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THESIS

ALTERNATIVE MAINTENANCE COMMUNICATION MODEL FOR A MARINE LIGHT ATTACK HELICOPTER (HMLA) SQUADRON

by

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September 2021

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A recent safety culture workshop revealed that despite having an appropriate number of qualifications and multiple maintenance meetings throughout a given day, Marine Light Attack Helicopter Squadrons (HMLAs) are still suffering from the problem of inefficient communication. When I was the quality assurance officer (QAO) at HMLA-267, I saw firsthand how inefficient communication between and within multiple shops led to multiple “down” aircraft and an inability to execute all flights on any given flight schedule.

The original intent of this research was to gather data about how communication was occurring in the maintenance department, including the time required for information to pass from Marine to Marine, to find ways to increase efficiency and throughput. The study focused on the sponsor’s squadron, with data obtained remotely due to coronavirus travel restrictions at the time this research was taking place.

The model created ended up answering a manpower problem instead of focusing on communication. The output showed that placing personnel within the Flightline shop first, followed by airframes and then avionics, would be the best way to cut down on maintenance times. This model can be used as a foundation for more detailed events to be added in the future, or to see how adjusting the personnel size of each shop affects completion times.

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ALTERNATIVE MAINTENANCE COMMUNICATION MODEL FOR A MARINE LIGHT ATTACK HELICOPTER (HMLA) SQUADRON

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LIST OF ACRONYMS AND ABBREVIATIONS

AMO	Aircraft Maintenance Officer
AMSRR	Aviation Management Supply and Readiness System
ASM	Advanced Skills Management
CDF	Cumulative Distribution Function
CDI	Duty Inspector
CDQAR	Collateral Duty Quality Assurance Representative
DES	Event Simulation
DOD	Department of Defense
FIFO	First In, First Out
FMC	Full Mission Capable
FOD	Foreign Object Damage
HMLA	Marine Light Attack Helicopter Squadron
IDE	Integrated Development Environment
IID	Independent, Identically Distributed
LEGO	Listener Event Graph Objects
MC	Mission Capable
MOS	Military Occupational Specialty
MOVES	Modeling, Virtual Environments, and Simulation
NAMP	Naval Aviation Maintenance Program
NaN	Not A Number
NMC	Non-Mission Capable
NPS	Naval Postgraduate School
OJT	On-the-Job Training
OOP	Object Oriented Programming
PDF	Probability Density Function
QA	Quality Assurance
QAR	Quality Assurance Representative

RBA	Ready Basic Aircraft
UDP	Unit Deployment Program

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THESIS DISCLAIMER

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

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I. INTRODUCTION

A. PROBLEM

Despite the fact that aviation squadrons and the Marine Corps are giving more consideration to an increasing number of qualifications and better tools for Marines to use, the problem of inefficient communication within and between shops throughout the Marine Light Attack Helicopter Squadrons (HMLA) maintenance department still exists. This is puzzling because all of the shops are located within the same hangar and, even with maintenance meetings twice a day, inefficient communication still persists.

Previous studies related to HMLA from 2015 focused on the effects of enlisted qualifications on aircraft readiness (Germershausen and Steele 2015). A two-year study, recently completed by the USMC Program Management Activity (PMA) 276, focused on every Marine light attack (HMLA), Marine Medium Tiltrotor (VMM) and Marine Heavy Helicopter (HMH) squadron in the Marine Corps trying to determine how the existing manpower model could be fixed to address manning gaps (Boydston, Seidel, and Kelley 2018). Both studies suggested that an increase in the number of personnel in certain areas would lead to an improvement in mission capability. However, neither of these studies specifically addressed how or where inefficiencies in communication may be occurring or their effects.

The Marine Corps is seeking ways to maximize a maintainer's time and effectiveness. The Marine Corps 2019 Aviation Plan specifically mentions using wireless-fidelity (WIFI) technologies along with Portable Electronic Maintenance Aids (PEMA) carts to enable faster lookup and checkout of required maintenance publications (Rudder 2019). This author witnessed this initiative in practice where maintainers were able to check out a PEMA (a robust-looking laptop), and take it out to the aircraft that they were working on. PEMAs, while helpful, do not prevent human error when it comes to passing data from one maintainer to another or from maintainer to supervisor/subordinate. Some of the inefficient communication that this author has witnessed included maintainers running back and forth to grab a tool that was forgotten or relaying the same message multiple times. When this happens over the course of an entire work shift, it decreases the amount of time a Marine can spend performing a maintenance action. This decrease in efficiency, has the compounding effect of increasing the amount of time an aircraft is not mission capable, reducing unit readiness.

B. HYPOTHESIS AND RESEARCH QUESTIONS

This author hypothesized that creating a model based on the maintenance processes of an active HMLA squadron, in this case HMLA-167, would illuminate gaps in the information flow during maintenance processes and sub-optimal communication between elements engaged in the maintenance process. Specific research questions provided by the research sponsor were the following:

1. How can the communication within a HMLA maintenance department be improved?

2. How does a model of the current HMLA maintenance department communication process compare to a model of the essential communication requirements?

Currently, a model like the one this author is trying to develop does not exist. Checklist procedures exist, but a model in the format of an event graph has not been attempted.

3. With limited funding available, how could we optimize improvements to increase efficiency and throughput in the HMLA maintenance department?

C. PURPOSE

The benefits of this study were to provide HMLA squadrons with a way to see themselves better and improve communication, specifically within the maintenance department. When maintenance time is squandered because messages are constantly being lost, it means that aircraft cannot be fixed, and the flight schedule cannot be executed. Since HMLA maintenance process modeling has not occurred, this study can uncover and demonstrate ways to reduce sub-optimal communication while increasing Marines' productivity leading to a greater number of mission capable aircraft. A potential secondary effect of modeling the existing communication process and correcting inefficiencies is increased flight hours, better pilot proficiency, and ultimately improve squadron readiness for deployments.

D. SURVEY QUESTIONS

This author's plan was to study and develop a discrete event model that demonstrated how communication flows during maintenance intensive actions at the HMLA. The sponsor of this project is the Aircraft Maintenance Officer (AMO) for HMLA-167. Data was collected using surveys given to senior shop leaders, desk sergeants, and as many enlisted personnel that were involved in the specific maintenance action. This thesis focused on specific maintenance actions such as an inspection or fuel bladder installation. If none of these had been on-going, this author would have focused on the most time-intensive maintenance that was occurring at the time of data collection. Surveys consisted of questions about actions the interviewee had to perform and what information they were required to pass on. The author took the perspective that Marines are nodes in a network and the information they carry is a variable to be tracked through the maintenance process. After they had written down their roles in the process, this author reviewed their responses and put them in the form of an event graph of where information was going, then integrated all the individual event graphs into one comprehensive event graph model. Once this was complete, the author developed a computational discrete event model using the Python programming language and simulated the maintenance process. The desired end state was to identify inefficiencies/errors in the process and recommend potential solutions for the squadron to experiment with. Some of these solutions included knowing where to add certain Marines in order to shorten maintenance times. The static event graph model was considered complete when the final maintenance action had been performed and all the actions had been signed off by someone from the Quality Assurance (QA) shop or a Collateral Duty Quality Assurance Representative (CDQAR).

The survey questionnaire included the following questions:

1. What is your name? The purpose of this question is to keep track of who the author has spoken with. Names will not be distributed to any other party.

2. What maintenance action was performed?

3. What maintenance shop did this action take place in?

4. How long did the portion of the maintenance action last?

5. Is there WIFI installed in the squadron hangar where the work was performed?

6. Was WIFI used to download anything for maintenance purposes?

Each of these questions was written such that the responses can be converted into parameters and state variables that this author used to develop the event graph, and the computational model and the discrete event simulation. A more detailed explanation of parameters and state variables are included in Chapter V, sections A and B. There was also a reasonable expectation that there would be numerous instances where the exact duration for an event cannot be determined since the author could not be physically present to time every single moving part. In order to solve this problem, the survey asked the following additional questions:

7. Describe in as much detail as possible, the flow of information and maintenance events from the point of view of this position, and what maintenance actions were performed (start times, finish times to include when a QAR or CDQAR signed off on a task?

8. Were there any abnormal events that interrupted maintenance subtasks? If so, how long did the interruption last?

9. What Maintenance Action Forms (MAFs) were open?

10. What is the fastest that the task can be done? *

11. What is the longest this task has ever taken? *

12. What is the average duration that the task takes to complete? *

13. Was there an error in workmanship that caused delay? If so, how long was the delay?

14. How many CDI's and CDQAR's are in each shop?

15. Were CDI’s, CDQAR’s, or QARs available when steps requiring their qualification were performed? Did this cause a delay? If so, approximately how long was the delay?

16. Are there computer workstations available to access the MAF without delay? How many workstations are there? If there was a delay, approximately how long was it?

17. Is following the book procedure step-by-step as it is written, the most efficient way to perform this task or is there a more efficient flow that could be achieved by revision to the procedure?

18. Was there a delay period for a part or tool to become available? If yes, how long did that take? Example: Does the shop have homemade specialized tools for some jobs due to the non-availability of a proper tool that could be ordered/properly produced and distributed?

19. Was HAZMAT involved in any way? If so, how long did HAZMATs portion last?

*These questions refer to the maintenance task being described in question 7.

These questions were asked to Marines is case they could not to provide an exact time for a particular task they had to perform. This method allowed for a pseudo-average number to be developed for the simulation. The purpose of the rest of the questions was to allow a free flow/ semi structured approach to gathering data. This technique was used in a UK study about the evacuation of the Twin Towers of the World Trade Center on 9-11. Researchers also designed a semi-structured interview process to allow the participants to be more relaxed which they hoped would ease memory recollection during that day (Galea et al. 2010).

Unfortunately, due to the nature of survey responses that were received, the focus of this thesis shifted from communication to manpower. The responses did not indicate any communication issues, but more of an issue with having enough trained personnel.

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II. BACKGROUND

A. OVERVIEW OF HMLA MAINTENANCE

This next section will be providing some background about the world of the maintenance department in a HMLA squadron. This orientation is meant for those readers who are not familiar with the types of aircraft in an HMLA or what each of the shops do. Figure 1 is an example of what a typical HMLA hangar looks like. From the labels shown, it is easy to see that all the shops are clustered together in the same space with helicopters and ground powered equipment in between. The two types of aircraft that belong to an HMLA are the Bell UH-1Y Venom Huey and the AH-1Z Viper Cobra, which are shown in Figures 1 and 2 on the next page. Both of these are twin engine utility and attack aircraft respectively and are so similar in build that many parts of one model can be used on the other and vice versa. A possible source of a delay that might be seen in the data collection phase would be with a maintenance practice called cannibalization that occurs when parts from one aircraft are used to fix another one. Usually this will be in the form of taking a part from a Long-Term-Down (LTD) aircraft and installing it on another aircraft that is needed for the flight schedule. According to the Naval Aviation Maintenance Program (NAMP), "Cannibalization is an acceptable management choice only when necessary to meet operational objectives" (Commander 2017). Although there are only two aircraft shown here, it is not uncommon for every available space to be filled with more aircraft, spare parts, and tool kits for ongoing maintenance.

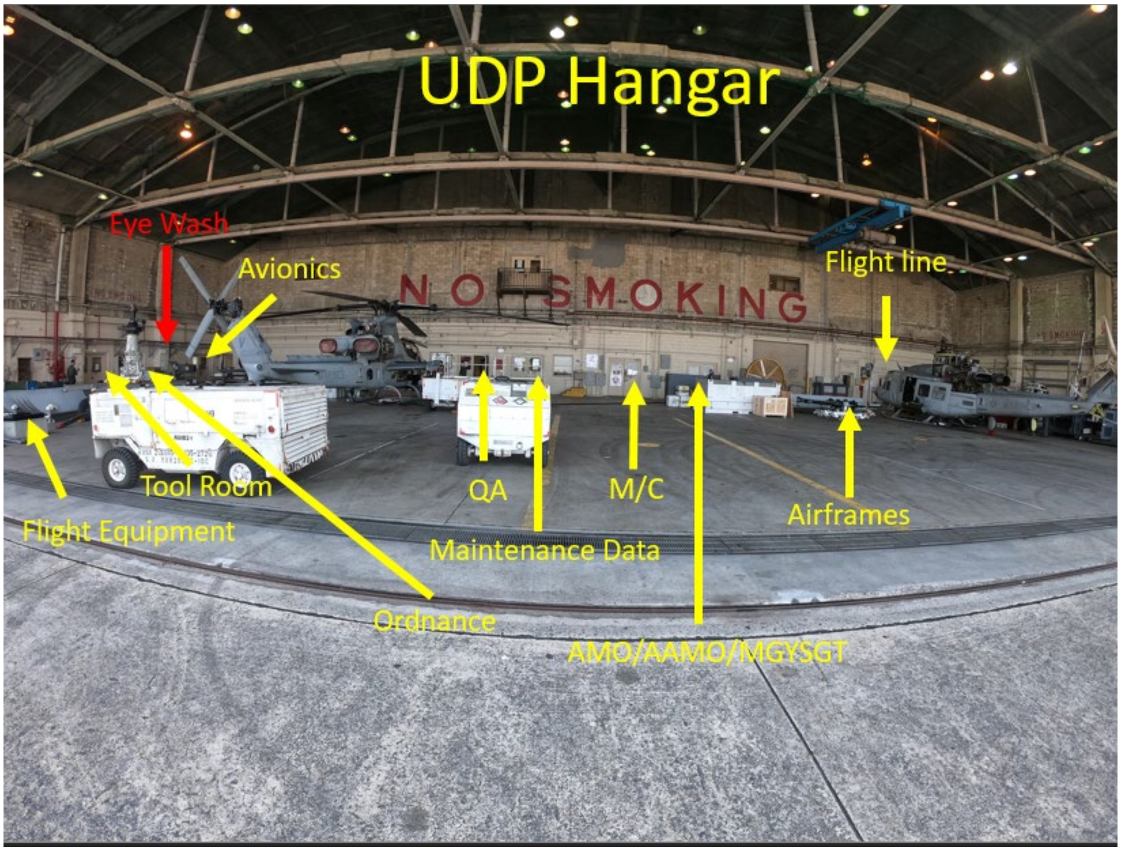

Figure 1. Picture of a HMLA Hangar Taken by the Author While Deployed to Okinawa, Japan.

Figure 2. UH-1Y Venom Huey (left), UH-1Y Huey and AH-1Z Viper Cobra on the Flight Deck of an LPD (right). Source: Marine Aviation Plan (2019).

Figure 3. Engine Replacement Being Done on a UH-1Y Huey.

Finally, Figure 3 shows a snapshot of what maintenance looks like, specifically the beginnings of an engine replacement. Both the Huey and the Cobra have two main engines, and sometimes they have to be replaced due to metal fatigue of the compressor blades or Foreign Object Damage (FOD), from rocks or birds that get ingested. Every maintenance action requires a toolbox checkout, the red box in the lower right of the figure, to bring the required adapters and connectors to the aircraft being worked on. Due to the weight of each engine, either a crane or heavy lift equipment needs to be scheduled as it is too unsafe for the engine to be lifted out by hand. Because the space is so restricted around the engine, only a couple maintainers will work on the engine to make sure all the fuel, oil, and electrical lines have been disconnected.

