



**AUTONOMOUS ROVERS: FLIGHT LINE DELIVERY OF
MAINTENANCE TOOLS AND PARTS**

Graduate Research Paper

Mary Ashley Stanton, Major, USAF

AFIT-ENS-MS-20-J-052

**DEPARTMENT OF THE AIR FORCE
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Degree of Master of Science in Operations Management

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Major, USAF

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Abstract

The AF faces severe maintainer shortages and a fleet-wide mission capable rate of 70%. As the USAF's fleet ages, aircraft will need increasing amounts of repair, and the need to remove constraints in the maintenance process is a concern. The expediter was identified as the constraint and autonomous rovers as the solution. The researcher demonstrated through simulations of the maintenance process at JB MDL, the differences in efficiency between the current expediter transport process, to one augmented with autonomous delivery rovers. In 24 hours, the KC-10's expediter saw 29.9% reduction in utilization, gained 7.2 hours, and drove 107.4 miles less, while the C-17's expediter saw 7.9% reduction in transportation, gained 1.9 hours, and drove 21.1 miles less. The simulations demonstrated how rovers, as an emerging technology, can address the flight line constraint, and augment the expediter to significantly reduce time and transportation costs. In the intermediate, tools and parts need to be co-located as close to the aircraft as possible, with bench stock parts kept with the tools to create the most streamlined process. Once rover delivery is successfully demonstrated, the technology can be incorporated fleet-wide, and has valuable impact across the Department of Defense.

To my family. Thank you for your support and encouragement through this project.

Acknowledgments

My first thanks is to my family, who provided me support to complete this project throughout the COVID-19 pandemic. I would also like to thank the people that provided me the opportunity to attend the Advanced Studies of Air Mobility, and the instructors and staff who have generously imparted their knowledge of supply chains and logistics. They have taught how to ask the right questions, and provided me tools to help streamline Air Force's processes. I initially wanted to explore the logistical use of drones on the airfield, but JB MDL currently has a strict 'no drone' policy. After a tour of the Amazon distribution facility in New Jersey, I clipped my prospective drone's rotors and turned instead to research rovers. That research was facilitated by Pamela Bennet Bardot, the Expeditionary Center's librarian, with whom I share my gratitude. I would also like to express my appreciation to my faculty advisor, Lt Col Jason Anderson, for his unwavering positive attitude and enthusiasm for this project. His insight, guidance and support were instrumental in its realization. I would also like to thank Col Gerald McCray who spoke with members of our class and provided his office's resources. Finally, I thank Brig Gen Linda Hurry for speaking to our class, for sharing information about the innovative projects that are being worked throughout the AF, and for sponsoring this research.

Mary Ashley Stanton

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AUTONOMOUS ROVERS: FLIGHT LINE DELIVERY OF MAINTENANCE TOOLS AND PARTS

I. Introduction

Background

United States Air Force (USAF) maintainer staffing is currently undermanned with a loss of 10% per year, with the more experienced personnel leaving at higher rates (Losey S. , 2019). A 2017 Governmental Accountability Office report shows that 12% of 5-levels, or journeymen, and 10% of 7-levels, or craftsmen, separate from the AF, with only 73.4% of all maintainers re-enlisting to continue serving as maintainers (Losey S. , 2019). The maintainer manning issue comes at a time when the USAF continues to extend the service life of an aging aircraft fleet which will require an ever increasing amount of manpower to perform inspections and maintenance (Losey S. , 2019). Comparing mission capable rates between 2017 and 2019, the USAF overall fleet wide readiness has decreased from 71.3% in 2017 to 69.97% in 2018 (Losey S. , 2019) and climbed slightly to 70.27% in 2019 (Everstine, 2020). Of note, Mobility aircraft mission capable rates in 2019 were between 63.16% (C-5M) and 82.23% (C-17A), with the average of 71.84%, as seen below in Table 1 (Everstine, 2020).

Table 1. Mobility Aircraft Mission Capable Rates 2017 – 2019
(Losey S. , 2019) & (Everstine, 2020)

AIRCRAFT	2017 MC RATE	2018 MC RATE	2019 MC RATE	2018 – 2019 DIFFERENCE
C-5M	60.25%	62.77%	63.16%	0.39%
C-17A	83.69%	82.57%	82.23%	-0.34%
C-130H	73.14%	68.30%	65.51%	-2.79%
C-130J	76.96%	76.68%	77.02%	0.34%
KC-10A	78.18%	79.68%	79.37%	-0.31%
KC-135R	73.19%	73.02%	72.50%	-0.52%
KC-46	-	-	63.11%	-

Autonomous vehicles are a solution to aid undermanned maintainers and to increase aircraft availability and mission capable rates (Saunders, 2015). Industry partners across the U.S. have incorporated the use of autonomous systems to streamline processes like transporting packages, meals, and groceries, and tackle the time-intensive ‘last mile’ of delivery (Glaser, 2017). One example is Amazon’s rover delivery platform called Amazon Scout, seen in Figure 1. As of November 2019, the Scout has been tested in cities in WA and CA to successfully deliver thousands of packages (McFarland, 2019). The Amazon Scout is learning to navigate sidewalk obstacles like parked cars, kids’ bicycles, recycling bins, and is just beginning to show the unlimited potential for its logistics capability (McFarland, 2019). A second company, Yelp in San Francisco, has an Eat24 ordering platform which uses Marble’s autonomous temperature-controlled rovers to deliver hot foods hot, and cold foods cold to customers throughout the city (Glaser, 2017). Marble’s rovers have a large footprint, standing waist tall (Glaser, 2017), as seen



Figure 1.
Amazon Scout
home delivery of
purchased goods
(Messier, 2019)



Figure 2.
Yelp's Eat24 with Marble's
temperature controlled food
delivery rover (Green, 2018)



Figure 3.
Starship Rover delivering
packaged goods
(Bayer, 2019)

in Figure 2, and navigate with LIDAR sensors (Heater, 2018). A third company, Starship Technologies, is also tackling the food delivery market with its six-wheeled rover, which travels 4 mph with a radius of three to four miles (Hawkins, 2019). Their rovers, as seen in Figure 3, navigate sidewalks and walking paths that fill college campuses such as George Mason University, Northern Arizona University, University of Pittsburgh, and Purdue University (Hawkins, 2019). The rovers successfully scale curbs to deliver food, groceries, and packages weighing up to 20 pounds, with one shortcoming of being unable to climb multiple stairs (Hawkins, 2019). The CEO foresees homes with a door specifically for the rover in the near future, similar to pet doors (Hawkins, 2019). From the above industry examples, there are multiple opportunities where rover delivery could benefit AF maintainers on Mobility ramps. The following research will explore the benefits of autonomous delivery of aircraft tools and parts from consolidated tool counters (CTKs) or supply depots to maintainers working on mobility aircraft parked on the ramp.

Problem Statement/Research Focus

Given the shortage of transportation vehicles compared to repair requirements, under the current system, maintainers are waiting for tools and parts, or for themselves to be transported to or from the aircraft. The maintainer must determine the tools and parts they require, call the expediter for pick up, be driven to the consolidated tool kit (CTK) or supply/Contractor Operated and Maintained Base Supply (COMBS), locate and checkout the necessary parts and tools, call the expediter to pick them up again, and then be driven back to the aircraft. Furthermore, there is the additional personnel time of other maintainers waiting at the aircraft for the tools or parts. As the U.S. Department of Defense (DoD) continues to expand its utilization of rovers and drones in logistical capacities and innovates for the Flight Line of the Future (FLoF), this study examines autonomous rovers fulfilling a portion of a maintainer's logistical supply chain for tools and parts on the airfield servicing C-17s and KC-10s. This study explores the costs of manpower and transportation, and looks for ways to streamline the maintainer's process, to increase aircraft availability.

Several studies have focused on autonomous delivery of items weighing less than 10 pounds and located less than 12 miles away for consumer and enterprise utilization (Brar, Rabbat, Raithatha, Runcie, & Yu, 2015). The authors found the limitations in drone use was the restrictive battery life, which constrained the payload and range, and preventative public sector regulations concerning drone use near people or aircraft (Brar et al., 2015). There have been only two military studies of autonomous delivery; both were by Naval Postgraduates and both studied unmanned aerial vehicles. The first

research paper explored the use of K-MAX, or Lockheed Martin's unmanned helicopter, to resupply troops in an operational environment (Peterson & Staley, 2011). The other thesis conducted a cost-based analysis of unmanned logistical support aerial vehicles to provide logistical support in forward-deployed locations (Denevan, 2014). This research wishes to fill a gap in the research, and explore autonomous rover utilization for logistical support of tools and parts to aircraft maintainers.

Limitations/Assumptions/Methodology

This study excludes the contested environment and is limited to the Air Mobility Command base, JB McGuire-Dix-Lakehurst. One assumption is that rover efficiency will improve as technologies advance to include capabilities such as multi-stop deliveries, en-route re-routing, longer battery life, and heavier payloads. Additional assumptions made in this study include access to a fleet of rovers, each carrying a defined payload, for delivery to a single location after dispatched from CTK or supply depot. Additional limitations include environmental factors, battery life, charge time, and current software for See-and-Avoid detection.

The research was conducted through the lens of the Theory of Constraints with the Theory of Modeling and the use of Simulations. Through the Theory of Constraints, this research realizes that there are not infinite supplies or time available; therefore, drawing on options that optimize the current set of resources provides more efficient and effective operations. To do this, current process maps for maintainers' tools and parts are observed and drawn. Next, the study proposes process maps utilizing the autonomous rovers to replace the constraint of the expediter vehicle in the system. Finally, this study

conducts multiple simulations with autonomous rovers to replace the expediter and maintainer trips to tool counters or supply depots, and determines the most cost effective number of rovers for the greatest benefit for the maintainers.

Research Question

This research paper explores the following research question:

What are the differences in efficiency between the current maintainer supply transport process and an autonomous rover delivering supplies to maintainers working on C-17s and KC-10s at JB MDL with respect to time and cost?

Investigative Questions

- What are the current maintainer process maps of expediters for the C-17s and KC-10s at JB MDL, NJ?
- What is a proposed maintainer process map that replaces expediters with an autonomous rover to deliver parts and tools to the maintainers?
- Based on simulations, what is the most efficient network of autonomous vehicles to ensure the greatest value-added time for the maintainers?

Implications/Summary

The Air Force faces a severe maintainer shortage and decreasing aircraft mission-capable rates. This research explores current technologies that can ease the daily routine and allow more 'touch time' performing maintenance with the fewer personnel, and provide a possible benefit of increasing aircraft availability. The results of this research will be vital for the future of USAF maintenance, as it will show how the use of

technologies, like rovers, can affect daily processes, decrease costs of transportation, and reduce the number of hours waiting to perform work tasks.

II. Literature Review

Overview

The purpose of this chapter is to start with an explanation of the Flight Line of the Future. Next, there is a review of current industry partner innovations in rovers and autonomous delivery methods. Then, there is a review of studies examining military-specific logistics and efforts to automate segments of the supply chain. Finally, this chapter addresses the current limitations of automated guided vehicles (AGVs).

Flight Line of the Future

Innovation is occurring in all sectors of the military and civilian industry. The Air Force Research Laboratory's experimentation office, the Strategic Development Planning and Experimentation Office, or SDPE, has been crucial in reducing the time it takes the AF to move technology into daily use (Cohen R. S., 2020). In the area of autonomous unmanned aerial vehicles, the SDPE has developed the Skyborg, or a combat 'robotic wingman' for manned fighters (Cohen R. , 2019). In the supply chain industry, there are, "radical innovations with augmented reality, virtual reality, advanced robotics, real-time inventory tracking, and 3-D printing" along with drones and automatic guided vehicles (AGVs) playing a prominent role (McLelland, 2017, p. 11). These technological innovations allow supply chains to move away from a traditional linear model with one large central hub to a smaller, more flexible 'immediate' supply chain (Kay, 2016). Larry

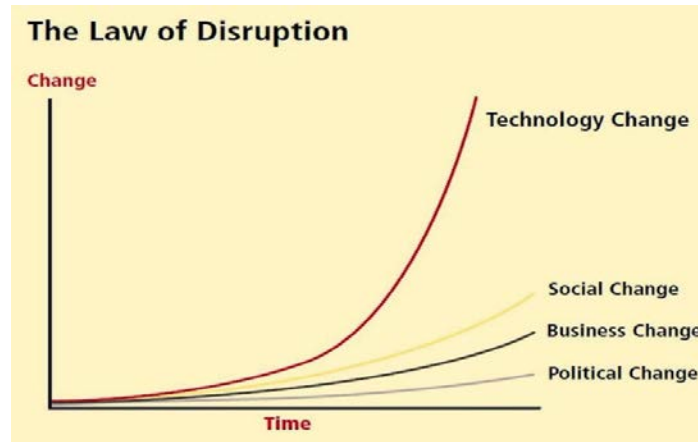


Figure 4. The Law of Disruption or Innovation’s Progress outpacing societal, business, or political climates (McLelland, 2017).

