorporated in the model based on requirements and priorities. The priority of work for the warehouse forklift systems focus on performing outbound tasks before inbound tasks throughout the warehouse workflow processes. This work priority disregards the inbound task build up and make the system susceptible to potential bottlenecks in the inbound process. Currently, the shift in the work prioritization is not established in the model to start performing inbound tasks until the requirement for available resources in the outbound process decreases enough. This adjustment may be necessary in the most extreme cases when both processes have a high demand for available forklift systems. Future research efforts should further evaluate these occurrences within the workflow processes to promote fluidity within the model. This effort requires additional observation of the warehouse processes and feedback from the sponsor to facilitate the implementation into the simulation model. For the purpose of this study, the shipment sizes remain uniform for both workflow process. An additional characteristic to the model could account for the different sizes of shipment or the arrival of specific equipment that impact the inspection time and overall performance of the system. Personnel behaviors are another detail that could be added to the model to account for personnel readiness to perform specific tasks in the workflow. The shortage of personnel to maintain high warehousing efficiency is realistic expectation that could impact warehouse throughput. Lastly, the representation of storage and space capacity are additional features that could be added to the model. For simplicity in the current model, one shipment takes up one inspection space. As the characteristics of a shipment are enhanced, there should also be additional characteristics implemented in the model to represent floor space with more detail. The thesis scope can be expanded to closely evaluate how space is being used within the warehouse to inspect and store equipment. Additional efforts could also focus on optimizing the warehouse inventory procedures. The efforts in this domain could potentially explore other aspects of warehousing by analyzing the effects of adopting modernize approaches such as random storage strategies.

Warehouse operating procedures continue to evolve with advance technologies such as warehouse management interoperability with resources and the use of artificial intelligence. Additional research efforts could be initiated to explore technological insertions or innovative methods that streamline the warehouse system. Amazon is a notable company that continues to perfect and modernize in the warehousing domain with advance technologies and strategies. Another study could leverage the success of warehousing initiatives and use of technologies adopted by industry partners to cultivate military warehousing capabilities.

LIST OF REFERENCES

Alrowaie, A. A. (2011). *The effect of time-advance mechanism in modeling and simulation*. (Doctoral dissertation). Retrieved from http://hdl.handle.net/10945/10798

Blankenbeker, M. J. (2018). *USMC depot-level maintenance of the light armored vehicle (LAV): A discrete-event simulation analysis*. (Master's thesis). Retrieved from http://hdl.handle.net/10945/59711

Buss, A. (2001). *Basic event graph modeling*. Retrieved from http://hdl.handle.net/10945/45519

Buss, A. (2017). *Discrete Event Simulation (DES) Modeling*. Unpublished manuscript.

Buss, A. H. (1995). *A tutorial on discrete-event modeling with simulation graphs*. Retrieved from http://hdl.handle.net/10945/38624

Buss, A. H. (2002). *Component based simulation modeling with simkit*. Retrieved from http://hdl.handle.net/10945/38635

Curling, T. (2016). *USMC inventory control using optimization modeling and discrete event simulation*. (Master's thesis). Retrieved from http://hdl.handle.net/10945/50528

Frazelle, E. H. (2002). *World-class warehousing and material handling*. New York: McGraw-Hill Education.

Frazelle, E. H. (2016). *World-class warehousing and material handling*. Retrieved from https://learning.oreilly.com/library/view/world-class-warehousing-and/9780071842839/

Hellström, D. (2002). *Using discrete event simulation in supply chain planning*. Retrieved from https://portal.research.lu.se/ws/files/6050314/625917.pdf

Manuj, I., Mentzer, J. T., & Bowers, M. R. (2009). Improving the rigor of discrete-event simulation in logistics and supply chain research. *International Journal of Physical Distribution & Logistics Management*, *39*(3), 172–201. https://doi.org/10.1108/09600030910951692

Marine Corps Logistics Command. (2009, July 21). U.S. Marine Corps Logistics Command playbook (1st edition.). Retrieved from https://www.logcom.marines.mil/Portals/184/Docs/Sites/Contracts/files/LOGCOM_CCO_Playbook_0709dlb.pdf

Marine Corps Logistics Command. (2019, April 8). Marine Corps Logistics Command history. Retrieved from https://www.logcom.marines.mil/About-Us/History/

Marine Corps Order 4400.201. (2016). Washington, DC: United States Marine Corps. Retrieved from https://www.marines.mil/News/Publications/MCPEL/Electronic-Library-Display/Article/900715/mco-4400201-volumes-1-17/

Robinson, S. (2008a). Conceptual modelling for simulation Part I: Definition and requirements. *Journal of the Operational Research Society*, *59*(3), 278–290. Retrieved from https://doi.org/10.1057/palgrave.jors.2602368

Robinson, S. (2008b). Conceptual modelling for simulation Part II: A framework for conceptual modelling. *Journal of the Operational Research Society*, *59*(3), 291–304. Retrieved from https://doi.org/10.1057/palgrave.jors.2602369

van der Zee, D.J., Tako, A., Robinson, S., Fishwick, P., & Rose, O. (2018). Panel: Education on simulation model simplification – beyond rules of thumb. *2018 Winter Simulation Conference (WSC)*, 3987–4001. Retrieved from https://doi.org/10.1109/WSC.2018.8632544

van der Zee, D.J. (2017). Approaches for simulation model simplification. *2017 Winter Simulation Conference (WSC)*, 4197–4208. Retrieved from https://doi.org/10.1109/WSC.2017.8248126

Sanchez, S. M. (2018, May 23). NOLH designs spreadsheet. Retrieved from http://harvest.nps.edu/

Sanchez, S., Sanchez, P., & Wan, H. (2018). Work smarter, not harder: A tutorial on designing and conducting simulation experiments. 237–251. Retrieved from https://www.researchgate.net/publication/330880196

JMP Pro Version 14.0.0. (2018). Cary, NC: SAS Institute Inc

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California