It is important to talk about what each of the shops are responsible for because they will be referenced in the event graphs and discrete event simulation that this author plans to use. There are three levels of maintenance that can be performed in Marine Corps aviation: Organizational-level (O-Level), Intermediate-Level (I-Level), and Depot-Level

(D-Level). O-level maintenance is performed at the squadron level either inside the hangar or out on the flightline and, according to the Naval Aviation Maintenance Program (NAMP), includes “inspecting, servicing, lubricating, adjusting, and replacing parts, minor assemblies, and subassemblies of aircraft, Unmanned Aircraft (UA) or Unmanned Aircraft Systems (UAS), and aeronautical equipment” (Commander 2017). This is the level of maintenance where the author’s research will be focused. I-level and D-level maintenance usually take place outside the squadron where more specialized equipment is available. As a former Quality Assurance Officer (QAO) at a previous command, this author was able to get a firsthand account of how maintenance occurs. The Quality Assurance shop is just one of eight different shops according to Figure 4, that exist to provide a certain level of oversight and expertise on how maintenance is conducted. According to the hierarchical structure shown in Figure 4, all of these shops ultimately report to the Aircraft Maintenance Officer (AMO), who is in charge of the entire maintenance department. The NAMP is the main governing document that is used to “achieve the aviation material readiness and safety standards established by the Chief of Naval Operations (CNO) and Commander, Naval Air Forces (CNAF) in coordination with the Commandant of the Marine Corps (CMC)” (Commander 2017). In short, the NAMP is the rulebook with established procedures and guidelines that describes maintenance actions in detail with the appropriate safety measures that need to be taken.

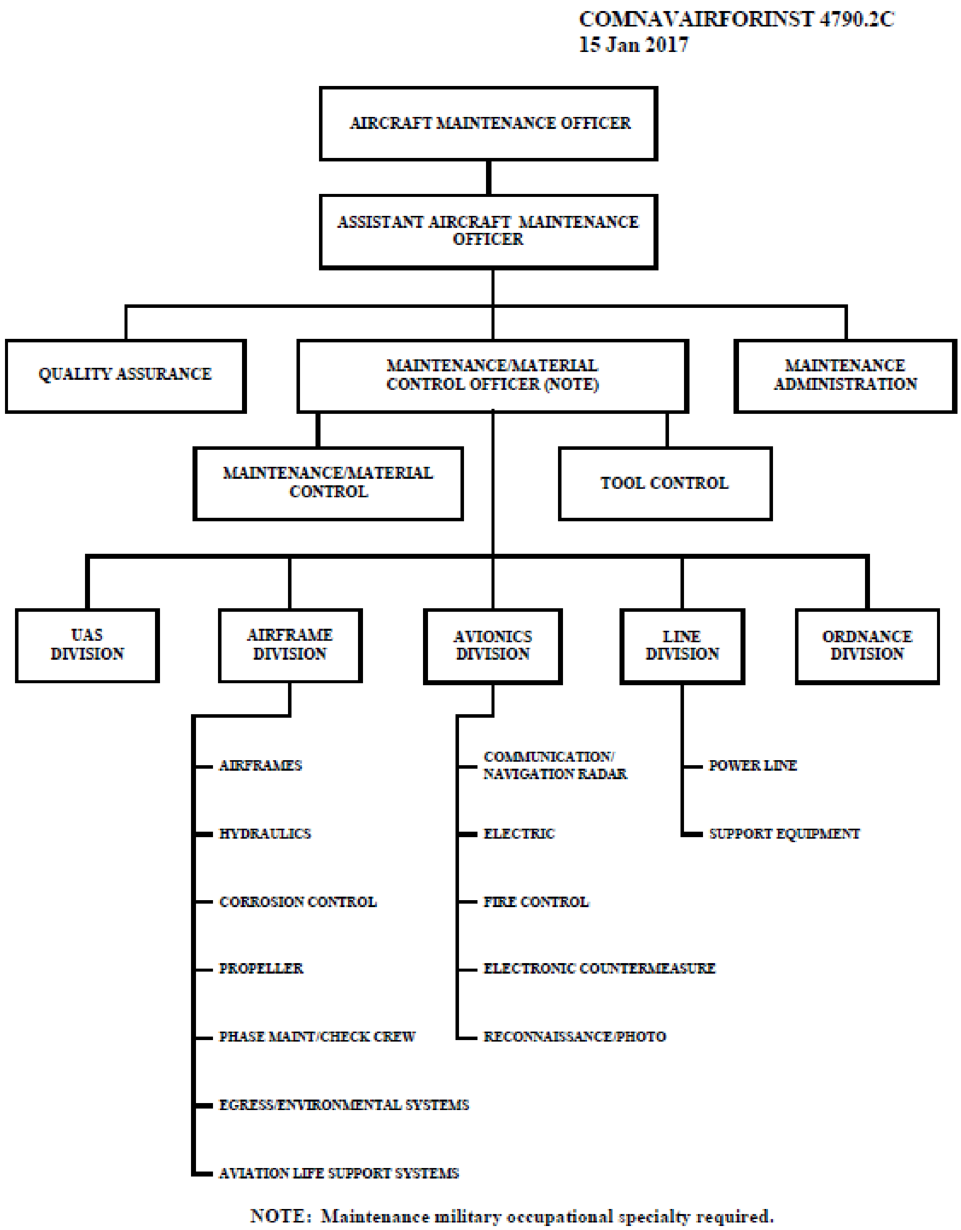

Figure 4. O-Level Maintenance Department Line and Staff Relationships. Source: Marine Aviation Plan (2019, chapter 3).

B. MAINTENANCE SHOP DESCRIPTIONS

The following paragraphs will go into detail about the tasks each of the shops (Quality Assurance, Maintenance Control, Airframes, Flightline and Avionics) performs, and then we describe how communication is supposed to happen throughout the day. Other shops not mentioned here are the Ordnance, Tool Control, Maintenance Administration and Unmanned Aircraft Systems (UAS). The HMLA squadron being studied does not have a UAS shop and the maintenance action that the author is trying to study will not involve any ordnance Marines.

1. Quality Assurance Division

"The QA division is directly responsible to the AMO for ensuring the regulations outlined in the NAMP are being followed" (Germershausen and Steele 2015). This shop typically consists of at least four Marines who conduct specific duties and have responsibilities providing years of experience to solve complex problems. The most important aspect they are responsible for is providing final approval of work done by CDIs or performing an action that can only be done by a Quality Assurance Representative (QAR). Such actions include "in process and final inspections of maintenance performed on egress systems, personnel parachutes, and floatation devices" (Commander 2017). This responsibility is delegated to a QAR because they have been certified after extensive training to inspect such items. There are also two other qualifications that maintainers are constantly striving for which is that of a Collateral Duty Inspector (CDI) and a Collateral Duty Quality Assurance Representative (CDQAR). A CDI is a maintainer who can go and work on a particular task without supervision. Since these Marines are working on $30 million aircraft, this qualification represents a great deal of responsibility and years of training to obtain. When they put their signature on a MAF for a particular maintenance action, it signifies that the maintenance followed the appropriate publications specified and was verified by a visual inspection. A CDQAR is the next qualification above a CDI and is someone who works in another shop outside of QA, such as Flightline or Avionics, but has the delegated authority of a QAR to sign off only on the maintenance actions pertaining to what their shop is working on. The qualification of a CDQAR is usually attained during the second enlistment and grants a maintainer the authority to sign off on higher levels of inspections such as those for a Functional Check Flight (FCF) (Germershausen and Steele 2015). A FCF is where an aircraft is flown to make sure a new component is working correctly in actual flying conditions. It is this final approval that the author intends to be the final end event for the simulation involving a high-level maintenance action.

2. Maintenance Control

The Maintenance Control shop is critical to the overall conduct of maintenance on a daily basis. Typically, there is a day crew and a night crew rotation in each shop and before any maintenance begins for that shift, a meeting is held with representatives from the other shops to discuss the priorities for the day. The goal from the NAMP is to, “manage all action required to retain or restore material or equipment to a serviceable condition with a minimum expenditure of resources” (Commander 2017, Ch.5). Basically, Maintenance Control assigns priorities of effort for personnel and aircraft. A common method of communicating priorities of effort is through the use of a large dry erase board. Usually, this whiteboard is located in the Maintenance Control shop and lists all of the aircraft that are awaiting maintenance with specific details as to what shop is still working on something. An example of the standard layout for this board is shown in Figure 5.

MAINTENANCE CONTROL BOARD				CONFIGURATION	
				1	2
				3	4
BUNO SIDE NO.	IN WORK	AWM	AWP	5	6
				7	8
101	(C)	(D)	(E)	(F)	
(A)					
102					
103					
104					
(B)		(G)			
110	ASSIGN./ 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20/ AVAIL.				
120	ASSIGN./ 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20/ AVAIL.				
130	ASSIGN./ 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20/ AVAIL.				
140	ASSIGN./ 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20/ AVAIL.				
210	ASSIGN./ 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20/ AVAIL.				
220	ASSIGN./ 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20/ AVAIL.				

BOARD LAYOUT: CURRENT DISCREPANCY STATUS DISPLAY METHOD

(A) BUNO/SIDE NO. - Space used to display the aircraft engine component time card(s) and information contained therein.

(B) WORK CENTER - Space used to display work center designations.

(C) Graduated space for displaying outstanding discrepancy registers that are in an "in-work" status.

(D) Graduated space for displaying outstanding discrepancy registers that are in an "awaiting maintenance" status.

(E) Graduated space for displaying outstanding discrepancy registers that are in an "awaiting parts" status.

(F) CONFIGURATION - Space used to display configuration of specific aircraft. Colored sliding tabs are used to indicate configuration status in accordance with the configruation key on the header. Space is provided for 8 items but can be subdivided to provide 16 configurations.

(G) MANPOWER INDICATOR - Space used to indicate number of personnel assigned to each work center, and the number of personnel available for work.

Figure 5. Example of how Maintenance Status is Tracked. Source: Marine Aviation Plan (2019: O-Level Maintenance Control Board).

3. Airframes Shop

The Airframes shop (MOS 6154) deals with three main tasks: hydraulic control, tire, and wheel maintenance and most importantly, corrosion prevention and control. Each aircraft has two hydraulic systems on board that help maintain directional control over the main rotor system. Anytime there is maintenance that involves the hydraulic lines, a hydraulic fluid sample must be collected. This activity takes about 15 minutes to complete and ensures that the hydraulic fluids supporting the main rotor system have not been contaminated. Corrosion prevention is the other major responsibility of this shop and can often be the most time consuming. If corrosion is discovered during the maintenance process, it can cause a delay in other maintenance actions due to the painting or replacement activities that must be executed on the affected part.

4. Flightline Shop

The Flightline shop (MOS 6154) is primarily responsible for providing plane captains and aircraft marshals for running the flightline. These are the Marines who are not only responsible for guiding aircraft in and out of their spots, but also have the responsibility to communicate a solution for any problems that occur while the aircraft is still on the flightline away from the close proximity and convenience of the hangar. For example, if a light is not working correctly, then they have to know what bulb to retrieve and where it is located long with the tools needs for the job. Additionally, this shop is responsible for making sure that oil samples for the four different gearboxes used in the engine are within limits (i.e., normal consumption rates and color) and is usually performed after a specific part replacement and when an aircraft has flown for a certain of hours. This is a crucial check as any problem involving oil while in the air could lead to a catastrophic engine or gearbox failure.

5. Avionics Shop

Finally, the avionics shop (MOS 6324) deals with all things relating to the electrical systems of the aircraft including the flight control computer, and ignition circuitry for the engines. What can make this part of maintenance so time consuming is that there are so many electrical lines, many of which are in hard-to-reach areas, that need to be visually inspected. If an incorrect wire is being worked on or there is a miscommunication about the component that is malfunctioning, then more delays are incurred. Everything from the multifunctional displays (MFD) to the Digital Electronic Control Unit (DECU) that helps control operation of the engine, to the auxiliary power unit (APU) that helps start the main engines, have an electrical component that requires continuous inspection and preventative maintenance.

6. Summary

The intent of this section was to provide a brief overview of the makeup of an HMLA maintenance department as well as provide some visual depictions of what a HMLA maintenance evolution looks like. The author's hope is that the reader now has a basic understanding of the workings of the maintenance shops in the HMLA that will be depicted in the event graph and subsequent computer program of this thesis.

C. MODELING AND COMMUNICATION

1. Discrete Event Simulation and Event Graphs

"It is not possible yet to point to a single theory of human behavior that has been successfully formulated and tested in a variety of settings"

— Elinor Ostrom (qtd. in Page 2018)

This section goes into detail about what a Discrete Event Simulation (DES) is and the components of an event graph to provide the reader with a foundational understanding of both of these items.

There are numerous types of models that could be used for representing how communication occurs. Some of them are network, broadcast diffusion and contagion (Page 2018). But since there are people for whom this study is intended to benefit who do not have a programming background, another type of data visualization is desired. This is where discrete event simulation and event graphs come in to play. The definition of an event graph from the book Stochastic Modeling is, "an intuitive graphical representation of a discrete event simulation" (Nelson 1995). The purpose of a discrete event simulation model is to help view something about a system that was not overt and collect certain statistics from that information. An example of a very simple event graph is given below in Figure 6.

A Discrete Event Simulation (DES) model consists of state variables together with events that specify how those state variables change from one value to another. Each event in the simulation first executes the state transition corresponding to that event and then may schedule other events to happen in the future. In a DES model, time advances from one event to the next scheduled event. This is managed by a construct called the Event List. Typically, a DES model also contains parameters, quantities that do not change in a given replication of the simulation. Thus, composing a DES model consists of:

1. Defining the parameters
2. Defining the state variables
3. Defining the state transitions (events)
4. Defining the scheduling relationships between events

The scheduling relationships between events can be represented as a directed graph in which the events are the nodes, and the scheduling relationships are the arcs between nodes. This graph is called an Event Graph. The canonical representation is shown in Figure 6.

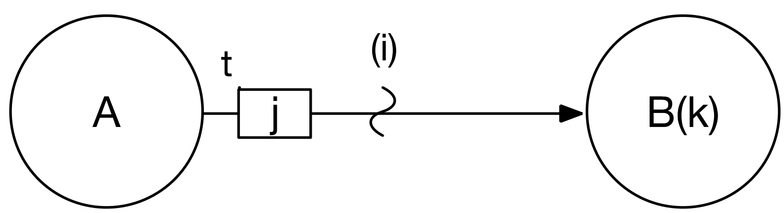

Figure 6. Simple Event Graph. Source: Buss (2017).

In Figure 6, A and B(k) are events; B(k) indicates that the event B has an argument denoted by k. The expression (i) is a boolean (i.e., either true or false). The interpretation is as follows. Whenever event A occurs, if boolean condition (i) is true, then event B(k) is schedule t (simulated) time units in the future. When event B(k) occurs, the argument k is set to the value of the expression j when it had been scheduled. If the time delay t is not specified, it defaults to 0. Similarly, if the boolean condition (i) is not specified, it defaults to "true."