Downes (2009)’s The Law of Disruption, illustrates, in Figure 4, how innovation often outpaces acceptance in the social, business, and political realms (McLelland, 2017). It is time for the USAF to bring innovations, like these, to the flight line to assist the maintainers in their daily tasks. Elbert Hubbard cautions that, “the world is moving so fast these days that the man who says it can’t be done, is generally interrupted by someone doing it” (BrainyQuote, 2020). Let the AF transform the supply chain industry and overhaul how maintainers get their tools and parts on the airfield.

According to the United States 2018 National Defense Strategy, one of the ways to build a lethal force, calls for modernizing essential capabilities, which includes advance autonomous systems (Mattis, 2018). For a competitive edge, the Department of Defense (DoD) “will invest broadly in military application of autonomy, artificial intelligence, and machine learning, including rapid application of commercial breakthroughs” (Mattis, 2018, p. 7). In the military, a department concerned with innovating logistics is Headquarters Air Force A4 (Affairs, 2015). During a 2018 symposium on the ‘State of Logistics,’ the Deputy Chief of Staff for Logistics,

Engineering, and Force Protection, Lt. Gen. Warren Berry, addressed future Air Force challenges, and highlighted the military and civilian team aspect of innovation (Downs, Hernandez, Larkins, Smith K., & Smith S, 2018). To encourage cross-talk between industry and the military, the Air Force started a program called Education with Industry (EWI), where Logistics and Maintenance officers work for a year at Delta, Amazon, UPS, and FedEx (Downs, Hernandez, Larkins, Smith, & Smith, 2018). The EWI officers provide the companies their leadership and a variety of experiences, and learn about the industry's operating procedures in exchange (Downs et al., 2018). The EWI officers then bring innovative ideas back to the military, when they return to their positions (Downs, Hernandez, Larkins, Smith, & Smith, 2018).

One of the biggest innovations the AF implemented from the EWI program was from 2017, the fellow with Delta employed Conditioned Based Maintenance Plus (CBM+) in the C-5 and B-1 fleets (Downs, Hernandez, Larkins, Smith, & Smith, 2018). CBM+ alters the repair cycle of aircraft parts by replacing the part just prior to failure per a planned schedule at home station vs. after failure when the aircraft could be away from its home station, requiring added delays as parts and maintainers travel to an off station location to fix the aircraft (Downs, Hernandez, Larkins, Smith, & Smith, 2018). CBM+ has been contributed to Delta's high aircraft availability, and the Air Force aims to achieve similar results (Downs, Hernandez, Larkins, Smith, & Smith, 2018). Additional EWI officers worked with Amazon Prime Air, who is working with autonomous drones to deliver packages weighing 5 pounds or less, to customers within 30 minutes of placing an order (Amazon, 2020). Utilization of such technologies has wide-spread uses in the AF, which have not yet been fully implemented. Amazon's drones fly at an altitude

lower than 400 feet, and are currently in Beta testing since December 2016 in the area around Cambridge, England (Amazon, 2020). Both CBM+ and other innovations, like Amazon’s Prime Air, have led to the AF’s proposed innovative ‘Flight Line of the Future’ (FLoF).

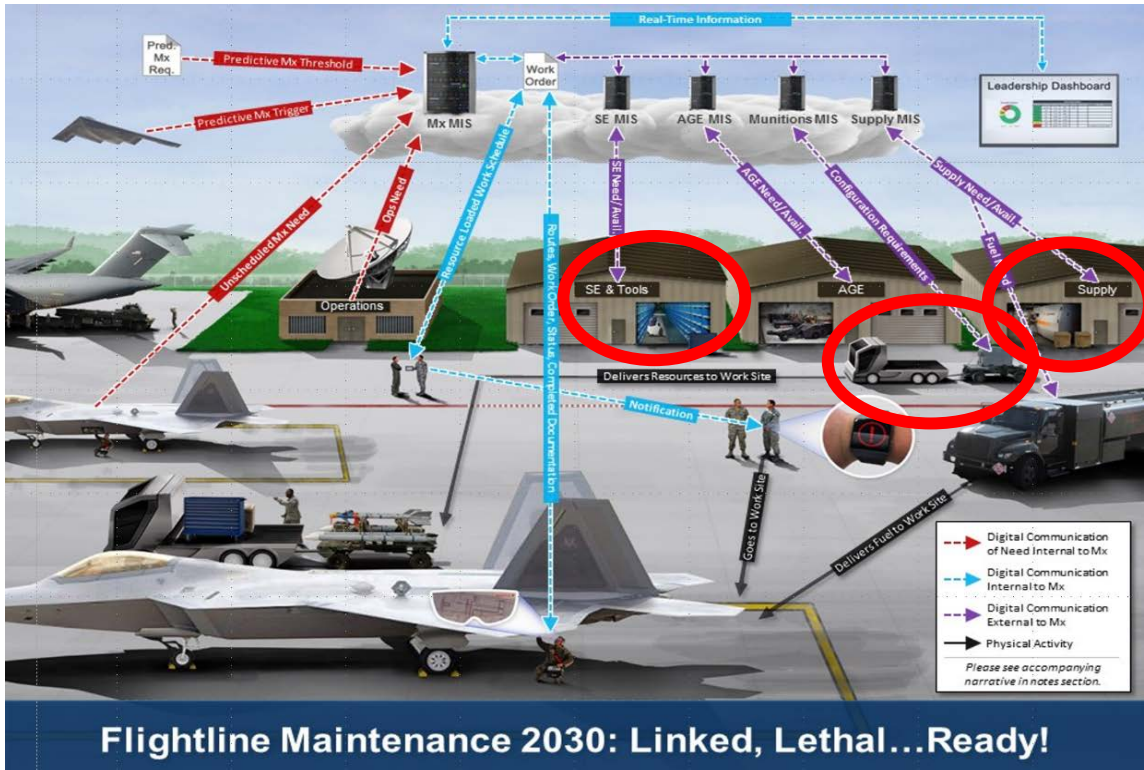


Figure 5. Flight Line of the Future (FLoF) as Illustrated in Lt Col DiGerolamo’s June 2018 Briefing. Note: Red Circles added to highlight areas of this research.

Illustrated here in Figure 5 from a June 2018 presentation, the FLoF is a fully connected airfield utilizing several autonomous systems (DiGerolamo, 2018). The FLoF concept “uses device connectivity and collaborative tools to integrate maintainers, aircraft support organizations and leadership, streamlining maintenance operations at USAF bases” (Smartronix, 2018, p. 1). While there are multiple areas of possible

exploration, this research will focus, solely, on the autonomous rover delivery of tools and parts to maintainers on the airfield.

Current Industry Partner Innovations

As mentioned in the Background, there are multiple autonomous vehicles currently employed to streamline supply chains. Amazon’s rover delivery platform, called Amazon Scout and seen in Figure 1, delivers customers’ packages (McFarland, 2019). Yelp, in San Francisco, has an Eat24 ordering platform that uses Marble’s autonomous rovers, seen in Figure 2, to deliver food and groceries to customers (Glaser, 2017). Starship Technologies is also tackling the food and small goods delivery market on more than four college campuses with its six-wheeled rover, shown in Figure 3 (Hawkins, 2019). On a larger scale, Google has a patent request for a driverless truck full of lockers where customers retrieve their item with a code or a swipe of a credit card, as seen in Figure 6 (Heine, 2016). Kay (2016) calls it a ‘driverless delivery vehicle (DDV),’ a cargo-only autonomous vehicle that waits at a hub filling with orders (Kay, 2016). To

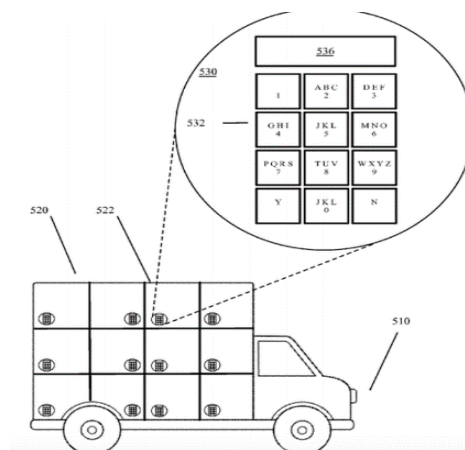


Figure 6. Google’s driverless truck patent request (Heine, 2016).

be most economical, the vehicle would only depart with a time sensitive item is loaded and deliver is triggered (Kay, 2016).

As current Secretary of Defense (SECDEF) and Federal Aviation Administration (FAA) regulations prohibit drone use on and around military installations, to protect both personnel working on the ground and aircrew flying military aircraft, rovers are the most suitable technology for use on a military base (Polhemus, 2020). From the above industry examples, there are multiple opportunities where rover delivery could benefit AF maintainers on the flight line. Driverless delivery vehicles (DDVs) and rovers on the airfield could deliver tools and parts to multiple maintainers on one run, while still ensuring critical tool accountability by requiring each maintainer to swipe their personal CAC to open their locker on a Google Locker Truck, or to unlock the rover itself. In addition, a mobile CTK truck holding the most commonly used tools and parts kits would reduce the time spent in transit. The following research will explore autonomous rovers delivering aircraft parts and tools from consolidated tool counters (CTKs) or parts supply depots to mobility aircraft parked on the ramp.

Advances in Automation in Military Logistics

There are several studies concerning military logistics and utilizing autonomous systems. These include one Army report, which investigated autonomous resupply convoys, and two Navy theses which explored unmanned resupply aircraft for the Marines. Finally, there is a Congressional Research report concerning the military use of robotics and autonomous systems (RAS).

Since 2004, the U.S. Army has been researching using automated vehicles for battlefield logistics to aid soldier sustainment (Henry, 2018). Henry (2018) suggests that in battle, automated vehicles, that do not require rest cycles, can perform ‘line hauls’ 24/7, and provide a more frequent, reliable, and predictable supply chain (Henry, 2018). Additionally, he suggests automated vehicles can be used by the National Guards to respond more quickly, with necessary supplies in emergencies or natural disasters, and provide platform for evacuations that responds faster than traditional manned platforms (Henry, 2018).

To resupply Marines in hostile environments, Troy Peterson and Jason Staley (2011) explored unmanned options to replace convoys (Peterson & Staley, 2011). Their aim was to eliminate fatalities experienced by resupply convoys from improvised explosive devices (IEDs) found along the roads, and instead explored unmanned aerial vehicles (UAVs) that could fly above the threat (Peterson & Staley, 2011). When compared with ground convoys, fixed-wing, and rotary-wing options, they found that the K-MAX UAV was the most cost-effective option that saved the greatest number of Marine lives (Peterson & Staley, 2011). The K-MAX unmanned aerial resupply missions were flown, usually at night, during their 33 month deployment in Afghanistan (Miller, 2019). During that time, the UAVs moved over 1.5 million pounds, and removed 900 convoy vehicles from the threats of “IEDs, direct fire, and other threats” delivering remote bases were provided critical supplies (Miller, 2019, p. 1).

Thomas Denevan (2014) also explored unmanned capabilities with autonomous logistical sustainment of deployed units in contested environments in his Naval Postgraduate Thesis. The author examined the U.S. Department of Defense’s inventory of

unmanned systems. He found most unmanned systems filled the role of Intelligence, Surveillance, and Reconnaissance (ISR), and that there were no ground-based autonomous systems (Denevan, 2014). In his recommendations, the author concludes that UAVs performing logistical roles can be a cost savings, only if there are adequate numbers of UAVs filling more critical ISR or targeting roles (Denevan, 2014). This was his conclusion because he looked at the K-MAX study where a manned aircraft was altered to operate in an unmanned capacity. He concluded that additional studies and pilot programs could prove the future applicability of cargo UAVs (Denevan, 2014). He stops short of exploring the use of an autonomous systems created from the beginning to be unmanned.

In a 2018 report to Congress, recommendations on how to support the development of Robotics and Autonomous Systems (RASs) are considered (Congressional Research Service, 2018). In the report, RASs are the ones to do the 'd'-jobs; or the military's 'dull, dangerous, and dirty' jobs (Congressional Research Service, 2018). The Army is already employing Leader-Follower technology where, in a convoy, one leader, the manned vehicle, is linked to three followers, unmanned vehicles (Congressional Research Service, 2018). Specifically, the Congressional report states that RASs can help with the logistic delivery of supplies, and quotes the 2017 U.S. Army's Robotics and Autonomous Systems Strategy, "air and ground unmanned systems and autonomy-based capabilities enhance logistics at every stage of supply movement to the most forward tactical resupply points" (U.S. Army Training and Doctrine Command, 2017, p. 1).

These studies and reports show that unmanned vehicles and systems, like the K-MAX, provide significant cost savings, can work 24/7, and fill the roles of the dull, dangerous, and dirty jobs. Driving back and forth from tool and supply depots could be considered any of the d-jobs, situation dependent. This research explores the ability of autonomous rovers to provide a 24/7 cost-effective logistical platform for use on the airfield.

Limitations of Automated Guided Vehicles or Autonomous Rovers

While there are advantages to autonomous vehicles, there are several studies that review the limitations for their applications that must be considered prior to using them. There is a difference between traditional logistics and the more modern ‘express’ logistics (Xia & Yang, 2018). Traditionally, goods are collected at a storehouse from multiple locations, and then distributed to various locations (Xia & Yang, 2018). To expedite the delivery, the warehouse needs to be as close as possible to the end-user, and each departure from the warehouse should make multiple deliveries per trip (Xia & Yang, 2018). On AF airfields, the warehouses of parts (Supply Depot) and tools (Consolidated Tool Kit or CTK) are located as close to the airfield as possible. With a more consolidated airfield layout, multiple deliveries could be made in one warehouse departure, to best streamline the supply chain. A solution for a fixed warehouse is a mobile warehouse, which can relocate to meet the need of more end-users who are themselves mobile (Xia & Yang, 2018), like maintainers on the airfield. JB MDL procured mobile tool kits to more readily meet the needs of the mobile maintainers on the airfield (DeBiase, 2019). Unfortunately, due to unresolved network access issues, JB

MDL's mobile tool kits are unable to be utilized, and are sitting in the corner of a hangar collecting dust (DeBiase, 2019).

Another limitation is highlighted by the speed vs. efficiency negotiation; should the speed of the delivery be prioritized, or should the delivery efficiency be more important (Voccia, Campbell, & Thomas, 2019). This conflict is seen by same-day deliveries filled by companies like Amazon, where it may be more efficient to hold a shipment until several items are consolidated into one box, than to ship multiple single items, as soon as they are picked from the shelves at the same distribution center. When a maintainer requests a part or tool, it would be assumed that the item would be needed immediately, or require a same-day delivery and a priority system needs to trump efficiency. Unlike Amazon who fills all same-day deliveries, some tools or parts will require higher priority, and the delivery system would need to distinguish that priority even amongst orders received at the same or at similar times. Studies have shown that if the delivery vehicle waits a calculated Maximum Delay Time (MDT), the wait can ensure service levels are not decreased for current or future customers, while filling more than one delivery, and serving more end-users (Voccia, et al., 2019). In other words, the study showed that if the vehicle waits a little longer, a calculated MDT, to have more than one item for delivery, efficiency for the distribution can be increased while the customer does not feel the wait.

Another way to ensure delivery system efficiency, is in how the orders are received. The maximum number of orders can be fulfilled if the orders are received at even intervals throughout the day (Voccia, et al., 2019). The daily flying schedule drives the ebb and flow for tools and parts requirements, and can set, if not an even interval

schedule, at least a predictable schedule. This is because the majority of regular flights launch in the morning, and return about the same time in the afternoon. The schedule can also include additional flights that depart, but do not return the same day. It is the high demand for tools and parts during the shift changes, every 12-hours for some communities, and every 10-hours for others, which causes spikes in the orders during a compressed time window. During these times, efficiency would be critical and the system would want to hold the delivery until multiple deliveries could be made on one run. However, this variance in demand and inability to ‘hold’ the tools until the rover is at maximum capacity before delivery, will introduce unavoidable inefficiencies in the system.

In 2002, Singh and Tiwari explored using intelligent agents to help generate routes, detect interruptions, calculate wait times, and select optimal routings for automated guided vehicles picking up and delivering loads in a manufacturing setting (Singh & Tiwari, 2002). They found that a rule-based system could successfully re-route AGVs that encountered pathway conflicts in the delivery system (Singh & Tiwari, 2002). Further studies on the advantages of vehicle routing in an environment where the agents are communicating amongst themselves, found an inefficient system of routing would include ‘selfish’ automated vehicles that are routed based on the shortest path to a destination for that individual vehicle (Bagloee, Tavana, Asadi, & Oliver, 2016). In contrast, connected and communicating vehicles can share their destinations and prospective routes in real-time, and the result is a traffic pattern that has twice the efficiency (Bagloee et al., 2016).

Efficient routing is critical in such a dynamic environment, like that of the airfield. Gonzalez (2016) reviewed several ‘motional planning and control techniques’ to allow autonomous vehicles safe movement through complex environments (Gonzalez, Perez, Milanes, & Nashashibi, 2016). They assert that the more dynamic the environment, the more important it is for the vehicle to have the ability to continuously evaluate and re-calculate its trajectory as it moves to its destination based on the traffic it encounters (Gonzalez et al, 2016). This is critical because Xia and Yang (2018) found that the navigation enabling vision systems, during dark, shadowy, foggy, dusty, and different levels of brightness, can cause the autonomous vehicle to perform poorly or not ‘see’ (Xia & Yang, 2018). The limitations of the vision systems will not be explored in this study, but are a concern in the literature. On an airfield, the presence of K-loaders, forklifts, maintenance vehicles, aircrew transportation, fleet service, fueling and oxygen servicing trucks and equipment, and personnel are only a few of the possible traffic obstacles an autonomous vehicle on the airfield would need to recognize, and avoid, in all conditions, and pose a thoughtful limitation to their use.

The following chapter outlines the methodology used to develop current process maps for the maintenance airfield expediter and develop the simulation.

III. Methodology

Overview

The research question is to find differences in efficiency between the current maintainer tool and parts transport process with that of an autonomous rover delivering supplies to maintainers working on C-17s and KC-10s at JB MDL with respect to time and cost. The results of the study were obtained through the observation of both the C-17 and KC-10 maintenance expeditors at JB MDL. To explore the differences in the current processes, with that of a process utilizing autonomous rovers, Kaizen principles and Business Process Management were used. Gemba walks helped define the steps in the current process, which were illustrated with a spaghetti diagram. Then process maps were developed to represent the process flow through various events, activities, and decision points. Combining the spaghetti diagram with the process map, the Theory of Constraints endeavors to optimize the limitations outlined in the system. Finally, the Theory of Modeling uses simulations to map, abstract, and fit the processes into a model where variables can be changed to see various outcomes and to explore innovative options. This chapter reviews the creation of the Spaghetti Diagram, the development of the Process Maps, and the creation of the simulation properties and assumptions.

Subjects

The researcher selected the subjects for this study because all parties were stationed at Joint Base McGuire-Dix-Lakehurst. The members were recruited after being told they would participate by going along their normal routines with a ride-along

observer recording the current process. The observed parties were members of the 605th Aircraft Maintenance Squadron, who maintain the KC-10 Extenders, and the 305th Aircraft Maintenance Squadron, who maintain the C-17 Globemaster III's. To delineate the subject pool for the study, a normal weekday day-shift of 10-hours for the C-17s and 12-hrs for the KC-10s was observed in March 2020. The two squadrons are located on opposite ends of the airfield at JB MDL, and each squadron ran their operations utilizing the buildings and hangars in their geographical areas. The location of these entities influenced their processes, and caused the two squadrons to meet their tool and parts needs through different processes. The KC-10s sourced their parts through a contractor, Contractor Operated and Maintained Base Supply (COMBS), while the C-17s utilized base supply. This arrangement allowed the C-17s to maintain 'Benchstock' parts in their centrally located CTK, and permitted greater ease in procuring consumables, or often-needed, smaller sized parts, called bench stock. All parts for the KC-10 were held at the COMBS facility. The C-17s have all their tools available for check-out at one CTK. The KC-10s have their tools in two locations; most tools are maintained at their CTK, while some 'calibrated' tools were maintained by the COMBS contractor in a separate building.

Instrumentation

There were several tools used for the collection of data. First, the spaghetti diagram was created by using the GPS tracker from the Cyclemeter App (Version 10.9.12) to illustrate the expediter shuttling maintainers around the airfield during the shift. The Cyclemeter App provides an advanced application that includes maps, graphs, intervals, and other data (Abvio, 2020). The researcher chose this App specifically due to

its internal map feature, which overlays a tracked route on the Apple Maps' satellite image of the street, or in this case, the airfield. Simultaneously, Microsoft Excel (Professional Plus 2016) was used to track the departure times and durations between the stops. Excel, a spreadsheet program, is a useful tool for calculations, charts, and recording data (Melendez, 2018). The researcher used Excel to also capture an explanation as to the 'push' or 'pull' that initiated the expediter changing locations to determine the utilization or transportation rates vs. the idle time. Then, the process maps were created by using the software, Lucidcharts. Lucidchart provides an intuitive platform where process segments are simply dragged and dropped into place (Content, 2019). The researcher chose Lucidcharts due to their ease of use as well as the clean presentation of the final product, especially when faced by the busy processes observed on the flight line. Finally, SIMIO was used in building the simulation both in a current-state model and utilizing a future-state with autonomous rovers. SIMIO, which stands for **Simulation Modeling framework based on Intelligent Objects**, is a simulation, multi-paradigm modeling tool, that boasts of 3D models quickly and accurately built to analyze alternatives and improve processes (Simio, 2020).

Procedures

Kaizen and Business Process Management

改善

Kai = Change Zen = Good

Figure 7. Japanese for Kaizen (Picture, 2020).

The Japanese word Kaizen, combines ‘kai,’ translated as ‘change,’ with ‘zen,’ translated ‘good’ (Hys & Domagala, 2018). Good change, referred to as continuous improvement is one of the foundations of Business Process Management (BPM), or a discipline that guides an organization to reflect and improve business processes (Dumas, La Rosa, Mendling, & Reijers, 2013). Improving business processes or creating a more efficient workflow is beneficial for both the customer and the organization; customer satisfaction improves, and the organization’s productivity is enhanced (Ng, 2018). In terms of the Air Force maintainer, the organization’s productivity can be thought of as mission capable rates, where there is room for improvement. A business process is defined as a set of events and activities that cause an outcome, or reach a goal when grouped together; events have no duration and can trigger activities, and activities can range from a single, or to simple tasks, or to multi-stepped work (Dumas et al., 2013). Decision points lie amongst the events and activities, which can change the flow of the process and introduce different events or activities (Dumas et al., 2013).

Spaghetti Diagrams

BPM illustrates interrelations between organizational processes; to help illustrate those relationships, process management often begins with the creation of spaghetti diagrams and process maps to provide an abstract view of the process, an example of

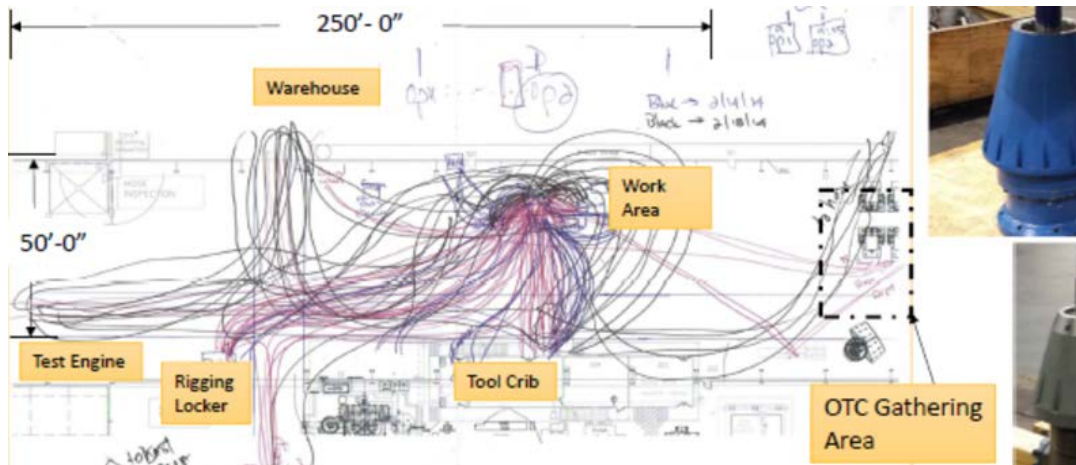


Figure 8. An Example Spaghetti Diagram Illustrating the Worker’s Repetitive Paths Through Their Marine Propulsion Manufacturing Workstation (Leaper, 2016).

which is seen in Figure 8 (Malinova, Leopold, & Mendling, 2014). The Kaizen method (Imai, 1986) recommends the spaghetti diagram because it is an image of a workspace, that uses lines to draw the paths taken by the worker during a process, and is a tool that creates a visual ‘zero state’ of movement through a process (Hys & Domagala, 2018). The spaghetti diagram is used to view the flow of the process, which when analyzed, can help eliminate waste and improve the value of the movement (Hys & Domagala, 2018). The researcher in this study engaged a GPS tracker from the Cyclemeter App (Version 10.9.12) to create the spaghetti diagrams to illustrate the expediter’s flow around the airfield. The expediter shuttled the 35 maintainers on a shift from the squadron, to and from the aircraft, CTK, and COMBS/Supply locations. The App provides a blue tracking line of the expediter’s route overlaid on the satellite image of the airfield and base. Where the expediter made multiple trips along the same routing, the individual lines merge to form a thick blue band. The individual lines reappear when the image is zoomed in. The

App provides a variety of statistics on the route, of which, the map, the total time, and the total number of miles were of pertinent interest for the research.