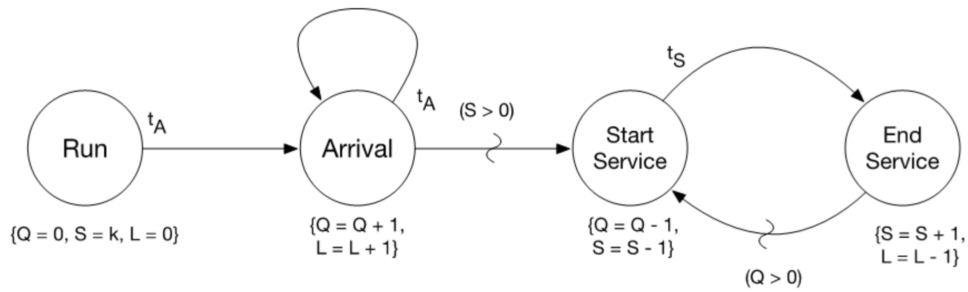

Figure 7. Basic Example of a Multiple Server Queue Event Graph. Source: Buss (2017).

The multiple server queue DES model in Figure 7 has parameters k, $\{t_A\}$, and $\{t_S\}$. These are, respectively, the number of servers, the interarrival times, and the service times. In a typical implementation, $\{t_A\}$and $\{t_S\}$ are generated from a random variable distribution. There are three state variables: Q, S, and L. These are, respectively, the number of customers in the queue, the number of available servers, and the number of customers who have been served.

There are four events in this model: Run, Arrival, StartService, and EndService. The Run event is special in that it is always executed first, and its state transition consists of setting every state variable to its initial value. In this case, there are 0 in the queue (Q) and 0 served (L), but k available servers (S). The Run event schedules an Arrival event with a delay of t_A, the first interarrival time.

When the Arrival event occurs, it increments the number in queue by 1, as indicated by its state transition in Figure 7. Then it schedules the next Arrival event with a delay of the next interarrival time (t_A). Finally, if there is an available server (i.e., if S > 0), then it schedules a StartService event with zero delay. If all servers re busy (i.e., if S = 0), then nothing further happens at that occurrence of the Arrival event. Note that subsequent Arrival events may find S > 0 and they will then schedule the StartService event. The other events proceed in a similar manner.

The event graph for a task within a maintenance department will be much more complex and likely involve at least a couple dozen variables.

Once the model is implemented in the computer, it can be executed repeatedly, and important statistics can be gathered. These statistics will be a function of the state trajectories for how the state variables evolve over time. In the multiple server queue example, one measure of interest is the average number in the queue. A single replication of the simulation can produce a time average of the state variable Q, which will give a single observation. Executing the model with multiple independent replications will result in independent, identically distributed observations from which a confidence interval can be obtained. This was important because there was not enough time or resources to run 30 replications of a maintenance action in a real world situation and collect all the relevant data.

One of the hardest parts of this thesis was gathering data, specifically exact times for multiple maintenance actions. To solve this, this author used a technique used by a UK study of the 9/11 evacuations: Getting the time of an event relative to when something happened that everyone could verify (Galea et al. 2010). In case of this thesis, those events occurred when a previous work order or MAF was digitally signed off or verbal confirmation to a supervisor was completed.

2. Optimal Communications

"The greatest problem with communication is the illusion that it has been accomplished"

—George Bernard Shaw, famous Irish playwright (qtd. in Pilkington 2013)

This section gives a brief overview of some of the communication strategies that are used in various areas of the civilian sector. This author believes that looking at studies and techniques done to improve the flow of information in areas such as the medical field, can have a positive impact on reducing sup-optimal communications within the HMLA maintenance department.

Like the results from the safety culture survey in the HMLA, studies of civilian companies struggling with communication issues have found that one of the top complaints from employees is about not being well informed (Pilkington 2013). The maintenance department attempts to solve this by holding meetings twice a day where the AMO, AAMO and usually a senior enlisted leader from QA passes important information regarding the status of maintenance actions supporting flight operations. But these meeting are mostly one-way forms of communication that do not always apply to everyone. Even though most Marines in attendance at these meetings take notes, spending time listening to another shop's problem might lead to delays in starting the actual maintenance. The mistake that tends to be made is that senior leaders think that what is important to them is also important to everyone else (Pilkington 2013). Most of the time it is, but this author has also been in meetings that run long and end up prolonging the start of maintenance because someone thought that what they had to say would be helpful.

During the late 1940s, two engineers named Claude Shannon and Warren Weaver developed what is considered to be the first model of communication based on the use of the telephone (Pilkington 2013). That model is shown in Figure 8. Although it is a simple model, there are important things this model tells us about real-word communications and some things it does not. First, in order to deliver a message, the source must encode their information for delivery. This encoding takes time and contributes to the overall time it takes for the message to be received. Then the message is sent over some medium such as at a group meeting or video/audio source and is decoded and received by the intended audience. What this model does not depict is whether or not the communication was understood or if a task will be completed the way the originator intended. One of the things that is needed to solve this is an effective relationship between the sender and receiver.

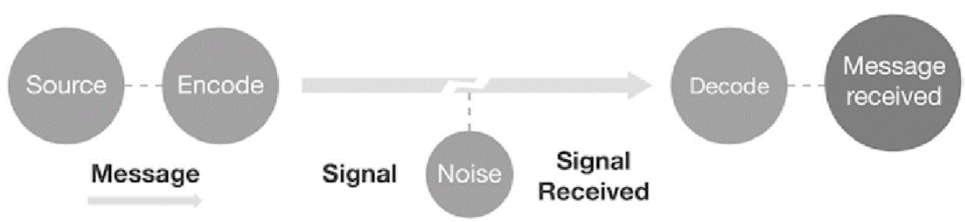

Figure 8. Early Model of Communication Source: Pilkington (2013).

It is important to understand that the medical field has been developing techniques to improve communication between a patient and doctor. One of the most important things they found is that more information can be gained when a doctor actively listens to their patient instead of administering a standard battery of questions. As a result of this mutual feeling of empathy, a noticeable change in body language occurs where both parties physically open up and actually mirror each other's postures. This same medical journal also suggests asking the patient to explain their understanding of the medical problem so the physician can either correct or guide them forward for better treatment (Drossman 2013). The takeaway here is that changing the way the two parties communicate can save time and make the meeting more productive.

To be clear, this thesis did not explore the qualitative aspects of communication in the maintenance department. This author has seen the positive effects when people have worked together for months or even years. These relationships allow people to understand how each other functions and helps eliminate delays because one person already knows what information another might need. This thesis was an attempt to look at communication from a quantitative point of view. The survey questions, which are explained in more detail in Chapter IV, were designed to ask, "about what" rather than "about whom." The purpose of this previous section was to show that there is a qualitative aspect to effective communication.

3. Benefits of Using Communication Models / Event graphs / Simulation in Business

This section provides more relevance for why event graphs are useful to improving communication and how they are used to study real world systems.

One of the main characteristics that an event graph and the subsequent simulation can show us is where a bottleneck is occurring. This knowledge can be used to optimize the system in order to save a company money, improve customer service or efficiency. For example, there was a company that wanted to know how many terminals they could have on their time-shared system with a single CPU and still provide a 30 second completion time. By modeling the system in using DES and the whole point of using event graphs was that it demonstrated the system could have 60 terminals and still give an average response time of 31 seconds (Law 2015).

III. RELATED WORK

This chapter focuses on previous research that has added significant value to the framing of this thesis. This section is divided into a section on modeling, one on maintenance, and the author's own experience going through a directed study for discrete event simulation.

A. DES FOR CFF (FURR 2019)

Work done by Major John M. Furr, USA, and his 2019 thesis titled "Modeling Forward Observer (FO) Operations Using Optical Data Communications" had a large impact on the current research. Although Major Furr's research was about the call for fire (CFF) process, the methods he used are most important and what this author found most useful. Furr focused on the effectiveness of using optical communications for fire support by creating a discrete event simulation (DES) that provides the full detail needed for considering the use of optical communications in fire support. The current thesis focuses on communication in support of aircraft maintenance utilizing DES and event graphs at the individual level. The event graph that Furr used for a Friendly CFF event demonstrated the complexity of visualizing all the actions that have to occur for a strike to happen. There are 26 different state variables, and 23 parameters used in the Furr model, which Furr wrote, "had to implement the real-world scenarios into schedulable events that mimicked the interactions of real-world events" (Furr 2019). One of the conclusions Furr (2019) reached was that processing time was able to be accurately modeled based off the Tactics, Techniques, and Procedures (TTPs) that the Army uses, and it was recommended that modifying the TTPs could result in a faster output in the simulation. This author's goal was to be able to do the same thing except processing delays were not solely based on maintenance doctrine. We attempted to take into account other factors such as physically walking to communicate a message or even repeating an event if information was dropped. However, the responses that were received on the surveys did not have the granularity needed to try and model those types of events.

B. OPTIMIZATION AND COST SAVINGS (GERMERSHAUSEN & STEELE 2015)

The third research question that this thesis explored, "With limited funding available, how could we optimize those improvements to increase efficiency and throughput in the HMLA maintenance department." A thesis completed in 2015 by Zachary Germershausen and Scott Steele found that "both the supply system and the number of qualifications have a dramatic effect on the level of readiness individual squadrons can achieve" (Germershausen and Steele 2015). Although it would be expensive to buy more parts to fill the supply system, the low-cost solution would be to increase the frequency of On-The-Job Training (OJT) given to young Marines during the process of obtaining their first major qualification as an aircraft maintainer. Until these inexperienced Marines earn the Collateral Duty Inspector (CDI) qualification, they must be constantly supervised by a more experienced maintainer. By implementing more frequent OJT, Marines could get their qualifications faster, results in more resources if there is a surge in maintenance.

C. DIRECTED STUDY

At the time of writing this section of the literature review, this author was in the process of taking a directed study designed to understand the concepts behind event graph modeling and discrete event simulation. Based on guidance from the instructor and a description of what HMLA maintenance is like, both the instructor and this author believed that the initial event graph would look something like a multiple server queue or a transfer line model. The only exception being that the arriving helicopter would be worked on by the maintenance shops simultaneously instead of in series. Throughout the directed course study about DES and event graphs, this author had the benefit of either looking at a pre-built event graph or a summary of how a semi-real event would function. These events focused on different versions of the multiple server queue model that was explained in chapter two. The modification to this standard model was that the "customer" was represented by the helicopters and the servers were the Marines performing the maintenance. Unlike the standard model for this, which only has four events, our event graph attempted to capture all the subtasks associated with the overall maintenance task and then break them up to make the graph easier to read. According to Buss (2017 pg. 5-1), “If the entire model consists of a single Event Graph, large models-those with many Events-become difficult to understand and maintain.”

Because there was a recognized need to break things up, this author was able to divide the event graph into a number of smaller components, basically miniature event graphs, that serve a particular function in the model. According to a document written by Dr. Buss called Project Planning Lite, the best way to tackle a large project like this will be to have multiple intermediate milestones that represent aspects of the real-world system. As the course of study progressed, one of the biggest things this author learned was that the most logical way to build a model is in small stages. Neglecting this strategy could have led to much of the author’s time being spent on debugging the model and not making sure it is validated. More details about the building of the model, including the survey questions, are provided in the Methodology section.

There were three important takeaways in this related work section. The first came from the Germershausen and Steele thesis which described metrics they used to determine how aviation maintenance qualifications affected performance. Although this author did not use all of them, the most important resource would be the maintenance hours that are tracked electronically. These hours were used to help validate this model. The second take away came from John Furr’s thesis. His research showed how a real-world military scenario can be viewed as an event graph and then programmed to simulate different outcomes. Finally, the directed study this author took was invaluable in terms of learning how to make a proper event graph and how to represent it using the Python programming language.

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IV. METHODOLOGY

A. EXPLANATION OF SURVEY QUESTIONS

This section will explain the reasoning behind each of the survey questions including how and why they were created, and what this author hoped to gain from them. The most important research question that these surveys were trying to figure out was how communication within the maintenance department could be improved. There are 19 questions in total that were sent via electronic mail once the entire maintenance task, was completed. What the author was also trying to do was build a model of communication for the maintenance department since an existing one could not be found. This chapter also explains what type of information the model output after the surveys were returned from the squadron.

One of the hardest parts of this thesis was gathering data, specifically exact times for multiple maintenance actions. To try and solve this, this author used a technique implemented by a UK study of the 9/11 evacuations: Getting the time of an event relative to when something happened that everyone could verify (Galea et al. 2010). In case of this thesis, those events occurred when a previous work order or MAF was digitally signed off on or verbal confirmation to a supervisor was completed.

The model that was attempted here did not have any pre-built sections of an event graph, so questions had to be developed that would give some valuable insight as to what was going on. Procedures exist to guide every maintenance activity. However, things happen in real-life that are not captured by pre-defined procedures e.g., delays due to resource constraints or part availability. Therefore, the questions that were developed here were written with the goal of providing the foundation for the event graph.

What maintenance action was performed and what shop did this action take place in?

These two questions help to determine not only what the main action was (i.e., Aircraft inspection, part repair, diagnostic check), but also what was accomplished by each Marine involved within their specific shops. For example, the main task might be an aircraft inspection after it is done flying for the day, but a Marine in the Avionics shop will have to check the condition of electric wires while another Marine in the Flightline shop will have to perform a non-destructive inspection (NDI) on the flight control surfaces. Each of these shops will have their own unique “events” in the event graph.

How long did the portion of the maintenance last? What is the fastest the task can be done? What is the longest this task has ever taken? What is the average duration that the task takes to complete?

These questions try to extract times that each maintainer within a shop takes to complete their respective tasks. Event graphs have scheduling relationships between events (Buss 2017). As previously discussed, these events look like a directional arrow with the origin at one event and the point at another which is read as: Event A schedules Event B as shown in Figure 7.

If nothing else is written, this means that there is no delay between the two events. This does not happen in the real world because before a task can be logged as complete there is a delay from the previous event. The last three questions dealing with the fastest and slowest times are used in case a Marine being interviewed does not have an exact time for the duration of a task.

Is there WIFI installed in the squadron hangar where the work was performed? Was WIFI used to download anything for maintenance purposes?

Most maintenance publications and procedures are stored digitally on PEMAs. Electronic laptop computers provide maintainers almost the same level of convenience as a Kindle. Maintainers have the ability to store hundreds or thousands of books with faster lookup and storage on a lightweight device. This question is designed to attempt to isolate the time delay in a request for information and the arrival of that information to the maintainer on the tablet.

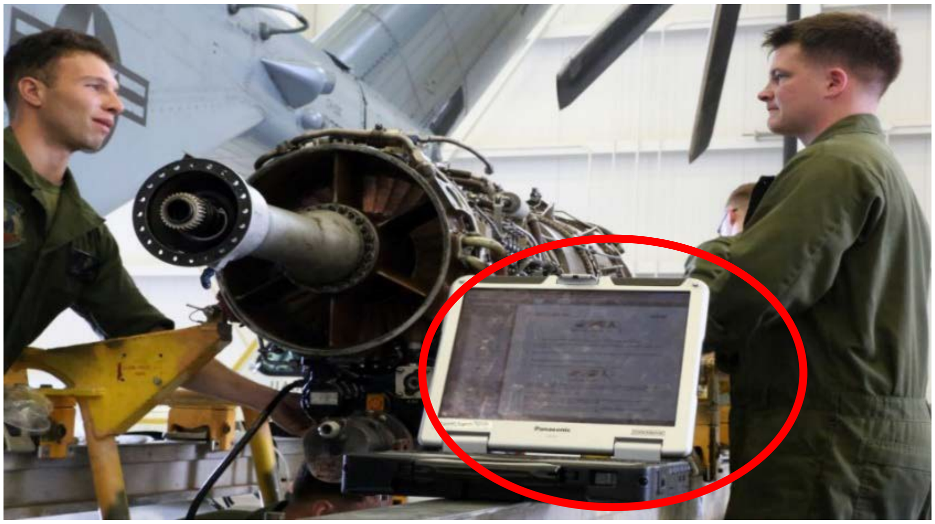


Figure 9. Portable Electronic Maintenance Cart (PEMA). Source: Rudder (2019).