Process Maps

After the spaghetti diagram, the researcher created a process map. Process maps vary in detail; some provide a basic overview, while others include detailed relationships between multiple sequences (Malinova et al., 2014). Some authors argue the importance of the completeness of the process map and the inclusion of additional elements like actors, resources, and data flow relations (Malinova et al., 2014). This view of completeness is echoed by additional authors who argue for the higher degrees of detail (Heinrich, Henneberger, Leist, & Zellner, 2009). The authors say that the more detailed the map, the easier it is to adjust when new products are introduced or when the process is redesigned (Heinrich et al., 2009). As this research looks to replace a portion of the process map with a different method of transportation, i.e., a rover, the process maps will include a high degree of detail and incorporate both primary and subsidiary paths.

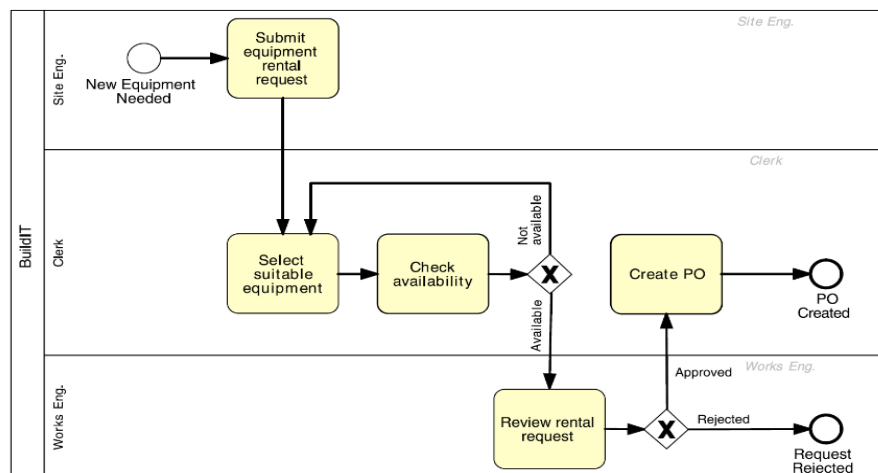


Figure 9. Example of a Basic Process Map with Symbols (Dumas et al., 2013).

Process maps are built using standardized symbols representing the events (circles), activities (rounded rectangles), and decision points (diamonds) through the sequence flow (arrows), as seen in Figure 9 (Dumas et al., 2013). An additional symbol used in this research is a 'D' shaped event, which represents a wait or delay in the process. To map the process, J. Womack (2011) recommends managers and observers perform Gemba Walks (Womack, 2011). 'Gemba,' translated from Japanese, is 'the real place' or where 'value is created' (Gesinger, 2016). As the managers walk through the process, they accumulate knowledge and understanding, ask why things are done that way, and then implement lean principles to add value to the process (Womack, 2011). The researcher followed the Gemba Walk principle, and conducted multiple visits to the CTKs to observe the operations and talk to the maintainers working there. This culminated in a shift-long Gemba Walk, which entailed a ride-along with the expediter to see first-hand the current processes.

From the ride-along, the researcher constructed detailed process maps for both the C-17 and KC-10 operations. The process maps were built using the Lucidchart online productivity platform. If there were any questions, the researcher interviewed the expediter during the ride-along and gained a clarified view of the portion of the process in question. The process map captured the day-in-the-life of a maintainer starting from his/her arrival at the squadron for roll call, and ending with the final drop off back at the squadron at the end of the shift. The process map focused solely on the transportation aspect of the shift. Each process incorporated multiple decision nodes, including asking if the expediter vehicle was immediately available to pick up the maintainer, or if the maintainer needed tools or parts, there were multiple delay nodes indicating time waiting

in a queue or waiting for transportation, as well as various activity nodes of travel, tools, and parts check out, and the event performing maintenance. The researcher created current process maps for both the C-17 and KC-10 operations, as well as envisioned process maps incorporating a rover to replace the COMBS/Supply to aircraft and CTK to aircraft routing.

Theory of Constraints

The spaghetti diagram and process maps are beginning tools used to identify areas in the process where improvements can be incorporated. The Theory of Constraints (TOC) outlines several problem-solving steps and is a ‘thinking method’ to tackle constraints in a system in order to change, improve, and streamline processes (Kuruvilla, 2017). Eliyahu M. Goldratt established the TOC, which uses a systems-oriented process improvement tool following the 5 steps, seen below in Table 2 (Chou, Lu, & Tang, 2012). The 5 steps outline the Process of On-Going Improvement (POOGI) (Wu, Zheng, & Shen, 2020), and has found success in production line scheduling methods, like Drum-Buffer-Rope, (Goldratt & Cox, 1984) and other production line methods, like the shifting bottleneck heuristic (Monch & DrieBel, 2005). In the flight line research, the main bottleneck, in both squadron’s process, was found at the squadron where 35 people arrive simultaneously for the start of their shift. There is one expediter, driving a panel van, who is responsible for those specific 35 people. The van is limited to 6 passengers at a time, and they have to be shuttled to multiple locations on the airfield to get their tools and parts, before and during their work on the aircraft.

Table 2. Theory of Constraints 5-Step Process as described by Chou et al. (2012)

1. Identify the constraint: Determine the system activity whose capacity is less than the demand placed on it.
2. Exploit the constraint: Maximize the efficiency of the constraint activity in its existing system configuration.
3. Subordinate all else: Synchronize the operation of all other system components with the constraint activity.
4. Elevate the constraint: Increase the capacity of the constraint activity to eliminate it as the constraint.
5. Return to step 1. but prevent inertia. Revisit all changes to ensure that they still support the current system configuration.

Kan Wu, Meimei Zheng, and Yichi Wu Shen (2020) argue that the POOGI steps focus too heavily on the throughput bottleneck. They instead propose exploring the dependence between the nodes, or in identifying a cycle time bottleneck through the 5-step process called the Generalized Process Of On-Going Improvement (GPOOGI), the steps of which are outlined below in Table 3 (Wu et al., 2020). The authors say GPOOGI requires multiple improvement cycles to improve cycle times, and more analysis than the conventional POOGI. The managers need to ensure each improvement, and the associated cost, is consistent with the company’s overall strategic plan (Wu et al., 2020). In this flight line research, the spaghetti diagrams and process maps were created and used to develop a simulation to model the current performance of the process.

Table 3. Generalized Process Of On-Going Improvement (GPOOGI) (Wu et al., 2020).

1.	Construct a simulation model to evaluate the performance of the production line.
2.	Evaluate the cycle time reduction due to the improvement action at each station.
3.	Calculate the cost of the improvement actions at each station.
4.	Select the station and action for improvement based on the cycle time reduction for each product type and the cost of the improvement.
5.	Go back to Step 2. And continuously reduce the cycle time.

Modeling Theory

Modeling Theory upholds that models are a critical resource during scientific inquiry (Halloun, 2006). A model is defined as being composed of five types of

- A. Systemic Structure:
 - a. Composition – internal parts (objects) in the system
 - b. Environment – external agents linked to the system
 - c. Connections – external and internal links
- B. Geometric Structure:
 - a. Position – with respect to a reference frame (external)
 - b. Configuration – geometric relations among the parts
- C. Object Structure:
 - a. Intrinsic properties of the parts
- D. Interaction Structure:
 - a. Properties of (causal) links
- E. Temporal (Event) Structure:
 - a. Temporal change in structure of the system

Figure 10. Conceptual Model's 5 Types of Structure (Hestenes, 2006).

structures, as seen in Figure 10, which include systemic, geometric, object, interaction, and event structures (Hestenes, 2006). The systemic structure includes the composition of the objects in the system, the environment, and the connections internally and externally (Hestenes, 2006). The geometric structure includes a position in reference to a frame, and configuration, which is in reference to other parts in the system (Hestenes, 2006). The creation of a model is accomplished in three steps: a map, an abstraction, and a fit for purpose (Dumas et al., 2013). Because a model is relevant only to a specific purpose, all five structure types are not incorporated into one model (Hestenes, 2006). The most often used model is a basic map, where the specific locations are specified using the geometric structure of modeling (Hestenes, 2006). The basic map can upgrade to a

motion map when an object’s motion is denoted with paths between points (Hestenes, 2006).

The first step in creating a model is mapping a real process (Dumas et al., 2013). The proper construction and deployment of a model during research is a critical aspect of the scientific inquiry (Halloun, 2006). The construction of the model is important because a model is an idealization of real-life events (Hestenes, 2006). While the physical world can be thought of as a ‘World 1,’ our minds create a mental model that is not a perfect copy of the physical world, or a ‘World 2,’ which is then used to develop a conceptual model, or a ‘World 3’ (Hestenes, 2006). The relationship between the three worlds is best illustrated by the Modeling Theory of Cognition shown in Figure 11 below. This mapping step was completed when paths were designed in the SIMIO program with the help of the before mentioned spaghetti diagram.

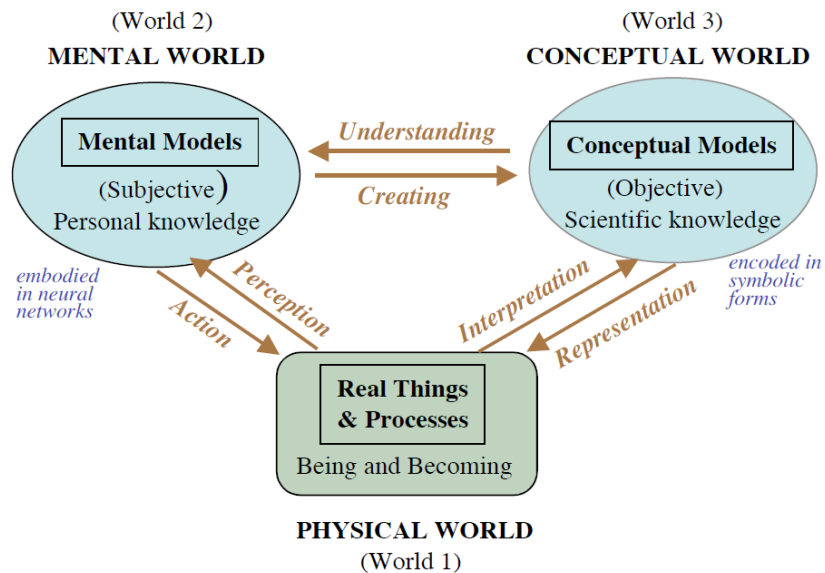


Figure 11. Modeling Theory of Cognition: Physical Worlds Create Mental Models Which Influence Conceptual Models (Hestenes, 2006).

The second step of building a model is to abstract irrelevant details from the map, while the third step is to ensure the model omits aspects that do not serve the particular purpose of the model (Dumas et al., 2013). One could say that creating a model itself is an abstraction of the real process, per the above mentioned Modeling Theory of Cognition. As the research question is focusing on the efficiency of the maintainer tool and parts transport process, the researcher, therefore, focused on the transportation aspects of the maintainer's work-day when creating the process maps. This is mirrored in the simulation set-up, where the most significant detail is in the paths between the central locations of the squadron, COMBS/Supply, CTK, a hangar for inspections, and the aircraft. Only sufficient details and data were included as relevant for the purpose of the current study. Although the process maps may have included less data, and there are multiple studies that support the more complete process diagrams as easier to make changes (Malinova et al., 2014; Heinrich et al., 2009), the researcher ensured the process maps included sufficient and pertinent details, concluding that the model abstractions did not misrepresent the overall process.

Simulation: KC-10 Set-Up

Simulation is used in a multitude of research to include autonomous supply chain networks through discrete event simulation (Gupta & Andersen, 2018); semiconductor fabrication, assembly, and testing (Monch, Uzsoy, & Fowler, 2017); early detection of multi-scale fractures in reservoirs (Bourbiaux, Basquet, Cacas, & Daniel, 2003); and to teach process flow and variability concepts (Dobson & Shumsky, 2006). A simulation was chosen to model the process on the flight line because the SIMIO multi-paradigm

modeling tool has the ability to show processes in a 3D model, that the company advertises, can easily be altered to analyze alternative processes (Simio, 2020). SIMIO can create a movie-like 3D simulation that moves in real-time, or in fast-forward, and quickly illustrates queues building, and vehicles transporting workers to their various stations, perfect for analyzing the maintainer process. The SIMIO tool also guides the user through the simulation set-up by providing a series of selection menus for each entity placed in the model workspace. Additionally, SIMIO provides a database of template problems with simple simulation solutions in the Support Tab called SimBit Solutions. The researcher found the following SimBits instrumental in learning how to set up various sections of the maintainer simulation: Vehicle Fixed Route, Entity Follows Sequence, Entity Follows Sequence with Table, Entity Follows Sequence with Relational Table, Choose Alternate Sequence, Vehicle Fixed Route, Routing without Paths, Worker Uses Work Schedule, Electric Vehicle, Dashboard Report Tallies, Dashboard Report Interactive Logs, and Dashboards Within Experiments; as well as multiple YouTube videos authored by C. Dennis Pegden, the CEO of SIMIO, David T. Sturrock, the VP of SIMIO, and Ashkan Negahban, a SIMIO employee. The SIMIO Insiders General Discussions Forum provided a platform to ask questions, and the replies from a SIMIO Employee, Ryan Welch Luttrell, were especially valuable.