Describe in as much detail as possible, the flow of information and maintenance events from the point of view of this position, and what maintenance tasks were performed start times, finish times to include when a QAR or CDQAR signed off on a task?

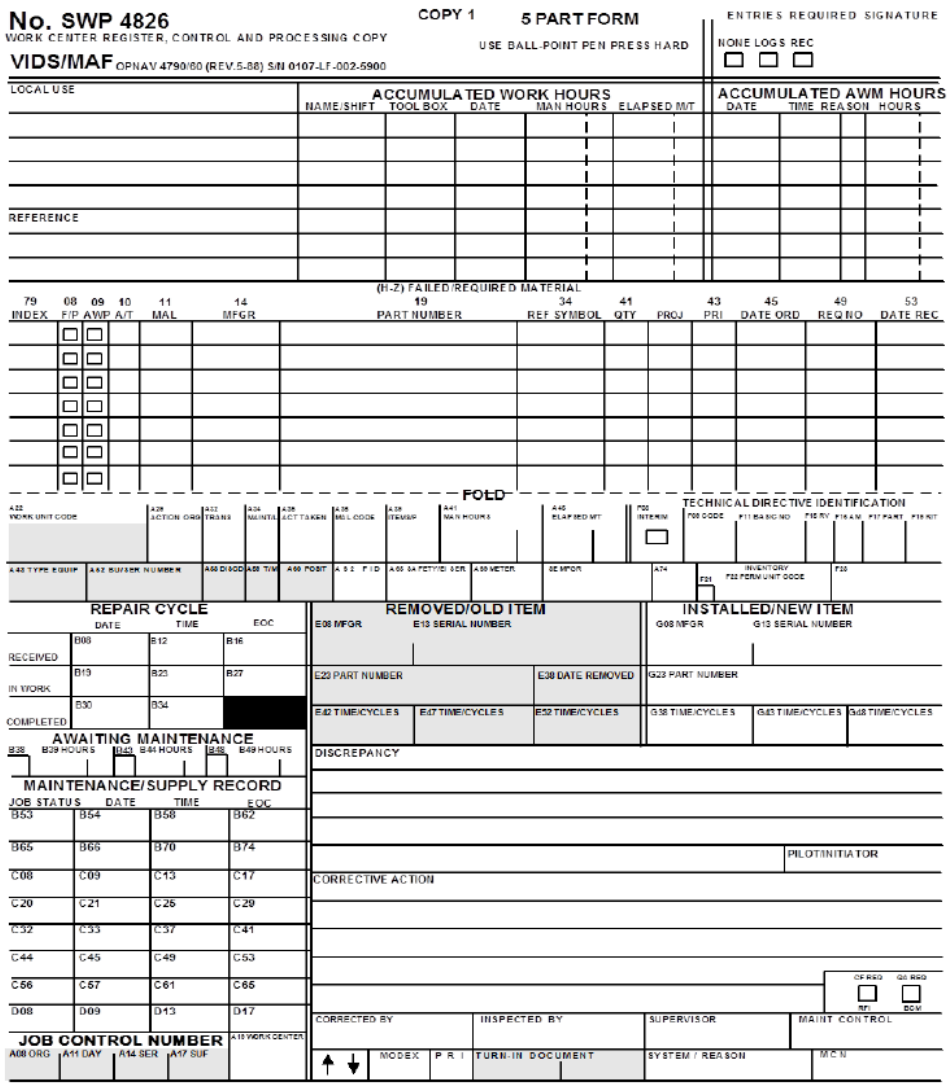
This is the question where this author believes the most time will be spent gathering information. The goal is to document the chain of events from the perspective of each individual Marine that was involved in the specified task. Event graphs will be built during interviews as possible to capture what the participants are saying. Then these graphs will be consolidated with the event graphs from everyone else who was involved and interviewed. “What maintenance tasks were performed” refers to the subtask that an individual completed which contributed to the overall maintenance task. QARs and CDQAR’s are specified here because without their signoff/ visual verification, a task is not officially considered complete.

Were there any abnormal events that interrupted maintenance subtasks? If so, how long did the interruption last? Was there an error in workmanship that caused delay? If so, how long was the delay? Was there a delay period for a part or tool to become available? If yes, how long did that take? Example: Does the shop have homemade specialized tools for some jobs due to the non-availability of a proper tool that could be ordered/properly produced and distributed? Was HAZMAT involved in any way? If so, how long did HAZMATs portion last?

The author is trying to determine if a worker was pulled off the task in question to go work on another job because of limited personnel availability. Such events could show how delays are affected if this occurs with any sort of frequency.

What Maintenance Action Forms (MAF) were open? How many CDI's and CDQAR's are in each shop?

As discussed in a previous section, a MAF is a document that explains the details of where a problem exists on an aircraft. CDI's and CDQAR's are those individuals who can inspect and certify respectively, the actions performed on the aircraft to fix the problem. This author believes that the number of MAFs, CDQARs, and CDIs could serve as state variables for the simulation since they are values that will change over time. An example of a MAF is given in Figure 10.



No. SWP 4826
WORK CENTER REGISTER, CONTROL AND PROCESSING COPY
VIDS/MAF OPNAV 4790/60 (REV.5-88) S/N 0107-LF-002-5900
COPY 1
5 PART FORM
USE BALL-POINT PEN PRESS HARD
ENTRIES REQUIRED SIGNATURE
NONE LOGS REC
LOCAL USE
ACCUMULATED WORK HOURS
NAME/SHIFT TOOL BOX DATE MAN HOURS ELAPSED M/T
ACCUMULATED AWM HOURS
DATE TIME REASON HOURS
REFERENCE
(H-Z) FAILED/REQUIRED MATERIAL
79 INDEX 08 F/P 09 AWP 10 A/T 11 MAL 14 MFGR 19 PART NUMBER 34 REF SYMBOL 41 QTY PROJ 43 PRI 45 DATE ORD 49 REQ NO 53 DATE REC
FOLD
TECHNICAL DIRECTIVE IDENTIFICATION
REPAIR CYCLE
DATE TIME EOC
RECEIVED B08 B12 B16
IN WORK B19 B23 B27
COMPLETED B30 B34
REMOVED/OLD ITEM
E08 MFGR E13 SERIAL NUMBER
E23 PART NUMBER E38 DATE REMOVED
E42 TIME/CYCLES E47 TIME/CYCLES E52 TIME/CYCLES
INSTALLED/NEW ITEM
G08 MFGR G13 SERIAL NUMBER
G23 PART NUMBER
G38 TIME/CYCLES G43 TIME/CYCLES G48 TIME/CYCLES
AWAITING MAINTENANCE
B38 B39 HOURS B43 B44 HOURS B48 B49 HOURS
DISCREPANCY
MAINTENANCE/SUPPLY RECORD
JOB STATUS DATE TIME EOC
B53 B54 B58 B62
B65 B66 B70 B74
C08 C09 C13 C17
C20 C21 C25 C29
C32 C33 C37 C41
C44 C45 C49 C53
C56 C57 C61 C65
D08 D09 D13 D17
PILOT/INITIATOR
CORRECTIVE ACTION
CORRECTED BY INSPECTED BY SUPERVISOR MAINT CONTROL
JOB CONTROL NUMBER
A08 ORG A11 DAY A14 SER A17 SUF
MODEX P R I TURN-IN DOCUMENT SYSTEM / REASON MCN

Figure 10. Maintenance Action Form (MAF). Source: COMNAVAIRFORINST 4790.2C.

Were CDI’s, CDQAR’s, or QARs available when steps requiring their qualification were performed? Did this cause a delay? If so, approximately how long was the delay? Are there computer workstations available to access the MAF without delay? How many workstations are there? If there was a delay, approximately how long was it?

These questions help to establish scheduling relationships between certain events in the form of an “if-then” statement. For example, the author believes that some event “x” will only be able to schedule event "y" if a certain qualification is available. As noted in the previous question, the number of available qualifications can be tracked because they are going to be used as state variables.

Is following the book procedure step-by-step as it is written, the most efficient way to perform this task or is there a more efficient flow that could be achieved by revision to the procedure?

This is a question that will not be used in creating the simulation model but will help to support the development of the conclusion and recommendation sections. To review again, one of the three research questions being pursued is how communication in the maintenance department can be improved. While most of the questions are designed to give quantitative answers, this question may also provide a qualitative solution from the maintainers' perspective. It is the author's hope that the responses, coupled with the output from the simulation, will reinforce why specific change recommendations should be strongly considered for implementation.

The takeaway from this section is a breakdown of all the question that the author intends to ask and what information will hopefully be gained. According to the Discrete Event Simulation book by Dr. Arnold Buss, there are four parts that make up a DES model: parameters, state variables, events, and scheduling relationships. Each of the questions developed in this section is designed to provide values for each of the parts of the DES model.

B. EXPLANATION OF SIMULATION OUTPUT

A baseline was developed using the following 12 output metrics from the simulation shown in Table 1.

Table 1. List of Simulation Output Metrics.

Number of Helicopters Fixed	Total Time in System	Delay in Queue Disassembly	Delay in Queue Repair
Delay in Queue Assembly	Time in Disassembly	Time in FL Repair	Time in AF Repair
Time in AVI Repair	Time in Assembly	CDI Utilization	CDQAR Utilization

A 95% confidence interval was obtained after running the simulation for 30 replications over four different time units representing hours elapsed. These time units were 730, 1460, 2190, and 8760 hours which represented one month, two months, three months, and one year, respectively. A total of six surveys were received from HMLA-167 after conducting a 28-day inspection.

Some assumptions were also made in how the model was run. They are as follows:

- All the shops start out with the same number of unqualified Marines (10) for the baseline.
- There is an 80% likelihood that a CDQAR will be needed for a higher-level maintenance approval. There is no solid data for this number. It is mostly based off the author's memory for how often CDQARs were needed.
- There is no other maintenance going on except for this one 28-Day inspection.
- According to Figure 18, one CDI and one CDQAR was deducted during the "start repair event" and added back at the 'remove panel' event. This

was done to represent a CDI going to monitor or train the maintenance Marine and the CDQAR going to observe the CDI.

The code for this thesis was written with Python 3.8 using the PyCharm Integrated Development Environment (IDE) along with the DESpy package from PyPi. The final version of the code is saved in a repository on GitLab with NPS and a small snippet of the code is shown in Appendix C. That snippet of code was taken from the Repair Process component and written in a way that the Python interpreter implements what the event graph shown in Figure 18. If future researchers need access to the code, please contact Dr. Arnold Buss at NPS. The times for the statistics of the time in system were collected from the "Total Time in System" variable and each shop had its own "Time at Repair" variable. An object called Simple Stats Tally was used with these variables. When a helicopter unit arrived at the Disassembly Process component, its arrival time was noted via the stamp_time () function as well as when each subcomponent arrived at the repair process component. The elapsed_time () function was used to calculate the amount of time the subcomponent spent in the repair component and at the "end assembly" event. The Simple Stats Tally object was then used to obtain an average time using the "mean" attribute.

V. DESIGN AND IMPLEMENTATION

This chapter will go over a description of how the event graph for an aircraft maintenance process was developed. The second research question this author was trying to answer was how a model of the current HMLA maintenance department communication process compares to a model of the essential communication requirements. Since there was no current model that could be found, one had to be built from scratch. The author's intent with this section is to familiarize the reader with the variables and terms that were used.

This author would also like to let the reader know that the event graphs do not cover specific communication problems. During the data collection phase, it was discovered that the survey responses were not what was expected. The responses indicated that the main problem was having enough people for a task. This caused a shift in the focus of the research from that of communication to a manpower study.

A. PARAMETERS AND STATE VARIABLES FOR THE MODEL

The first things shown in the Figures 11 and 12 are the parameters and state variables respectively, that were tracked throughout the simulation. As a reminder to the reader, parameters are those variables that do not change during the simulation. Parameters can be thought of as being similar to the settings for a video game such as brightness or noise level. State variables are items that change value over time (Buss 2017).

Event Graph **Parameter Assumptions**

Repair Time Generator

Total number of CDIs

Total number of CDQARs

Total number of Marines

Probability of CDQAR Inspection, p

Figure 11. Event Graph Parameters.

Event Graph **State Variable Assumptions**

Number Available Marines

Number Available CDIs

Number Available CDQARs

Figure 12. Event Graph State Variables.

B. EVENT GRAPH DESCRIPTION

This section walks through the event graph that was used in the computer simulation. The intention is to describe in detail what each component is going to do and how it will compute the results this author is looking for. This will not be a deep dive into how event graphs work. The reader should refer to Chapter II, section C, where some of the terminology and components of a simple event graph were discussed. Also, due to the complexity of the event graph, it will be presented in pieces to help simplify explanation. The reader should refer to Appendix B for a complete view of the components together.

The event graph core is a slight modification of a disassembly-repair-assembly model. Figure 13 shows a basic overview of how the model functions. There are three components that comprise the model: Disassembly, Component Repair, and Assembly. The disassembly phase represents when a helicopter enters the maintenance process and is then assigned to the various shops. The component repair process will represent each shop that is involved in the process. The original intent of this part of the model was that a part of some kind would be physically taken apart and repaired. Instead, this component represents each shop working on their specific part of the aircraft which may not be actually disassembled. Finally, the assembly phase kept track of all the repair components for each individual helicopter. When all the repair components are complete then that individual helicopter was considered complete with the maintenance action. The reader should also notice that the final events in each component will have the same state variables. These were put in place to track the delay in queue and total time that each helicopter unit spends in each component. The final event in "assembly" produces the total time that the helicopter spent in the whole process.

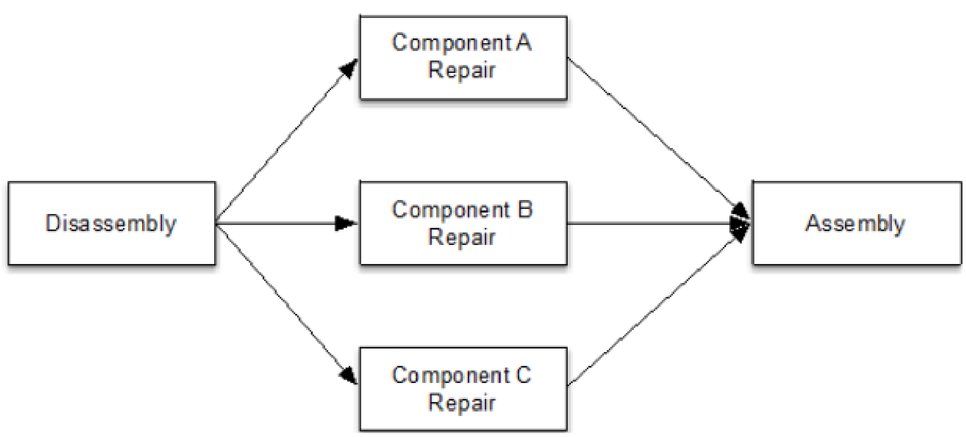


Figure 13. Flow of Repair Process.