The following simulation information pertains to the building of the simulation. The next few paragraphs will review the SIMIO property selections that the researcher made when setting up the KC-10 and C-17 maintainer simulations, and state any underlying assumptions.

To build this simulation, the researcher started with a screen capture of a Bing Maps image of the JB MDL flight line, surrounding base area, and map scale. This map was saved in Paint as a PNG file, was imported as a symbol to the background of the Facility Window in SIMIO, and was scaled to match the program's scale. This allowed the researcher to define the vehicle's speed as a speed limit, and not have to define specific distances or times between nodes. The image map allowed the researcher to then place the components of the simulation, like the squadron building or the tools or parts locations, onto their real locations, and connect the nodes with paths that mirrored the real roads.

The researcher began the simulation modeling for the KC-10s with the following simple system setup involving two sources, *SquadronBldg* and *SecondShift*, a sink, *EndOfShift*, and four servers, *COMBSParts*, *CTKTools*, *AvgAircraftLocation*, and *Lunch*. Unidirectional paths drawn with single-lane road path decorators connected the source to all the servers and the sink. Additionally, there was a walking path from the squadron to the CTK. This was for maintainers who thought they had waited too long at the squadron for the expediter vehicle to pick them up, and walked to the CTK instead (0.4 miles). The vehicle was added from the Standard Library, titled *ExpediterVehicle*, and the image was changed to the appropriate panel van image. In the vehicle properties, the Initial Ride Capacity was set to 6, with a requirement to park to unload, limited to 15 mph, and traveling on the network only (or limited to the researcher defined paths), following network path if possible, avoided collisions, and limited the model to one vehicle. The maintainers were added as *ModelEntities* from the Project Library and uploaded as a

male and female, AF uniformed images, titled *WorkerCommNav* and *WorkerHydro*.

Their ModelEntity properties remained as the preset values.

Two Data Tables were created to define additional relationships concerning how many people would leave as a team from the squadron and go to the aircraft to work, and if they needed Tools or Parts, or if they were going on a lunch break. The first Data Table, *Jobs Table*, consisted of 5 columns and is seen in Figure 12. The first column was the *Job Number*, the second was the *Specialty Team* required for the job, and then there was the *Number of Workers*, *Parking Spot*, and *Route*. The *Job Number* listed the 2 jobs

	Job Number	Specialty	Number Workers	Parking Spot	Route
1	1	WorkerHydro	Random.Triangular(3,6,9)	Input@AvgAircraftLocation	A
2	2	WorkerCommNav	Random.Triangular(3,6,9)	Input@COMBSParts	B

Figure 12. *SquadronBldg*'s Jobs Table

to be completed on that day. The *Specialty* designated which entity was picked up at the squadron. The *Number of Workers* was defined as an expression with a Random Triangular distribution with a minimum of 3 people, an average of 6 people, and a maximum of 9. The *Route* column was designated as the primary key of the table. The primary key column connected this data table with the next table, a sequence table. The sequence table had three columns: *Sequence*, *Route*, and *ProcessTime*, as seen in Figure

13. When the model was run, the vehicle would arrive at the Source and start loading the first team of maintainers. The *Jobs Table* defined how many people were going to which job, and then the key column drove the logic to search for the key in the sequence table to find the routing for that team. The researcher defined the *Route* for team A as the following sequence of server nodes: Input@AvgAircraftLocation → Input@LunchBreak → Input@AvgAircraftLocation → Input@EndOfShift. The additional add-on processes implemented at the *AvgAircraftLocation* drove maintainers to get tools and parts. The

Sq1	Jobs Table	Inspection	Tools	Parts
	Sequence		Route	Process Time
1	Input@AvgAircraftLocation		🔑 A	Random.Triangular(.333,1.5,6)
2	Input@LunchBreak		🔑 A	Random.Triangular(.667,1,1.5)
3	Input@AvgAircraftLocation		🔑 A	Random.Triangular(.333,1.5,6)
4	Input@EndOfShift		🔑 A	0
5	Input@CTKTools		🔑 B	Random.Triangular(.25,.33,1)
6	Input@AvgAircraftLocation		🔑 B	Random.Triangular(.333,1.5,6)
7	Input@LunchBreak		🔑 B	Random.Triangular(.667,1,1.5)
8	Input@AvgAircraftLocation		🔑 B	Random.Triangular(.333,1.5,6)
9	Input@EndOfShift		🔑 B	0
*				

Figure 13. The *SquadronBldg*'s Sequence Table Titled Sq1 for the Routing and Process Time for the Maintainers at Those Locations.

before processing add-on sent 5% of the maintainers to get tools before starting to work on the aircraft, and the processing add-on sent another 5% to get parts after they started working on the aircraft, as seen in Figure 14. This describes a team getting picked up after roll call, getting dropped off at the aircraft, sending a runner for tools, finding they need a replacement part, and sending a runner to COMBS. The process of sending the 5%

for a tool or part occurs every time the expediter van arrives at the *AvgAircraftLocation*. They get shuttled back to the squadron for a staggered lunch break and then back out to the aircraft. At the end of the day, they depart from the squadron. The process time defines the length of time for each activity as is set as an expression with a Random Triangular distribution with the following minimum, average, and maximum times in hours displayed in Table 4.

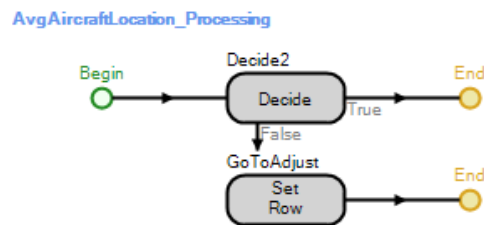


Figure 14. Add-On Processes to Send Maintainers To Get Tools & Parts

Table 4. Process Time for Each Service Node Defined as Random Triangular Distribution with the Following Min/Avg/Max Times in Hours:

Service Node	Minimum	Average	Maximum
CTK Tools	.25	.33	1
AvgAircraftLocation	.333	1.5	6
COMBSParts	.25	.333	1
LunchBreak	.667	1	1.5

The following are additional custom settings for the sources, *SquadronBldg* and *SecondShift*, and the Transfer Nodes. To create multiple entities from the single Squadron source, the Table Row Referencing section is set to *JobsTable.Specialty*, with Time Offset, set to zero, the Interarrival Time set to zero hours, and Stopping Conditions/Maximum Arrivals set to 35. In the Buffer Logic, there is a Balking & Reneging Option set to ‘1 row.’ Renege Triggers are set to a ‘2-minute’ wait duration

with a probabilistic renege decision type, and a 10% or (.1) renege condition or probability. The renege reroutes the entity to the Renege Node Name of *WalkerStartNode*. This means that the maintainers at the Squadron will wait 2 minutes at the squadron before 10% of those waiting will get tired of waiting and move to the *WalkerStartNode* and walk to the CTK. Finally, the Table Row Referencing Property, Table Name is set to *JobsTable* and Row Number to *JobsTable.NumberWorkers.RandomRow*. The *SecondShift* source uses the entity type, *WorkerHydro*, and has an interarrival time of 12 hours, and a stopping condition and maximum arrivals set at 35. Concerning the Output Transfer Nodes for all the Sources, the Transport Logic has the entity destination type set 'by sequence' and 'ride on transporter' selected as 'True' with the Transporter Name defined as *ExpediterVehicle*. Both entities route by the initial sequence, *Sql*. Finally the *ExpediterVehicle* has an initial ride capacity of 6, must park to load or unload, and is limited to 15 mph. The vehicle also has a network only travel mode, follow network path if possible free space steering parameter, avoids collisions, and has the home node of *Output@SquadronBldg*.

Simulation – C-17 Set-Up

The C-17 model also had the *Squadron* source that produced the entity, *Maintainers*, at a rate of 35, in two shifts, offset by 12-hours. The server locations included the *AvgAcftLocation*, *CTK/BenchStock*, and a *LunchBreak*. There was also the *EndOfShift* sink. All entities moved through the model by demand via a sequence table, and were transported by the *Expediter* vehicle, with the output transfer nodes for the source and all servers set to ride on the transporter, *Expediter*. The sequence table

included the following routing for the maintainer entities: *Input@AvgAcftLocation* → *Input@Lunch* → *Input@AvgAircraftLocation* → *Input@EndOfShift*. There was an add-on process trigger set at the *AvgAcftLocation* at the ‘before processing’ step, which sent 10% of the maintainers who arrived at the *AvgAcftLocation* back to the squadron’s CTK for tools or bench stock parts, the *Input@CTKBenchStock* server. The add-on process was a probability based decision type set at 0.9. Thus for every van load of maintainers, which had an initial ride capacity of 8, one was sent back to get tools or parts. The add-on process sent the maintainer back using a ‘GoToAdjust’ SetRow process, using the logic of the second sequence table, titled ToolsParts. The routing for the second sequence table was *Input@CTKBenchStock* → *Input@AvgAcftLocation*. The vehicle also had a load time of .3 minutes, an unload time of .2 minutes, and a 15 mph speed limit. The process times for the servers are listed in Table 5 below.

Table 5. Process Time for Each Service Node Defined as Random Triangular Distribution with the Following Min/Avg/Max Times in Hours:

Service Node	Minimum	Average	Maximum
AvgAircraftLocation	.5	2	5
CTKBenchStock	.3019	.5019	.6019
LunchBreak	.667	1	1.5

Simulation Set-Up With Rovers

When the rovers were added to the simulations, multiple different network configurations were explored. These included a shared or ‘same’ networks where the paths connected all the locations. Or a separate network was explored, in the KC-10 simulations, where COMBS rovers only delivered parts and CTK rovers only delivered tools. Added to the models were sources to create the tools and parts, as well as sinks at

the aircraft where the tools and parts were delivered. There were also sources at the aircraft to create the need to return a faulty tool or part, or to return the checked out tools. These sources, at CTK, COMBS, and the aircraft, had a defined process time based on the observed rate at which the expediter traveled to those respective locations. There were 1.136 trips/hour to the CTK or an interarrival rate of .88 hours, and 1.273 trips/hour to the COMBS or an interarrival rate of .7855 hours. Therefore, the researcher used those rates as the average production rates for the tools or parts. For the KC-10 simulation, the *CTKTools* and *Return2CTK* both produced at a random triangular distribution of min, avg, and max of .7103, .8803, and 1.0503 hours. The *COMBSParts* were created at a random triangular distribution of .6155, .7855, and .9555 hours. There were 3.313 trips/hour to the CTK for the C-17 Expediter, or an interarrival rate of .3019. Because not all these trips were for tools, as the squadron is in the combined location, this rate was used as the minimum and larger numbers used for the average and maximum. For the C-17 simulation, the *CTKBenchStock* and *ReturnToolsParts* both created at a random triangular distribution rate of .3019, .5019, and .6019 hours. The consolidated rate table is seen below in Table 6.

For both the KC-10 and C-17 Simulations, when the rovers were added, the properties of the vehicle are as follows. The rover had load and unload times of 1 minutes, it must park to load or unload, was limited to 4 mph, rotated in place for a network turnaround, followed the network path if possible for free space steering, and avoided collisions. The rover was parked at the respective model's CTK, unless there was a COMBS specific rover for that particular simulation, which was parked at the COMBS parts source.

Table 6. Source Random Triangular Distribution Rates in Simulations With Rovers

Service Node	Minimum	Average	Maximum
<i>KC-10 CTKTools</i>	.7103	.8803	1.0503
<i>KC-10 Return2CTK</i>	.7103	.8803	1.0503
<i>KC-10 COMBSParts</i>	.6155	.7855	.9555
<i>C-17 CTKBenchStock</i>	.3019	.5019	.6019
<i>C-17 ReturnToolsParts</i>	.3019	.5019	.6019

Statistical Analysis

Simulation Process Times to check out tools or parts or perform maintenance was modeled with a random triangular distribution. The time the maintainer waited to get picked up by the expediter, or the time spent in a non-value added queue, waiting for the tool or part, was not observed directly to collect a normalized sample. In such situations, Little's law can be used to estimate the average waiting with the equation $L = \lambda W$ when $L = \text{average number in the system}$ and $\lambda = \text{average arrival rate}$ (Kim & Whitt, 2013). However, this basic Little's Law has been shown to have a bias in situations where arrivals are time-varying with long service times (Kim & Whitt, 2013). The time-varying Little's law is more appropriate for such situations. This is an area for future research as the researcher limited the scope of this study to miles driven by and time spent by the Expediter.

IV. Results and Analysis

Overview

The research question is exploring differences in the current maintainer tool and parts transport process with a process incorporating autonomous rovers and time and cost savings. The first step was creating spaghetti diagrams and process maps for the C-17s and KC-10s at JB MDL. These illustrated the flow of the process through various events, activities, and decision points. The next step was to use the Theory of Constraints and optimize the system's limitation of the expediter. This was accomplished through applying the Theory of Modeling to the transportation process. The researcher explored multiple simulations incorporating 1, 2, and 3 rovers in the process. The simulation also investigated two different network configurations; one with two separate closed looped networks for tools separate from parts, and a second network where paths allowed rovers to service either tools or parts. Included in the modeling are the time and cost benefits associated with that decision.