1. Components Section

Due to the type of maintenance process being studied, there are only three different subcomponents within the repair process. The following changes have been made to the code: Component A will represent the Flightline shop, Component B will represent the Airframes shop, and Component C will represent the Avionics shop. If more shops contributed to the maintenance action, then those would simply be added as Component D, E and so on. As shown in Figure 14, these components would have Boolean values of True or False depending on their completion status.

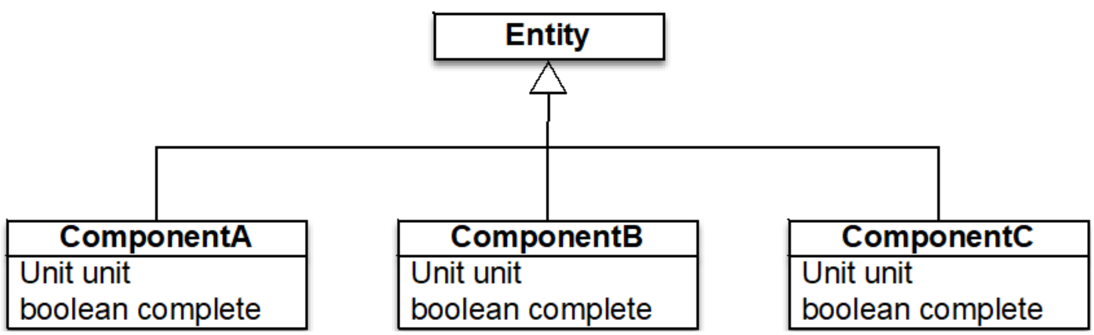


Figure 14. Entity Components.

2. Disassembly Component

Figure 15 shows the detailed event graph for the disassembly process. It has three state variables: "S" representing the number of available workers, "D" representing the total delay in the disassembly queue and "W" representing the total time of each helicopter entity in the disassembly process. All times are in hours. This component represents the shop of Maintenance Control that processes each helicopter and assigns it a priority for when it will be worked on by the other shops. For simplicity, the model assumes that helicopters are only coming in for one type of maintenance and can only be distributed to the other shops one at a time. The state variable for the number of workers represents the number of Marines working in that shop. There is also a queue represented by the letter "q." This will begin to fill up with helicopter entities and slowly be emptied after the "start disassembly" event. When a helicopter unit arrives, each entity is marked with an arrival time that is measured against the elapsed time at "end disassembly" to get the total disassembly time. For the "start disassembly" event to be scheduled there must be at least one Marine worker available, represented by the S > 0 condition.

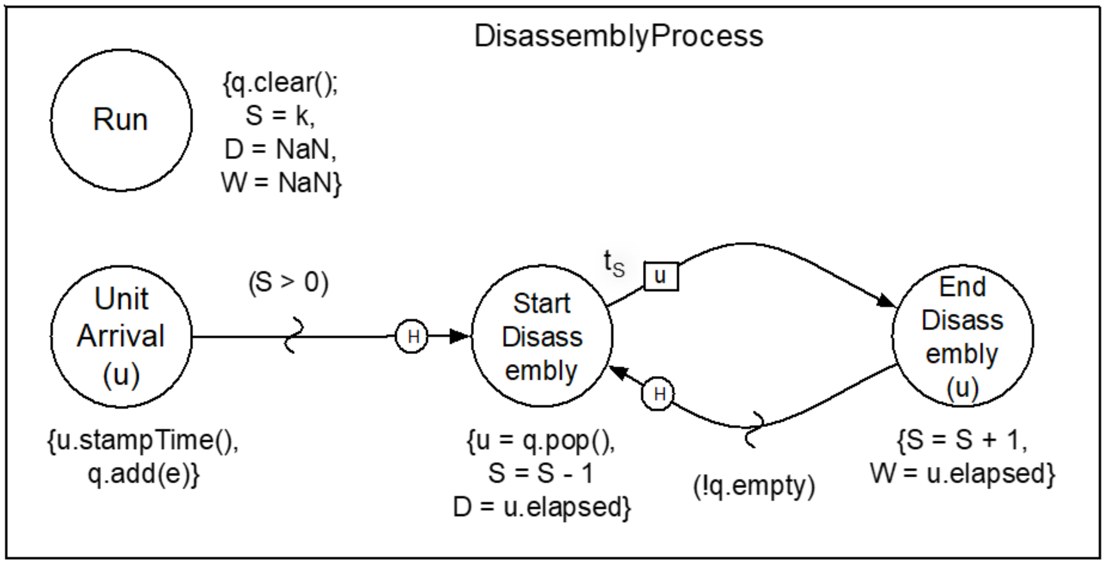


Figure 15. Disassembly Process.

3. Component Dispatcher

Next in the model is the component dispatcher as represented below in Figure 16. The purpose of this component is to distribute the helicopter entity to the appropriate shops. This action simulates the real-world action of assigning a helicopter for work to a shop. The assignment is represented by the arrows with a "u.a," "u.b," "u.c" meaning that each helicopter unit will have a flightline, airframes, and avionics component.

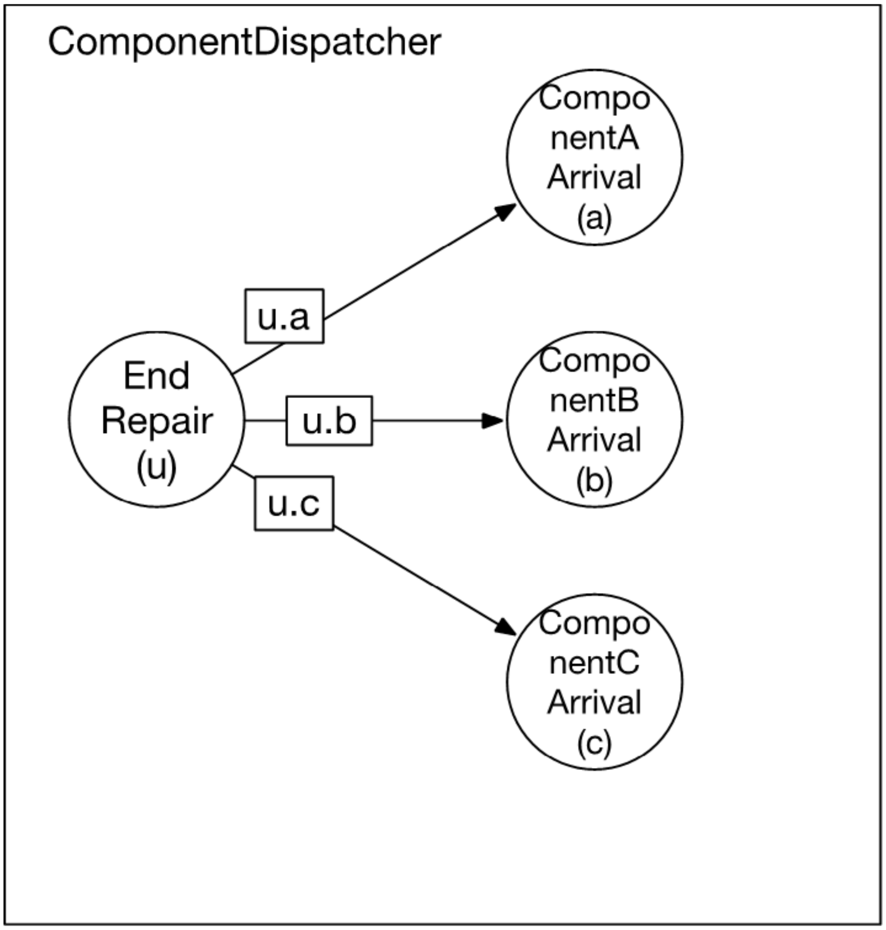


Figure 16. Component Dispatcher.

4. Repair Process Component

The most important part of the model comes from the Repair Process shown in Figure 18. It is here that the model attempted, as best as the author could, to replicate a maintenance event via an event graph and software. This component contains five parameters and three state variables. The initial intent was to make separate classes for each of the shops due to the situation that each shop will have separate and distinct events from another shop. Instead, one class has been created with a generic set of events that all the shops can reasonably be expected to perform based on the author's own experience. According to the NAMP, in the 28-day inspection there are several parts of the aircraft that have to be inspected for corrosion which involves removing specific panels. The first version, shown in Figure 17, shows what was used to test basic functionality and a second version that has the extra state variables and events. It is the second version of the repair process that was implemented in the final model.

There are some notable differences between the two versions that are worth mentioning. The second version has 13 events compared to the three in the first version as well as two additional queues for CDI and CDQAR inspections. The additional events were inserted between start repair and end repair in an order that matches the author's memory. More specific events could be added in future studies.

Another significant change was the addition of two more queues: one for CDI qualified Marines to conduct an inspection and another for CDQAR Marines. Before a helicopter component can be scheduled for its "end repair," these Marines need time to finish their inspection. Since there are a limited number of each of these qualifications available and numerous other components going thought the model, there will inevitably be a backup created when someone is not available. Without these additional queues and the conditions associated with them, the inspections would be scheduled immediately and not accurately represent the maintenance event.

The other change to the updated component was the addition of another random variate generator. This is a condition located between the "End CDI Inspection," "Needs CDQAR inspection," and "End repair" events. The reason for this is to signify, just as in practice, not every subtask will require a CDQAR inspection. The condition for these events compares a randomly uniform generated number between 0.0 and 1.0 against a chosen probability that a CDQAR inspection will be required. This value, 0.8, is being used as a placeholder until more detailed information can be gained about how often a certain event will need a higher-level inspection.

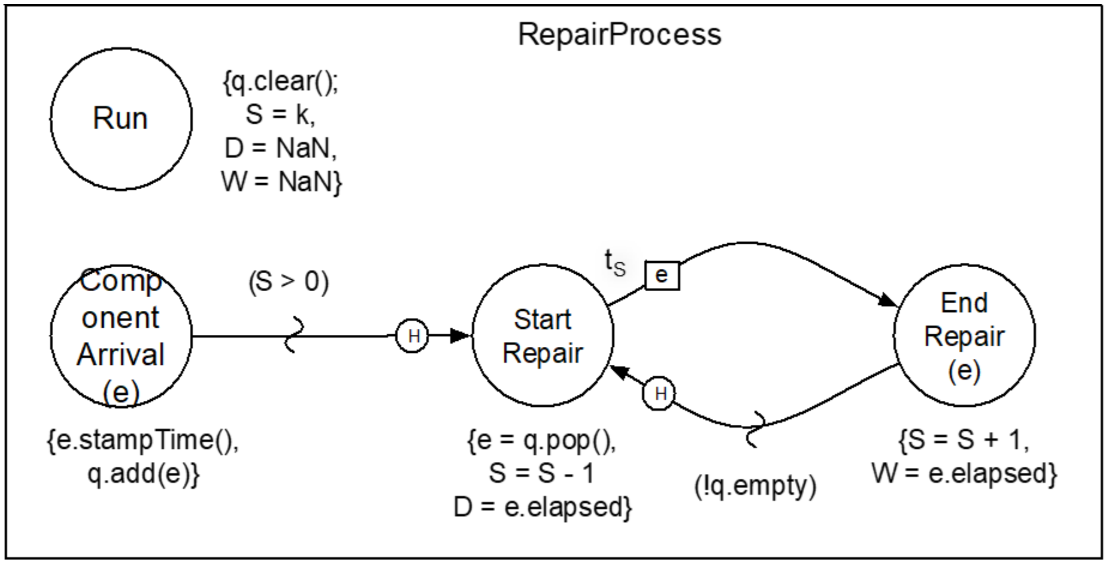


Figure 17. Original Version of Repair Process.

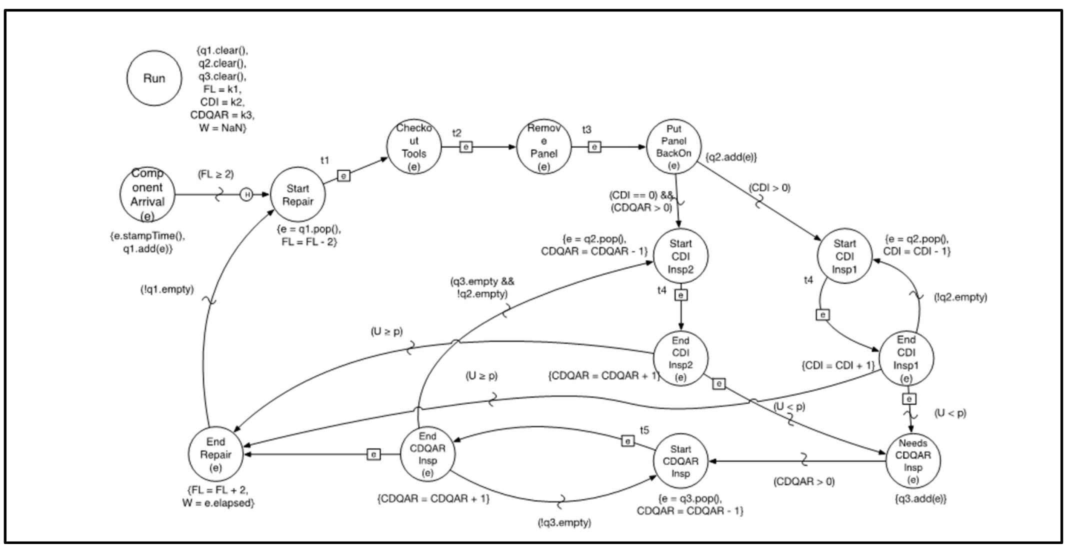


Figure 18. Updated Version of Repair Process.

5. Assembly Process Component

The final component in the model is the Assembly process shown in Figure 19. As the name implies, this component "assembles" the three individual helicopter components to form a complete unit. This process represented maintenance control receiving the signed MAFs for a helicopter and taking that aircraft off the maintenance board shown in Figure 5. The total number of Marines here will be the same.

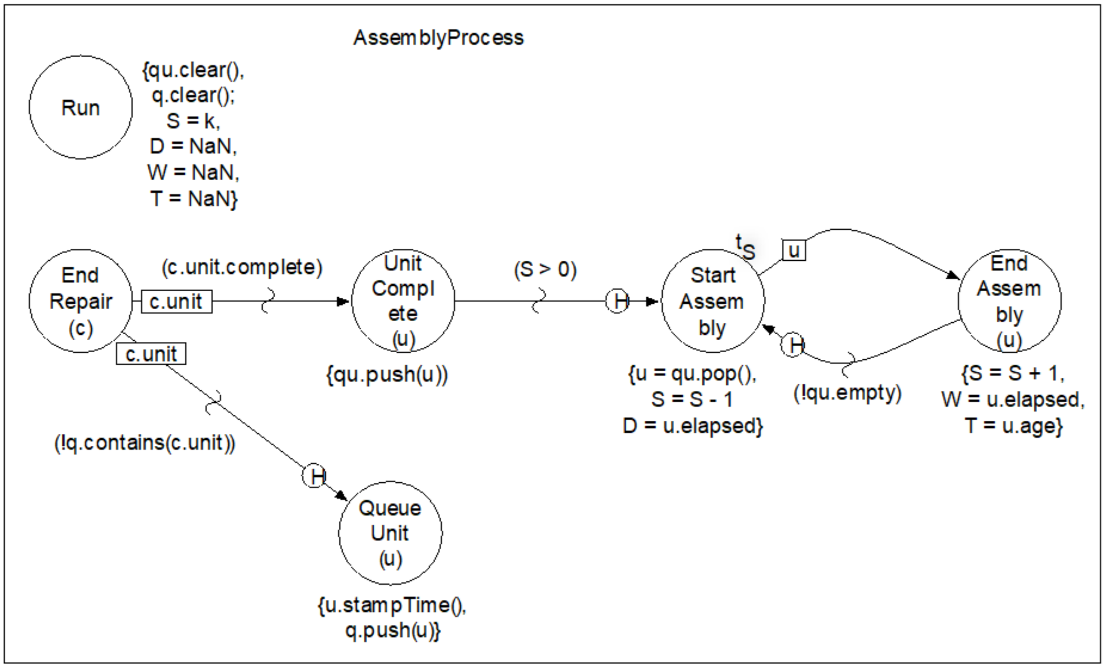


Figure 19. Assembly Process.