C-17 and KC-10 Spaghetti Diagrams

To identify the constraint, the spaghetti diagrams were created. The researcher filled the role of an observer participant, or a researcher that interacted with the participants (Sauro, 2015), and conducted a ride-along for an entire day shift with the maintenance expediter for both the KC-10s and C-17s to observe and record their operations. While riding in the van, a GPS tracker from the Cyclemeter App was enabled to create the following spaghetti diagrams to illustrate the route the expediter drove;

Figure 15 shows the route of the KC-10 expediter taken on 10 March 2020, and Figure 16 displays that of the C-17 expediter taken on 12 March 2020.

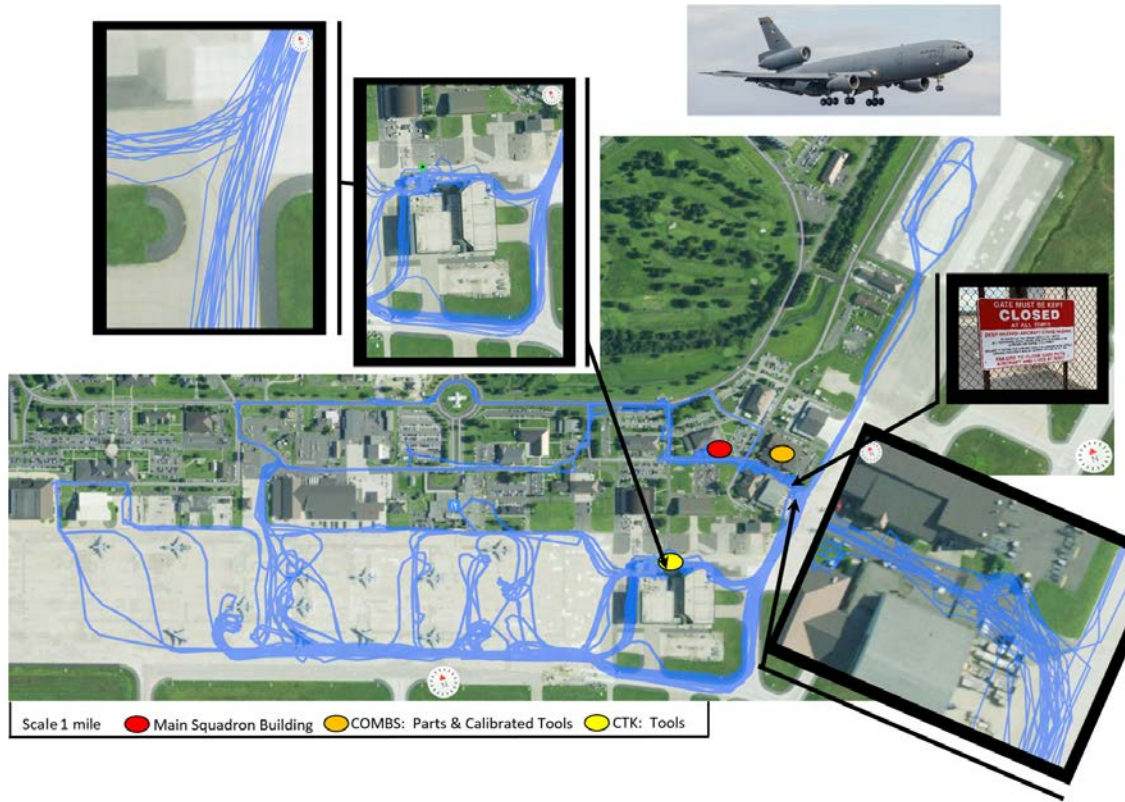


Figure 15. Spaghetti Diagram: GPS Tracking of Ride-Along with KC-10 Expediter at JB MDL, NJ. (KC-10, 2020)

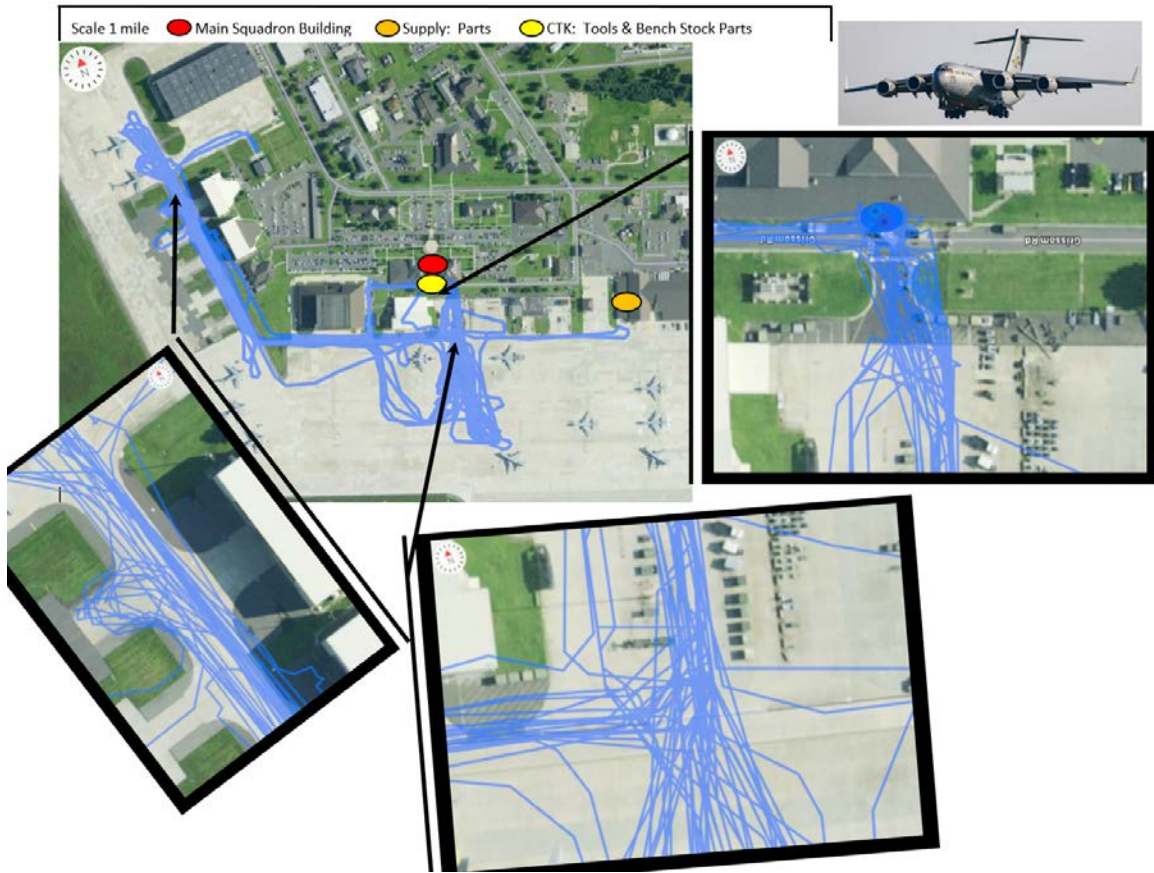


Figure 16. GPS Tracking of Ride-Along with C-17 Expediter at JB MDL, NJ. (C-17, 2020)

Annotated on the maps are the main squadron buildings, the CTKs with the tools, and the supply location with the parts, or full contractor logistics support, Contractor Operated and Maintained Base Supply (COMBS), for the KC-10s, and a one-mile scale. The numerous back-and-forth trips blurred to a thick line, so the map was zoomed in at various points to better show the individual trips. For both squadrons, the CTK was the most highly trafficked area, shown by the yellow circle. Of note, the C-17 main squadron area is co-located with the CTK. For the KC-10s, the CTK is positioned in an airfield hangar, located a 0.4 mile walk from the main building, or a 2 minute drive. The drive

takes 3 to 4 minutes if an airfield gate for wildlife is not open for other vehicular traffic. The process to drive through the gate involves someone getting out of the expediter van, dragging the gate open, driving the vehicle through, closing the gate, and then getting back in the van. There is no gate in the area of operations for the C-17s, as they operate solely in the airfield premise.

Also, while CTKs distribute tools, there are differences between the two operations. For the KC-10s, COMBS has the aircraft parts, and also maintains certain calibrated tools. For the C-17s, the CTK checks out tools and also issues bench stock, or small parts that are maintained and issued to the maintainers by CTK. Bench stock parts are consumables, or parts that have a high frequency of use. Being issued from the CTK eliminates frequent trips to the Supply Depot, trips which are reserved for larger, less often required parts. On the day observed, there was one trip to Supply and that was to show the researcher the layout and location. In part due to the location of the bench stock, and in part due to the differences in squadron buildings layout, the miles driven by each respective aircraft varied significantly. The KC-10 Expediter drove 79 miles in a 12-hour shift, or 158 miles per 24 hour period, while the C-17 Expediter drove 37.5 miles in a 10-hour shift, or 90 miles in a 24 hour period, or 57% fewer total miles every 24 hours. The utilization, or rate that the expediter was actively transporting a maintainer, tool, or part contrasts with the idle rate, where the expediter is not transporting but waiting to be called for a pick-up. The KC-10 Expediter reported the day observed as an average and typical day, while the C-17 Expediter reported the day as less busy than normal. The simulation, therefore, modeled the KC-10 close to the observed rates and mileage, while the C-17's mileage in the model was increased 20% to better represent a normal day. The

total durations and distances drawn in the spaghetti diagram from the observation for both the KC-10 and C-17 expeditors are listed below in Table 7.

Table 7. Rates and Total Miles Observed on Ride-Along Driven by Expediter

Aircraft Serviced	Utilization Rate	Idle Rate	Average Miles per (#-hour) Shift	Average Miles per 24-Hour Period
KC-10	43.8%	56.2%	(12-hr) 79 miles	158 miles
C-17	35.0%	65%	(10-hr) 37.5 miles	90 miles

Current Day-in-the-Life of a KC-10 and C-17 Maintainer Process Maps

From the observed transactions, the process maps were then created. The Start (Oval), Processes (Rectangles), Decisions (Diamonds), Delays (D-Shaped) and the End (Oval) are all connected through the flow lines for the expeditor and maintainers for each aircraft. The green rectangles show the travel throughout the airfield and base. The red d-shapes are delays in a maintainer’s day waiting for pickup by the expeditor van, walking due to an extensive delay waiting for the expeditor, opening and closing the airfield gate, or in a queue for tools or parts. The blue decision diamonds represent the questions the maintainers ask themselves throughout their shifts concerning airfield transportation, provided by the expeditor, and their tools and parts requirements. A significant advantage of a process map is the ability to see the entire process on one page. The viewer can easily distinguish between a complicated and a straightforward process, while the colors on the maps also help to easily identify how many of and of what kind of action is being taken.

Figure 17 shows the current KC-10 maintainer's process map which begins at roll call in the main squadron building. The roll call is followed by a 3 to 35 minute wait as the expediter shuttles groups of 6 (the vehicle's capacity) to the CTK and then to the flight line, and then shuttles to and from the aircraft to COMBS or CTK depending on requirements for parts or tools. Figure 18 shows the current C-17 maintainer's process map which also starts at roll call in the main squadron building. However, in this squadron, the role-call assembly room is adjacent to the CTK. Immediately following the morning briefing, the maintainers file out of one room and create the queue in the next room for tool issue. Only after they have their tools and bench stock parts do they exit the building and require transportation from the expediter to shuttle them to the aircraft. The process maps easily illustrate the more complicated from the more straight-forward processes and through the colors, the number of each type of step in the process is shown.

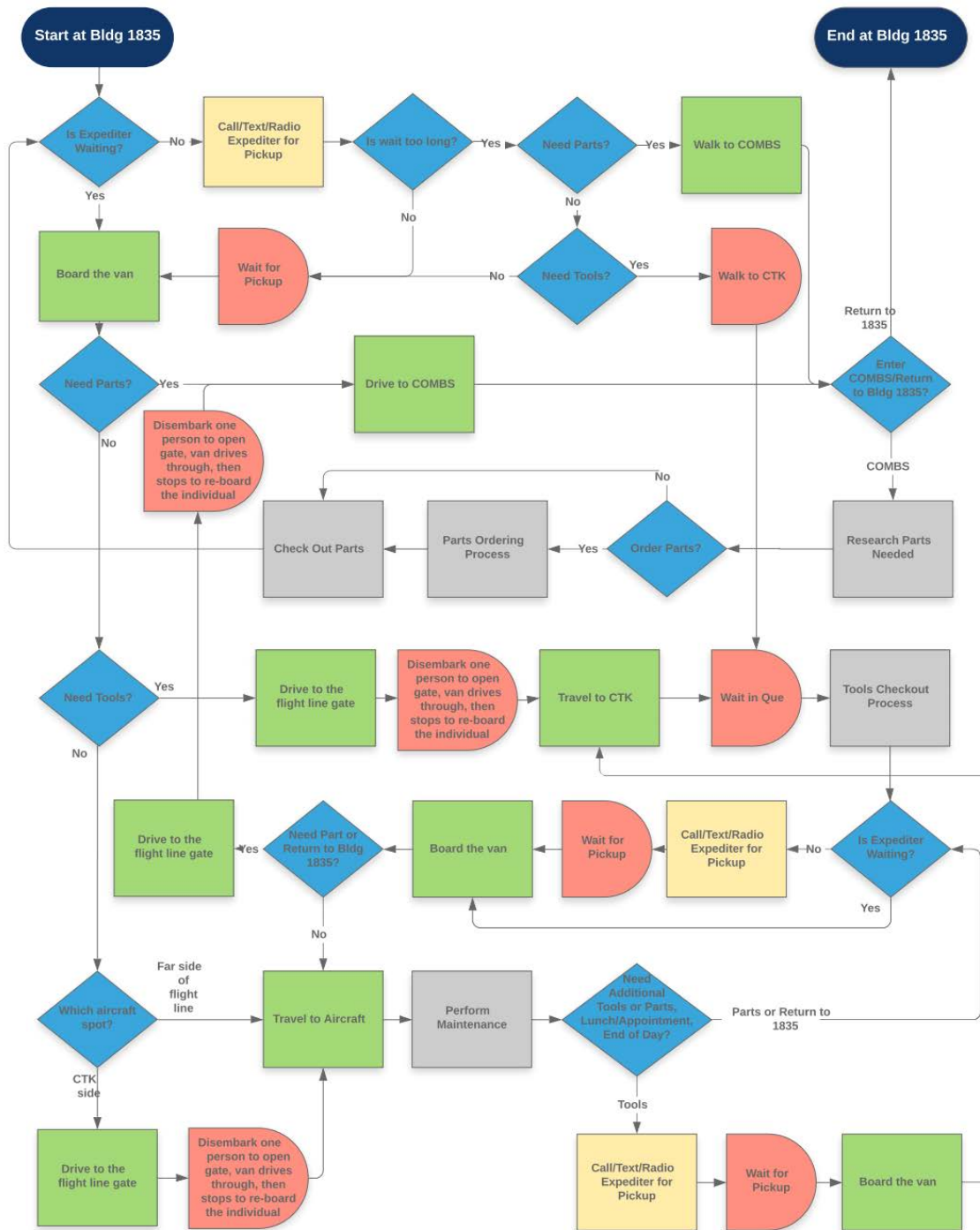


Figure 17. Current KC-10 Maintainer Typical Day Process Map

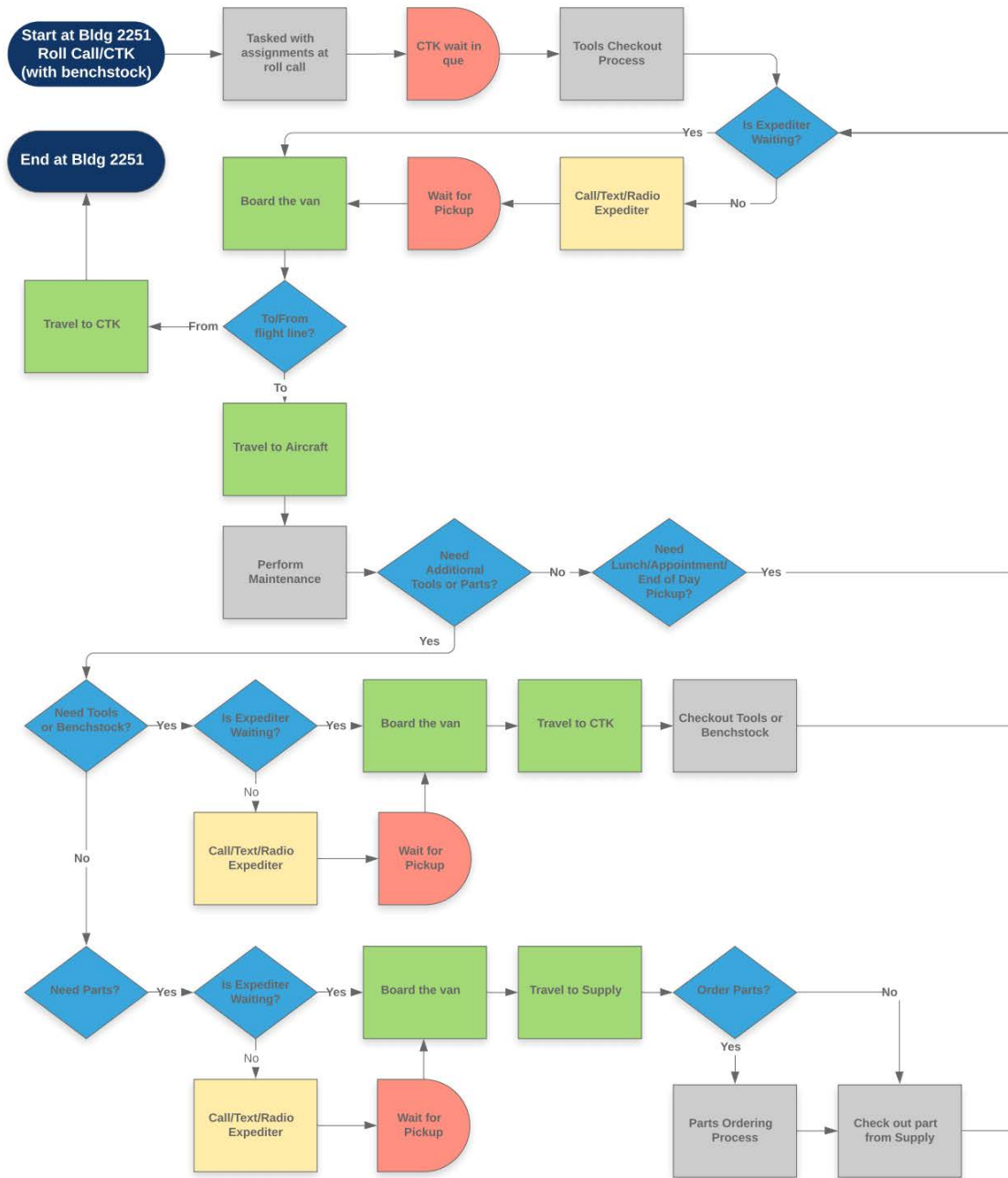


Figure 18. Current C-17 Maintainer Typical Day Process Map

Proposed KC-10 and C-17 Maintainer with Process Maps Incorporating Rovers

The maintainers wait the longest after roll call. This is because 30-35 individuals arrive simultaneously for their shift and there is one expediter assigned to transport those individuals. This research proposes to replace those trips to CTK or COMBS/Supply with autonomous rovers that deliver tools and parts to the pre-programmed aircraft parking spot. The rover's substitution would include a mobile ordering app to streamline the supply chain from part to maintainer. The proposed app would allow the maintainer to select either the tool or part individually, or search the job they are performing and select the tool or part required for the specific task. The order would be processed by COMBS/Supply/CTK. When the tool or part is ready, COMBS/Supply/CTK would call a rover to their location. If the tool or part fits within the size or payload weight of the rover, COMBS/Supply/CTK personnel would then load the part into the rover. The rover would transit along the edge of the apron on a pre-defined route away from other airfield vehicles or aircraft. The parking spot destination is included in the order and the rover would wait at the spot to be unloaded by the maintainer. To ensure tool accountability, the maintainer would have to unlock the rover with a CAC, or have a unique pin number provided to be typed into the rover. Once the unique pin was entered, or the maintainer's CAC chip was read, the part or tool would be checked out to that specific maintainer.

To aid in the 'calling' of the expediter for pick up, an Uber type app could be utilized. The feature to 'schedule a pickup' could be used to set a future time and place requesting a pickup, or request an immediate pickup. The streamlined supply chain ordering app, the Uber-type app, and the use of the rovers, all maximizes the efficiency of the expediter constraint. Figure 19, below, outlines the proposed process chart for the

KC-10s. The process chart uses the following standardized symbols: circles to denote events, rounded rectangles for activities, diamonds for decision points, and a 'D' shaped event for delays in the process. The various symbols, or nodes, in the process, are connected with arrows denoting the sequence flow. With the automation, the KC-10 decisions nodes are decreased from 12 to 9, the delay nodes are reduced to 3 nodes from 8, and the transportation is halved from 10 nodes to 5. In the C-17s, Figure 20 below, there are 9 decision nodes in the current process and 7 decisions with the rovers, the wait nodes are decreased from 4 to just 1 in the model with the rover, and transportation nodes are reduced from 7 to 2 nodes. The augmentation with the rovers and Uber-type app have streamlining effects for both processes.

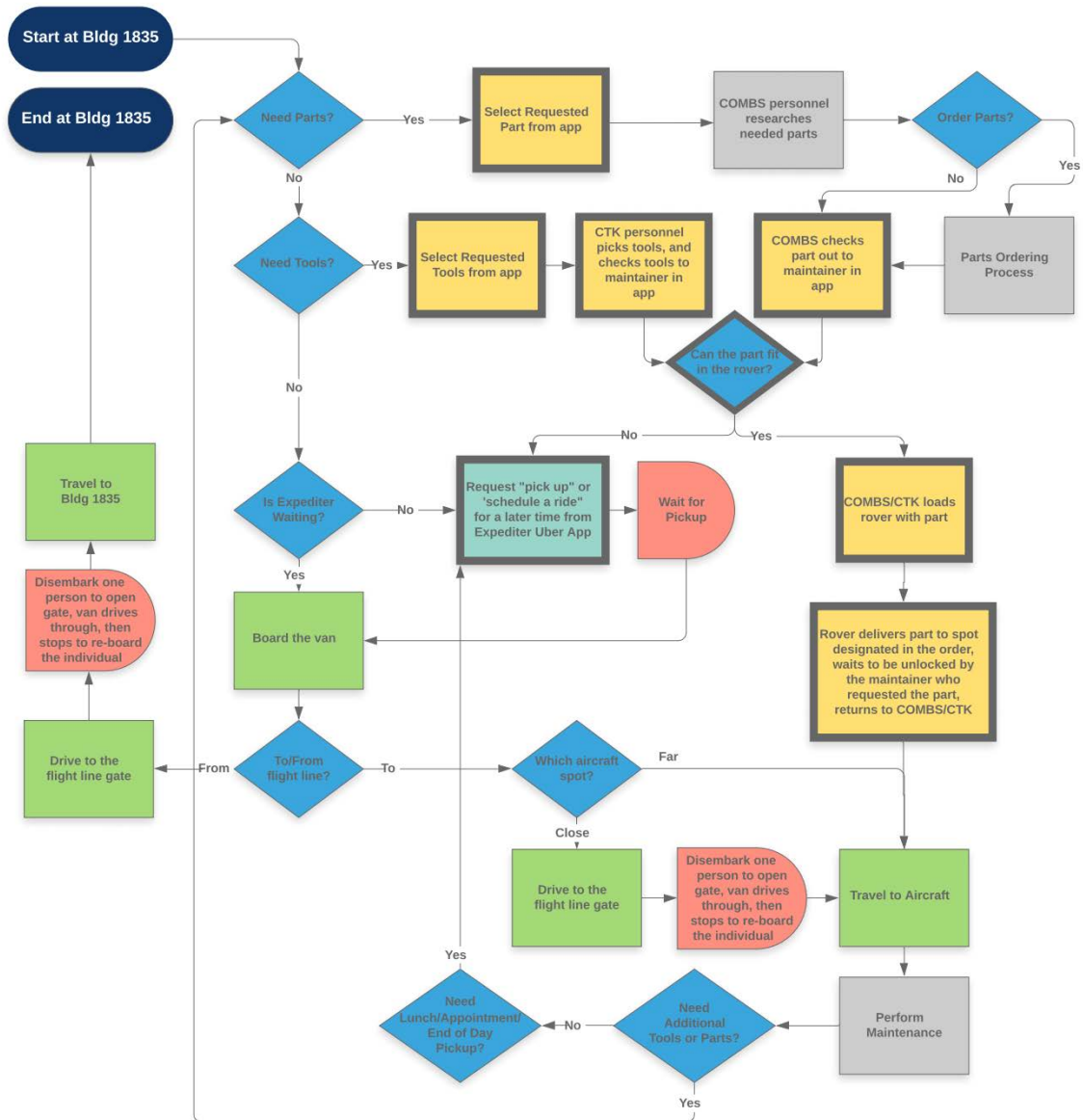


Figure 19. Proposed KC-10 Maintainer Process Map with Rover and Apps.