6. Listener Component

The purpose of the listener components in Figure 20 is to allow the code of the model to function correctly. The way it works is that the arrow points to the component that listens for events from the source component. For example, the Repair Process A component (Flightline) "listens" for the component arrival from the Component Dispatcher. The output from the Component Dispatcher in the code are the flight arrival, airframes arrival, and avionics arrival. Through the use of an adapter, each of the arrivals are viewed as component arrivals that are heard by each of the Repair Process. As a reminder, Repair Process A is for Flightline, Repair Process B is for Airframes, and Repair Process C is for Avionics.

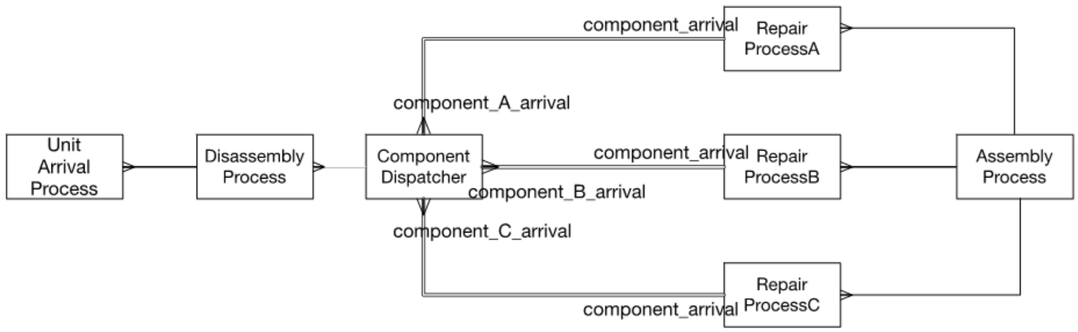


Figure 20. Listener Diagram.

VI. TEST RESULTS

The reader will recognize going through this section that the results do not support the hypothesis or original intent of the research study. The hypothesis was that by creating a model based on the maintenance processes of an active HMLA squadron, in this case HMLA-167, it would illuminate gaps in the information flow during maintenance processes and sub-optimal communication between elements engaged in the maintenance process. One of the research questions this author hoped to answer was how communication in the HMLA maintenance department could be improved. Due to the generalized answers that were received on the survey, this question was not able to be answered. What the model did reveal was where to add more personnel to reduce maintenance times.

A. ANALYSIS OF SURVEY QUESTIONS

The questions that were developed helped to establish a range of values that could be inserted into what is called a triangle distribution. Just as a triangle has three points, there are three values that are needed to make this function work in computer programming: Minimum value, maximum value, and the mode. The probability density function (PDF) of a triangle distribution is shown in Figure 21. For each task in the simulation, the values in Figure 21 were extracted from the surveys and used in executing the model.

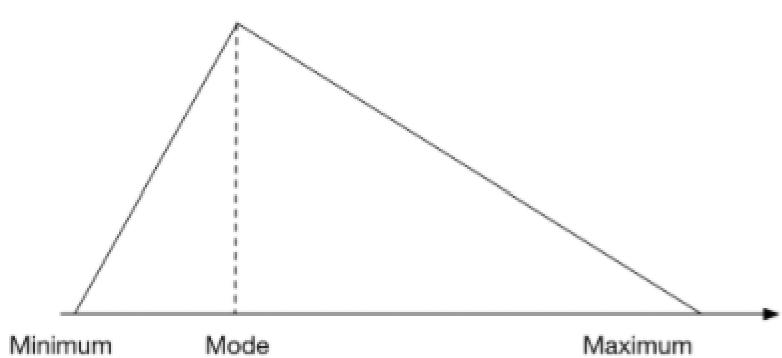


Figure 21. Triangle Distribution PDF.

In order to establish a baseline to run the simulation, metrics were obtained from the surveys for the total amount of CDI and CDQAR qualified Marines who are in the Flightline, Airframes, and Avionics shops. These totals are displayed in Table 2. The other metric was the amount of time each shop spent on the task with a minimum, maximum, and average. These times are displayed in Table 3. The metrics were input on lines 44–52 of the "TestRepairProcess" code. To set a baseline for the model before experimentation, it was necessary to use historical data from past inspections. This data came in the form of number of man-hours per shop per aircraft.

Table 2. Survey Responses for Number of Qualifications.

Maintenance Shop	Number of Qualifications
Flightline	8 CDI 5 CDQAR
Airframes	9 CDI 4 CDQAR
Avionics	5 CDI 5 CDQAR

Table 3. Work Times for Each Shop

Maintenance Shop	Work Times
Flightline	Minimum: 6 hours Maximum: 8 hours Average: 7 hours
Airframes	Minimum: 3 hours Maximum: 8 hours Average: 5 hours
Avionics	Minimum: 2 hours Maximum: 3 hours Average: 2.5 hours

B. SIMULATION OUTPUT

The baseline is shown in blue in Figures 22 through 27. It represents the values mentioned in the previous paragraph before any values were changed. The title of each box and whisker chart represents the specific statistic that the simulation was displaying in its output.

The first graph (Figure 22) represents the metric of the total time a single helicopter unit spent in the maintenance process (28-Day Inspection). This includes the time spent in the disassembly, shop repair, and assembly components measured in hours. There are four different box and whisker charts that were developed. The baseline chart, represented in blue, shows the baseline output based on survey responses input into the model. Those numbers are shown in Tables 2 and 3. A triangle distribution was used to create a minimum, maximum and mode for maintenance times of each of the shops. According to the responses, Flightline required six to eight hours to complete their task, Airframes required three to eight hours, and Avionics required two to three hours. It was assumed that there were ten additional non-qualified Marines in each shop since this was not a specific question asked in the survey. The baseline median output time was 12.986 hours which closely matched historical data for the maintenance action on a UH-1Y at 13 hours.

Experimentation for the Total Time in System consisted of adjusting only one parameter at a time. The author chose the number of Marines parameter because two of the surveys indicated on question 17 that having more personnel could help speed up the process. The orange box and whisker chart shows what happens when two additional Marines are added only to the Flightline shop while keeping the other shops at the baseline numbers. The orange output indicates that adding two Marines to Flightline will reduce the overall time in the system by 0.953 hours or about 57 minutes. The gray output indicates that adding two Marines only to Airframes will reduce the overall time in the system by 0.025 hours or 1.5 minutes. The yellow output indicates that adding two Marines only to Avionics will actually increase the total time by 0.07 hours or 4.2 minutes. The takeaway from this graph is that adding Marines to Flightline will be the best shop in terms of reducing aircraft maintenance time.

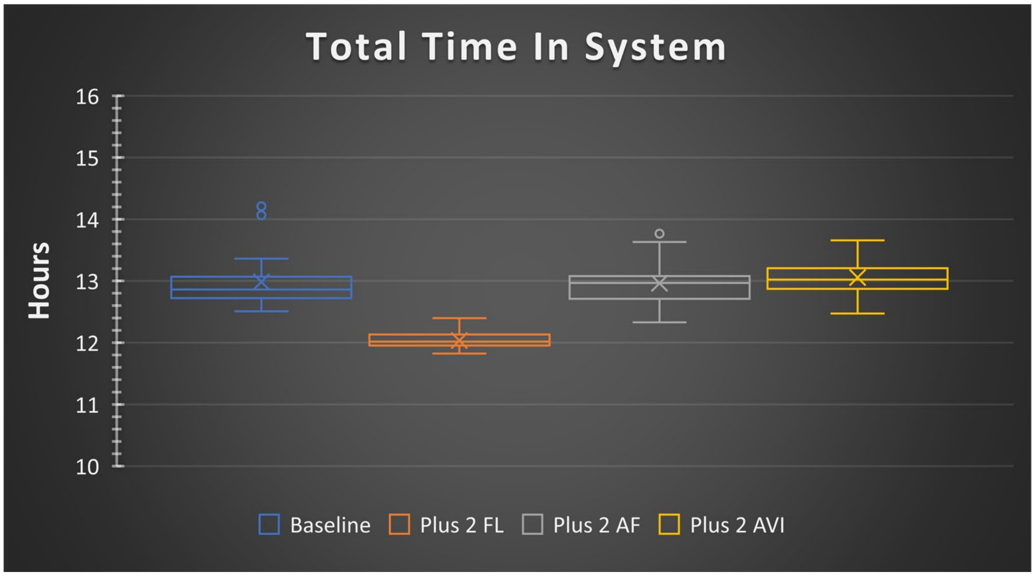


Figure 22. Total Time in System. Numbers Represent How the Total Time Statistic Is Affected When Two Marines Are Added to One Shop at a Time.

For the experimentation, multiple simulations were run to compare the differences when an additional two Marines were added to one shop at a time. Two were added because the author found that adding only one additional Marine per shop did not have any positive or negative change to the output times.

The baseline median time for Total Time in System was 12.986 while the median values for adding Marines to the other shops were as follows:

- Flightline: 12.033 hrs.
- Airframes: 12.961 hrs.
- Avionics: 13.056 hrs.

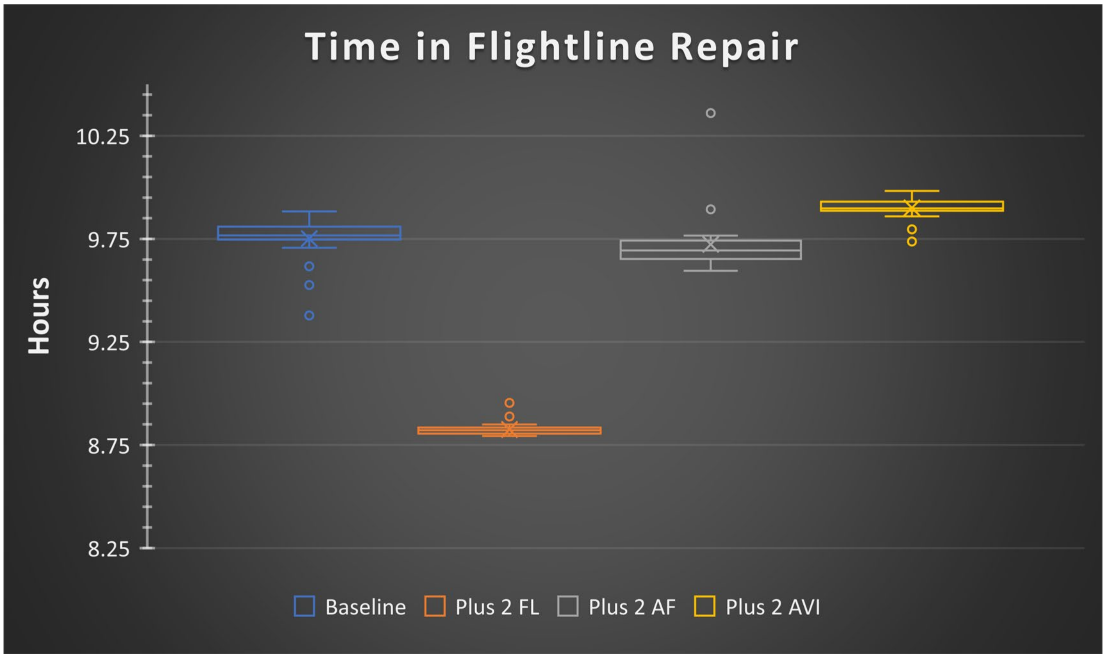


Figure 23. Total Time in the Flightline Repair Shop. Numbers Represent How the Flightline Repair Statistic Is Affected When Marines Are Added to One Shop at a Time.

The baseline median time for Time in Flightline Repair was 9.751 while the median values for adding Marines to the other shops were as follows:

- Flightline: 8.825 hrs.
- Airframes: 9.723 hrs.
- Avionics: 9.900 hrs.

The second graph (Figure 23) represents the time spent in only the Flightline repair component, not the entire system. For reference, the shop repair component is shown on Figure 18. Again, the blue box and whisker chart represents a baseline output and shows that the median time was 9.751 hours which almost matched the historical data range for Flightline (28-day) at 9.9–13 hours. The orange chart shows that adding two additional Marines above baseline, 10 to 12, only to the Flightline shop reduces the time spent in that shop by 0.926 hours or 55.56 minutes. The gray chart shows that adding two additional Marines to Airframes reduces the time spent in the Flightline shop by 0.028 hours or 1.68

minutes. The yellow chart shows that adding two additional Marines to the Avionics shops actually increases the time spent in Flightline by 0.149 hours or 8.94 minutes. The takeaway from this graph, and backed up by Figure 22, is that adding Marines to the Flightline shop should be the first choice to reduce maintenance time based on the model's output.

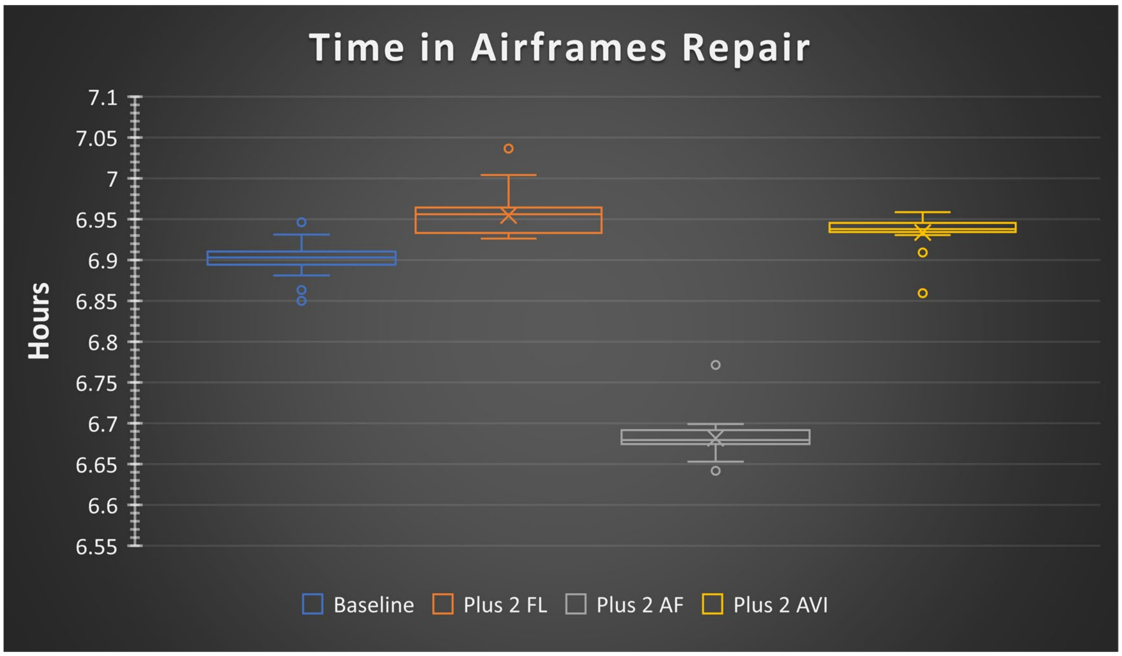


Figure 24. Total Time in the Airframes Shop. Numbers Represent How the Airframes Repair Statistic Is Affected When Marines Are Added To One Shop at a Time.

The median time for Time in Airframes Repair was 6.903 while the median values for adding Marines to the other shops were as follows:

- Flightline: 6.954 hrs.
- Airframes: 6.681 hrs.
- Avionics: 6.933 hrs.

The third graph (Figure 24) represents time spent only in the Airframes repair component. The blue box and whisker chart represents the baseline output with a median time of 6.903 hours which was in the range provided by the surveys of three to eight hours but lower than the range of the squadron historical data at 7.9-12 hours. The orange chart shows that adding two Marines only to the Flightline shop increased the time in Airframes by 0.051 hours or 3.06 minutes. The gray chart shows that adding two Marines to the Airframes shop reduces the time spent in Airframes by 0.222 hours or 13.32 minutes. The yellow chart shows that adding two Marines to the Avionics shop also increased the time spent in Airframes by 0.03 hours or 1.8 minutes. The takeaway from this graph is that adding Marines to the Airframes shop would be the next best option after Flightline if they are already maxed out on personnel.

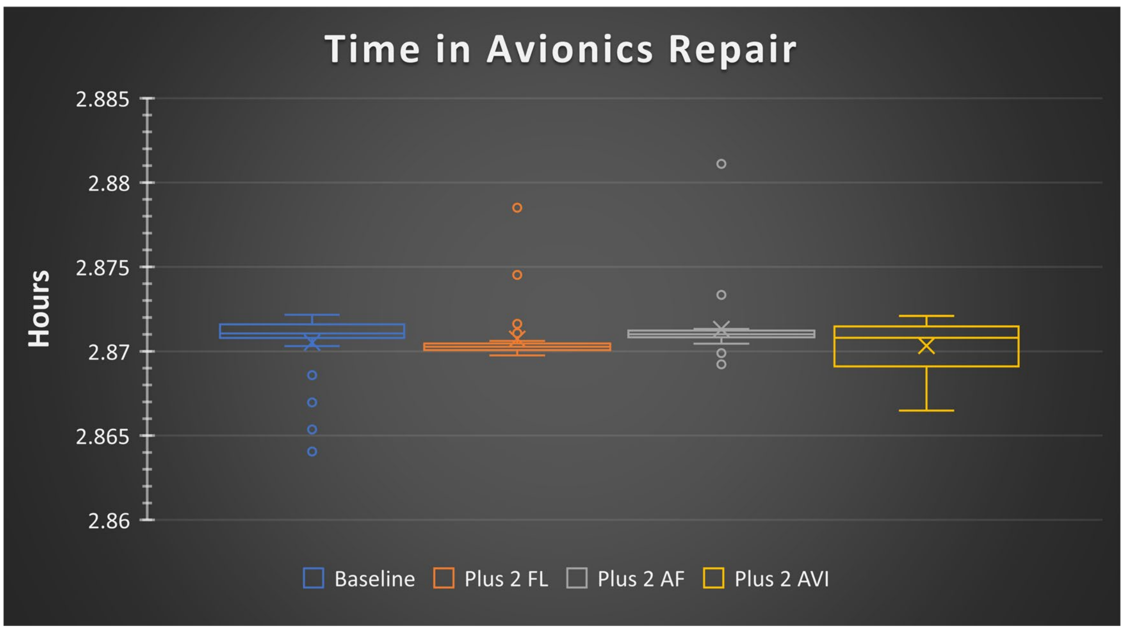


Figure 25. Time in the Avionics Shop. Numbers Represent How the Airframes Repair Statistic Is Affected When Marines Are Added to One Shop at a Time.

The median time for Time in Avionics Repair was 2.871 while the median values for adding Marines to the other shops were as follows:

- Flightline: 2.870 hrs.
- Airframes: 2.8713 hrs.
- Avionics: 2.8703 hrs.

The fourth graph (Figure 25) represents the time spent only in the Avionics repair component. The blue box and whisker chart represents the baseline output with a median time of 2.871 hours which was below the range of squadron historical data at 4.7 – 6.4 hours. The orange chart shows that adding two Marines to the Flightline shop decreased the time spent in Avionics by 0.001 hours or 0.06 minutes and the gray chart shows that adding two Marines in the Airframes shop kept the times within the baseline range. The yellow chart shows that, at best, adding two Marines to the Avionics shop reduces the time spent there by 0.005 hours or 0.3 minutes. The takeaway from this graph is that if the Maintenance Officer has new Marines coming to the department, then the Avionics shop is the last place to put them in terms of reducing repair time when compared to Flightline and Airframes.

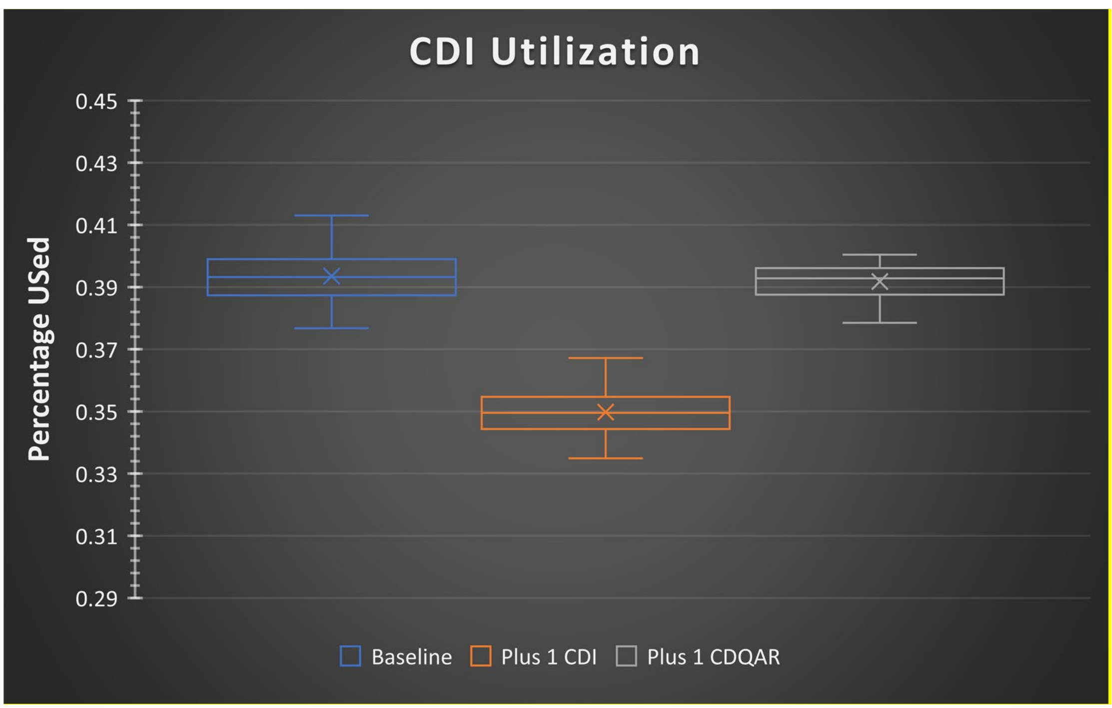


Figure 26. CDI Utilization. Numbers Show How Often a CDI gets Used after One CDI is Added to Each Shop vs. One CDQAR Added to Each Shop.

The median percentage for CDI Utilization was 39.35% while the median values for adding one CDI Marine to the other shops were as follows:

- CDI: 34.98%
- CDQAR: 39.17%

The fifth graph (Figure 26) represents how often a CDI qualified Marine is being used in the Repair component. The blue box and whisker chart represents the baseline output with a utilization of 39.35% assuming CDIs are used according to the behavior shown in Figure 17. The orange chart shows that by adding one extra CDI Marine to each of the three shops, the CDI utilization drops 4.37% to 34.98%. The gray chart shows that adding one CDQAR Marine to each shop decreases the CDI utilization by 0.18% to 39.17%. The takeaway from this graph is that adding one CDI Marine can save the maintenance department 2.622 minutes per hour giving the shops more Marines to spare since they are being used less often. This will mean that CDIs are available for other tasks on another helicopter.

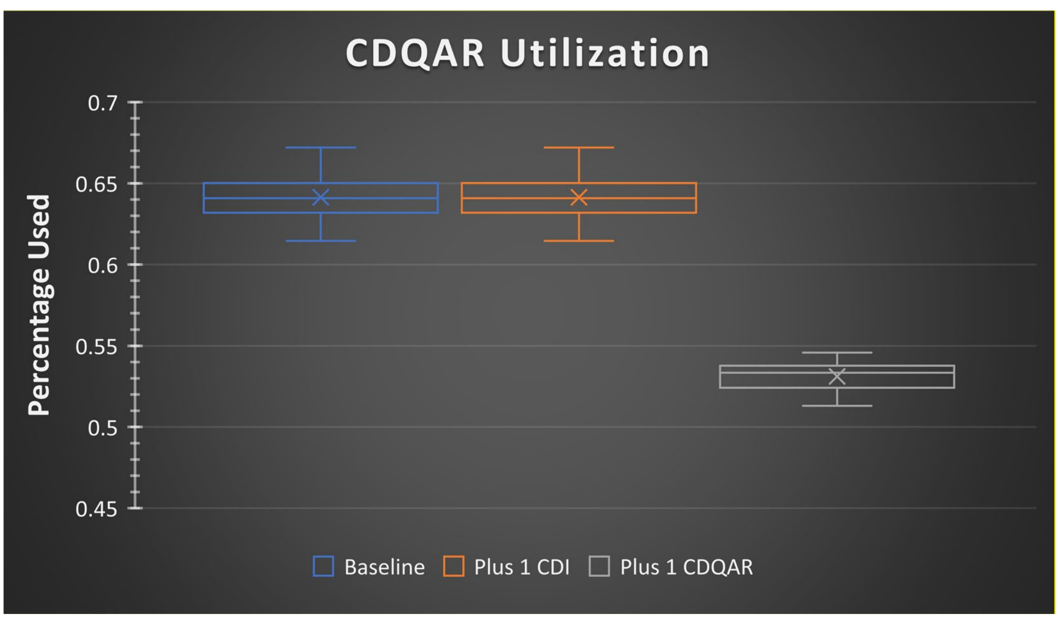


Figure 27. CDQAR Utilization. Numbers Show How Often a CDQAR Gets Used after One CDI Is Added to Each Shop vs. One CDQAR Added to Each Shop.

The median percentage for CDQAR Utilization was 64.13% while the median values for adding one CDQAR Marine to the other shops were as follows:

- CDI: 64.13%
- CDQAR: 53.11%

The sixth graph (Figure 27) represents how often a CDQAR Marine is being used in the Repair component assuming an 80% probability that they will be needed to inspect and sign off on work done by a CDI. The blue box and whisker chart represents the baseline output with a utilization of 64.13%. The orange chart shows that adding one CDI to each shop has no effect, but adding one CDQAR Marine to each shop decreases the CDQAR utilization by 11.02% to 53.11%. The takeaway from this graph is that adding one CDQAR Marine can save the maintenance department 6.61 minutes per hour.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Although the original intent of the thesis was to focus on improving communication between maintenance shops, the outcome turned into more of a manpower study. The main takeaways from the simulation output are as follows. Adding two Marines to the Flightline shop resulted in the greatest reduction in the Total Time in System vice adding two Marines in Airframes or Avionics. If a maintenance officer is ever wondering where to put incoming Marines, then they should be added to these locations in the order mentioned to provide the most benefit.

Surveys generally work better when they are administered in person versus having them mailed back and forth. The surveys received did raise a separate issue with tool availability. Half of the surveys mentioned that the screwdrivers, specifically the #2 Phillips, usually wear out faster and are not replaced soon enough. Supplying the squadrons with more of these tools should also help reduce maintenance times as Marines will not have to wait around for a functional tool to become available.

Finally, the model can be used for future calculations to see where personnel should be placed. As people come and go from a squadron, the parameters that the model uses to run will change. It will help to keep these numbers up to date so that leaders can more accurately see how adding or removing Marines from certain shops will affect maintenance times.

B. STRENGTHS AND WEAKNESSES OF THE MODEL

One of the biggest weaknesses of this model is that it used a large amount of abstraction due to the lack of detailed responses in the surveys. Instead of having multiple events in the Repair component that would have represented various communications that took place, three simple events were used (“Checkout tools,” “Remove panel,” “Put panel back on”) to represent actions that would have to take place. A simple example of what this author was originally envisioning is shown in the event graph in Figure 28. Another weakness is that the model handles only one type of maintenance task at a time. What this means is that the model does not track other helicopters going through other forms of maintenance such as 7-Day or 200-Hour inspections. Sometimes Marines need to go back and forth between other helicopters if someone needs assistance and it was this type of observation that this author was not able to obtain due to not being physically present at the squadron.

A timing problem was encountered when the model was initially run after receiving the survey results. All the completion times, including total time and individual repair times, were in the hundreds of hours range, and this did not match what the Marines had written down. The reason this was occurring was that the "schedule" object had a "delay" attribute where this author put the times given by each shop. The problem was that the delay time was being added on to itself for every event in the repair process. To fix this, the delay times for every event within repair process was set to 0.0 except for the first event of "checkout tools" using the object-method combination of repair_time_generator.generate ().

Another problem that was encountered as the simulation was being run was that certain statistics, such as time at repair for the Avionics shop and CDQAR utilization, were not being displayed in the output. The solution was to simply create a new variable to collect the specific statistic (ex., Outer_time_in_assembly_stat) with the Simple Stats Tally object along with a print statement.

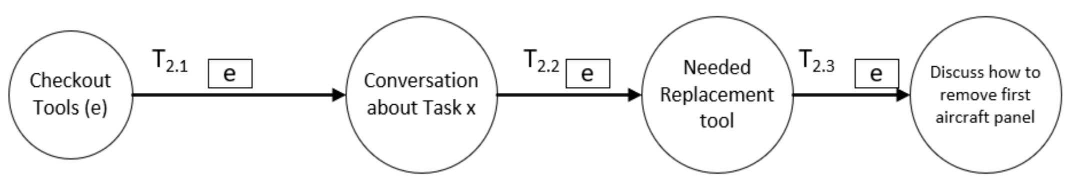


Figure 28. Author's Estimate of What was Originally Expected To Be in the Event Graph Repair Component based on the Hypothesis of Modelling Communication.

Figure 28 shows a few extra events that might have occurred based on the author's experience. After checking out the required tools, there would have been a short conversation about what needed to be done, represented by "conversation about task x." This conversation could have included verifying the correct aircraft to perform the maintenance on or asking where extra Marines are located to assist with the task. After the conversation, what happens often is that maintainers will arrive at the aircraft, begin trying to loosen screws to remove panels, and realize that the tool they are using is stripped in some way. This realization then causes a delay to go and find a replacement. Once a new tool has been acquired, the original conversation within a shop can resume and the maintenance can begin. It was hoped that a discussion about a certain topic between shops or within one some might reveal a possible bottleneck where long delays occurred and could be fixed. Unfortunately, this was not the case, but the model was able to answer questions relating to manpower placement.

One of the strengths of this model is that it does help answer the question of where to place personnel for the greatest reduction in maintenance times. It is like a more complicated calculator that can output whatever statistics the user desires. Another strength is that the model very customizable. If a future researcher wanted to build off this model and add more events, they could simply write them in and make sure another event schedules it. The entire code could be maintained without having to start over again. Other statistics could be added in for whatever the researcher might want to track. One of the final strengths of this model is that it was built off the event graphs described in Chapter V. Those event graphs provide a way to visualize the code to help troubleshoot bugs that may show up if additions are made.

C. LESSONS LEARNED

This next section will go into detail about things the author would have liked to have known prior to the start of this project. Although hindsight is 20/20, it is hoped that future researchers will heed this advice to improve upon the model.

One of the biggest revelations this author learned was that some of the survey responses were not what was expected. Questions that asked for a quantitative answer (#4, 9–12, 14) resulted in data that was able to be used for the triangle distribution of work times or adjustable parameters. However, questions asking for qualitative answers (#7, 17, 18) yielded short answers that did not help to solve the communication problem in the hypothesis. Being physically present would have allowed this author to track the times of all the major maintenance events and listen to the conversations that each of the Marines were having. It also would have allowed me to gain more complete and accurate answers to questions 7 and 8. Question 8 asked if there were any abnormal events and all the responses except for two said no. The two responses that were different just stated that there was time lost trying to find appropriate personnel to do a task. Being present would have allowed me to capture events like going for a smoke or bathroom break, searching for a correct tool, clarifying information, and any side conversations. In short, this author had a different idea of what counted as "abnormal" events that could have been solved with better instructions or being on-site. Due to the COVID pandemic, this author was unable to travel to the squadron to ask the survey questions in-person. Instead, the author coordinated with one of the maintenance officers to issue the surveys to the specific Marines who conducted the agreed upon maintenance action (28-day) and then emailed back to the author for review.

Questions 5 and 6 asking about Wi-Fi could have been eliminated as they served no purpose in the model. Question 9 asking about open MAFs also did not have any usefulness. Questions that should have been included would have asked about the exact number of workers in each shop instead of just the Marines with qualifications. This answer would have eliminated the need to assume how many Marines each shop started out with. Another useful question would have been one that directly asked about communication problems between the shops since that was the original problem that this thesis was trying to solve. Instead, it was hoped that questions 7 and 17 would have shed some light on the communication problem.

If more responses could be obtained, it is also recommended that a cognitive analysis be done for future research. Upon receiving surveys or conducting in-person interviews, the next researcher should carefully look at the responses that talk about communication issues and assign different values to them. Those values could then be used to rank various issues on their importance based on how often they came up.

Finally, the manner in which the surveys were printed might have contributed to why the answers were so short. The questions did not have much white space between them and, as a result, many of the responses were written in small font that barely fit in the available space. In the future, questions should have enough room for a small paragraph to be written or specify that the answers are to be written on a separate page.

D. RECOMMENDATIONS FOR FUTURE WORK

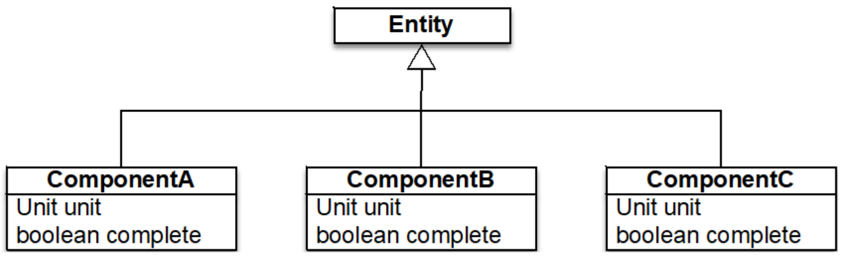
The first recommendation is that more data is needed to improve the accuracy of the model. The model developed here could serve as a foundation for a more advanced simulation. Such a simulation would require a team of people to go to a unit and, for a period, conduct observational research i.e., observe every moving part and consider the other maintenance evolutions that are going on simultaneously. This could lead to a much more detailed model that would have more parameters and functions to adjust but would more accurately represent an average maintenance day.

As was stated in the lessons learned, the next researcher(s) that want to advance this research should go to the squadrons in-person to conduct interviews and observe various maintenance operations. These researchers should focus on specific details of communication such as how often certain information is being asked for or what factors the Marines' think is leading to a breakdown in communication. Such information could adjust the model to study the original hypothesis.

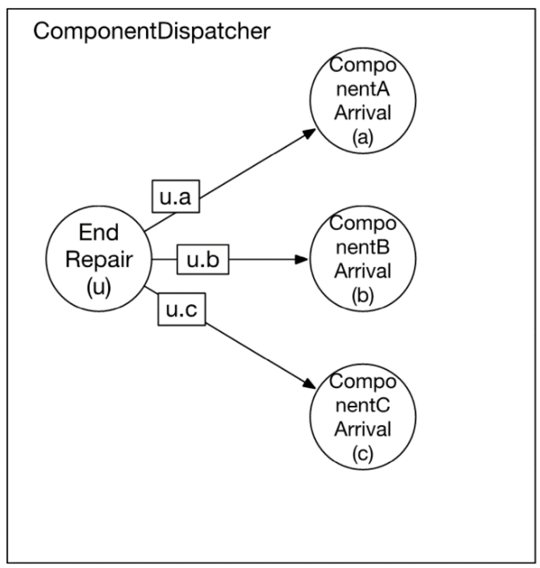
The HMLA needs to continue sending new personnel to the shops where the most time is being spent on maintenance tasks. The top two from this thesis and survey responses are the Flightline and Airframes shops. Another suggestion is that they keep extra #2 Phillips screwdrivers on hand. This would help prevent time from being wasted having to search for a functional tool to do their job.

Finally, the USMC might want to consider a program where Marines can earn their CDI qualification before arriving at a squadron. Just as the USMC has a training squadron for pilots before they are assigned to a fleet squadron, there could be a separate unit specifically for attaining CDI before being assigned to a squadron. This is an ideal solution as it would save time from having to be spent training and ensure every Marine in the maintenance department is available for aircraft on the flight schedule. However, it is also not practical due to fiscal constraints. The better option was one recommended by Germershausen & Steele in their 2015 thesis where they found that more frequent OJT would be the best way to earn qualifications in a shorter period of time.

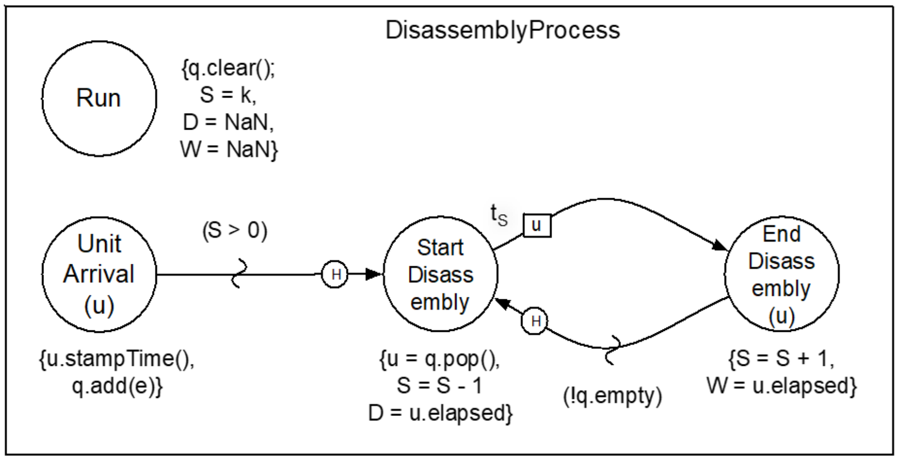
APPENDIX A. COMPLETE EVENT GRAPHS FOR MODEL



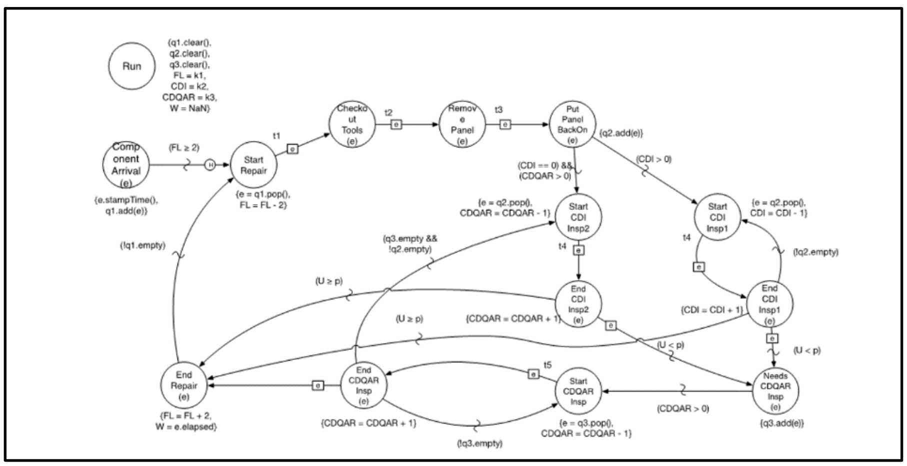
Entity Components



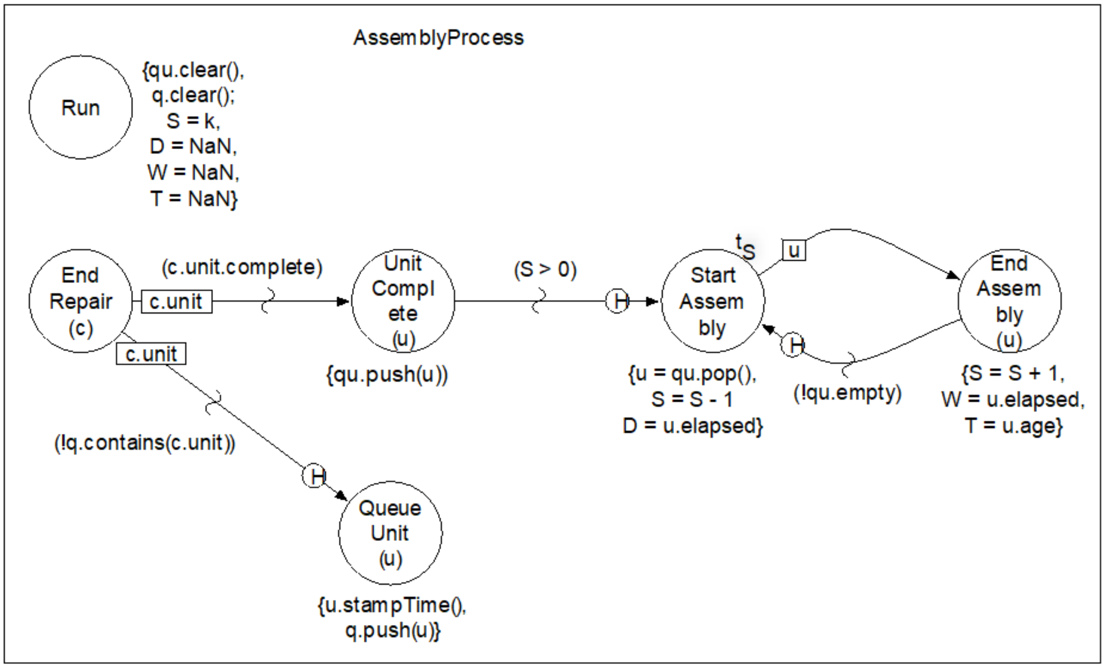
Component Dispatcher



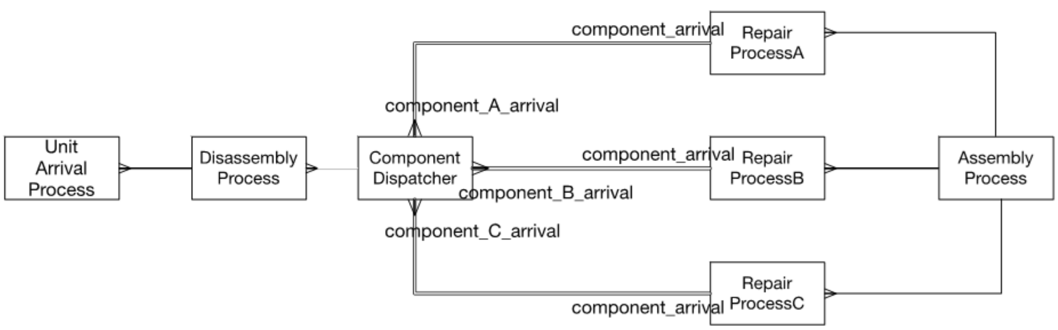
Disassembly Process



Repair Process



Assembly Process



Listener Diagram

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APPENDIX B. SURVEY QUESTIONS

1. What is your name? The purpose of this question is to keep track of who the author has spoken with. Names will not be distributed to any other party.
2. What maintenance action was performed?
3. What maintenance shop did this action take place in?
4. How long did the portion of the maintenance action last?
5. Is there WIFI installed in the squadron hangar where the work was performed?
6. Was WIFI used to download anything for maintenance purposes?
7. Describe in as much detail as possible, the flow of information and maintenance events from the point of view of this position, and what maintenance actions were performed (start times, finish times to include when a QAR or CDQAR signed off on a task?
8. Were there any abnormal events that interrupted maintenance subtasks? If so, how long did the interruption last?
9. What Maintenance Action Forms (MAFs) were open?
10. What is the fastest that the task can be done? *
11. What is the longest this task has ever taken? *
12. What is the average duration that the task takes to complete? *
13. Was there an error in workmanship that caused delay? If so, how long was the delay?
14. How many CDI's and CDQAR's are in each shop?

15. Were CDI's, CDQAR's, or QARs available when steps requiring their qualification were performed? Did this cause a delay? If so, approximately how long was the delay?

16. Are there computer work stations available to access the MAF without delay? How many workstations are there? If there was a delay, approximately how long was it?

17. Is following the book procedure step-by-step as it is written, the most efficient way to perform this task or is there a more efficient flow that could be achieved by revision to the procedure?

18. Was there a delay period for a part or tool to become available? If yes, how long did that take? Example: Does the shop have homemade specialized tools for some jobs due to the non-availability of a proper tool that could be ordered/properly produced and distributed?

19. Was HAZMAT involved in any way? If so, how long did HAZMATs portion last?

*These questions refer to the maintenance task being described in question 7.

APPENDIX C. SAMPLE CODE FROM MODEL: REPAIR PROCESS

```
def start_repair(self):
    component = heappop(self.queue)
    self.notify_state_change("queue", self.queue.copy())

    self.notify_state_change("repair_queue_delay", component.elapsed_time())

    self.number_available_fl_Marines -= 2
    self.number_available_fl_CDI -= 1
    self.number_available_fl_CDQAR -= 1

    self.notify_state_change("number_available_fl_Marines", self.number_available_fl_Marines)

    '''Statement below will be moved to the new function before end_repair'''
    # self.schedule("end_repair", self.repair_time_generator.generate(), component)

    self.schedule("checkout_tools", self.repair_time_generator.generate(), component)
#                               self.repair_time_generator.generate()

def checkout_tools(self, component):
    # self.notify_state_change("repair_queue_delay", component.elapsed_time())

    self.schedule("remove_panel_from_helicopter", 0.0, component)
#                                               self.repair_time_generator.generate()
```

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