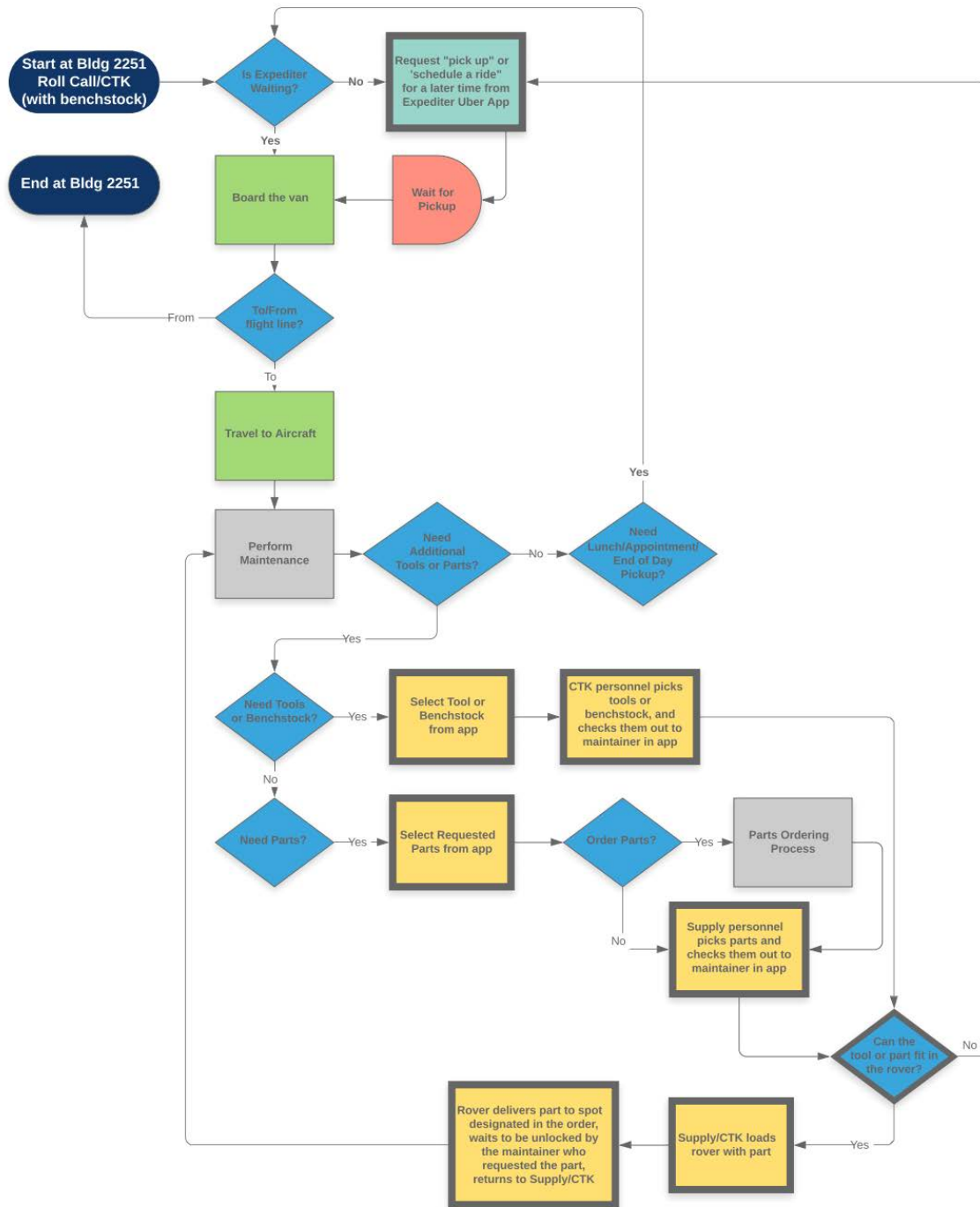


Figure 20. Proposed C-17 Maintainer Process Map with Rover and Apps Highlighted.

Simulation: Model of the Current KC-10 Process

To verify the model before proceeding with further analysis, the simulation was created, parameters defined, and the results tab reviewed. The most critical and time-consuming part of using simulation in the modeling process was ensuring the desired parameters behaved in the programmed manner to accurately model the desired process. For the current KC-10 simulation, the results reported that the correct number of entities, as seen in Figure 21 below, were created and removed at the correct times in the model runs; 16 *WorkerCommNavs*, 54 *WorkerHydros*, for a total of 70 workers in two, 35-entity shifts. For the server, *AvgAircraftLocation*, 167 entities traveled through the aircraft node to perform maintenance. In other words, in one 12-hour shift, each person went through the *AvgAircraftLocation* 2.39 times; once at the beginning of the day, once after lunch, and 40% of them after get tools or parts. As the researcher observed several trips of one or two people being shuttled back and forth for tools and parts during the ride-along, this



Figure 21. The Two Worker Entities for the Simulation.

was a reasonable model assumption. Once a shift, an entity was also given a lunch break, and ended their day back at the squadron.

The simulation entities are displayed as action symbols. They form a line to wait for the expediter vehicle to take them to their destinations. While they wait in line, they fill idle time fidgeting and using cell phones. The workers step side-to-side, make phone



Figure 22. Line of Worker Entities Waiting at the Squadron for Pickup Following Role-Call; Some Distractedly Look at Their Phones or Make Calls, Presumably Asking the Expediter for Pick-Up.

calls, and text while they wait. Figure 22, above, shows a line of workers waiting at the *SquadronBldg* for pickup at the beginning of their day following roll-call. They do not have their tools or parts. In a 24-hour period, six workers in the model stopped waiting for the expediter, exited the queue, and walked to CTK. This is according to the programmed 10% of entities who have waited more than 2 minutes, as seen below in Figure 23.

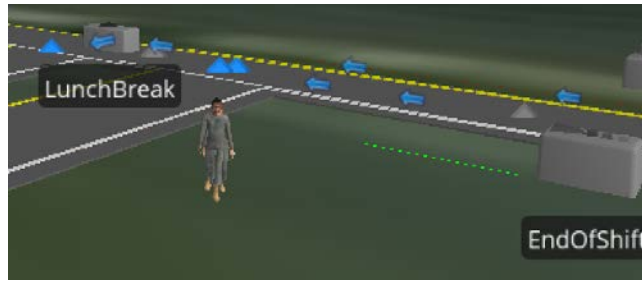


Figure 23. Two Worker Entities Reneged After Waiting 2 Minutes for Pick Up by the Expediter and Walked to the CTK.

The simulation's expediter vehicle, seen below transporting workers in Figure 24, had a utilization rate of 42.8% and was actively transporting workers 10.3 hours of the 24-hour period, or 5.2 hours on one shift, and was idle the remaining 57.2% or 13.5 hours of the 24-hour period, or 6.9 hours on one shift. This is in contrast to the researcher observing a utilization rate of 43.8% and an idle rate of 56.2% on the ride-along as seen in Table 8 below. Because the researcher created the simulation with an average aircraft parking spot vs. every possible parking spot, as seen in Figure 25, having the model produce the same overall miles was an important check for model validity.

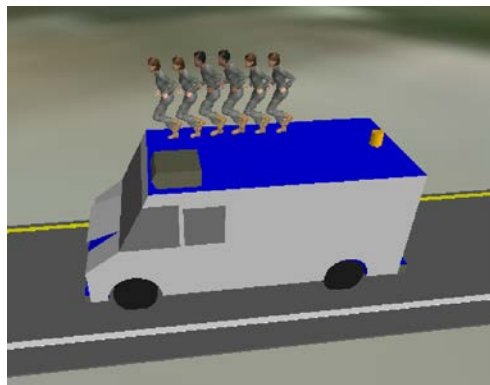


Figure 24. The Expediter Vehicle with Maximum Load of 6 Worker Entities Transporting to CTK for Tool Pick-up.

Table 8. KC-10 Observed Vs. Simulated Expediter's Utilization Rate, Transportation Hours, Waiting Rate, Idle Hours, & Distance Driven (In Miles) - During 24-Hours

Simulation Vehicle	Utilization Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)
Observed	43.8%	10.5	56.2%	13.5	158
Simulation	42.8%	10.3	57.2%	13.7	154



Figure 25. Aerial View of the KC-10 Simulation Workspace and the Expediter Vehicle Paths and Node Locations.

Simulation: Model of the Current C-17 Process

The three observed parameters from the ride-along, were the utilization rate, the idle rate, and the total distance driven. The researcher altered the locations of the servers until the simulation resulted in the approximate miles observed on the ride-along. The C-17 Expediter reported that the observed day was uncharacteristically 'slow' for what they normally accomplish. Therefore, the researcher increased the mileage by approximately 20%, for a simulated total mileage of 106 miles as seen in Table 9. The researcher also found that the most efficient way to get the model to best approximate the observed

utilization and idle rates, was though changing the load and unload times and server process times. The model came within 6% of the observed utilization and waiting rates. With the additional 20% of mileage, or 16 miles, traveled at 15 mph, that equates to an additional 1.1 hours transporting. In the simulation, the additional 16 miles resulted in an additional 0.8 hours of transporting. Therefore, this is confirmed as an accurate base model as seen in Figure 25.

Table 9. C-17 Observed Vs. Simulated Expediter's Utilization Rate, Transportation Hours, Waiting Rate, Idle Hours, & Distance Driven (In Miles) - During 24-Hours

Simulation Vehicle	Utilization Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)
Observed	35.0%	8.4	65.0%	15.6	90
Simulation	41.3%	9.9	58.7%	14.1	106.3



Figure 26. The C-17 Base Simulation Model

Simulation: Model of the KC-10 Expediter with One Rover

Having established a baseline model, as seen in Figure 26, that is representative of the current observed process, the simulation was used to do what simulations do best, try new processes. Initially, the paths to and from CTK and COMBS were replaced with a single rover to perform all the necessary deliveries of tools and parts to the *AvgAircraftLocation* parking spot. The Rover's route, as seen in Figure 27 below, connects COMBS and CTK with the *AvgAircraftLocation* by skirting the edge of the parking apron. This routing ensures separation with taxiing or parked aircraft, and other vehicles on the ramp. The Rovers are able to be programmed for a particular parking spot on a GPS defined path along the perimeter of the parking apron for delivery. The researcher assigned the one rover to the CTK, as seen in Figure 28, and used 'on demand' logic to call the rover to a location that needed a tool or part delivered as seen in Figure 29. The researcher defined the rate the tools or parts were produced at the COMBS, CTK, and the Aircraft locations.



Figure 27. 1-Rover's Route on the Edge of the Apron, To and From CTK, COMBS, and the Aircraft.



Figure 28. Rover Housed at CTK; Delivers Tools and Parts To and From the CTK, COMBS, and the Aircraft.

The process for a maintainer to acquire a part or tool is as follows. The maintainer at the aircraft places an order for a part or tool on their phone's app. When CTK or COMBS has the item ready, they place a demand call for the rover. The rover is called to that location, CTK or COMBS, whomever has the item ready first, the personnel load the item on the rover, and the rover delivers it to the maintainer at the aircraft, as seen in Figure 30. If the maintainer at the aircraft has a malfunctioning or failed part or damaged tool, they can place a call for the rover at the aircraft parking spot. This return route happens at a less frequent rate. Nevertheless, the rover travels to the aircraft parking spot, the maintainer loads the rover with the malfunctioning tool or part, and the rover delivers it to either CTK or COMBS per the order.

The simulation results with the rover are all predicated on the researcher's inserted parameters of rates of tools or parts. During the ride-along, there were 15 trips from the Aircraft to COMBS, or 1.364/hour, and 13 trips from COMBS to an Aircraft, or 1.182/hour. Additionally, there were 11 trips from an Aircraft to CTK, or 1/hour, and 14 from CTK to an Aircraft, 1.273/hour. If taking the average of the COMBS and the CTK

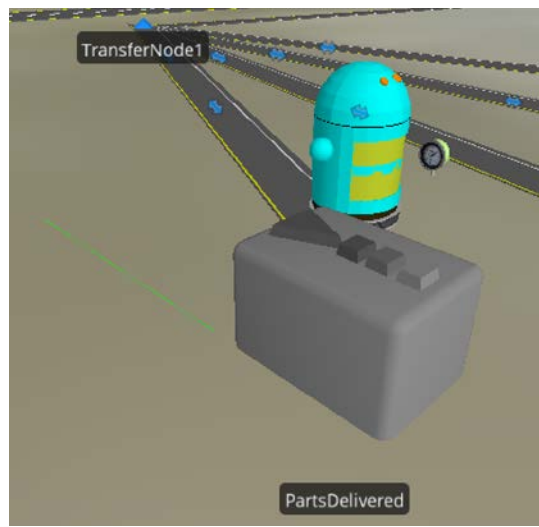


Figure 29. Rover Delivering an Aircraft Gauge from COMBS to the Aircraft.

rates, respectively, the final rate for the COMBS trips is 1.273/hour, and for CTK trips is 1.136/hour. Because the ride-along rate is in x trips/hour and the simulation's interarrival time is defined as the time until the next arrive, the inverse of the rates was taken, and the researcher set the average interarrival rate to .7855 hours until the next unit for COMBS and .8803 hours for CTK.

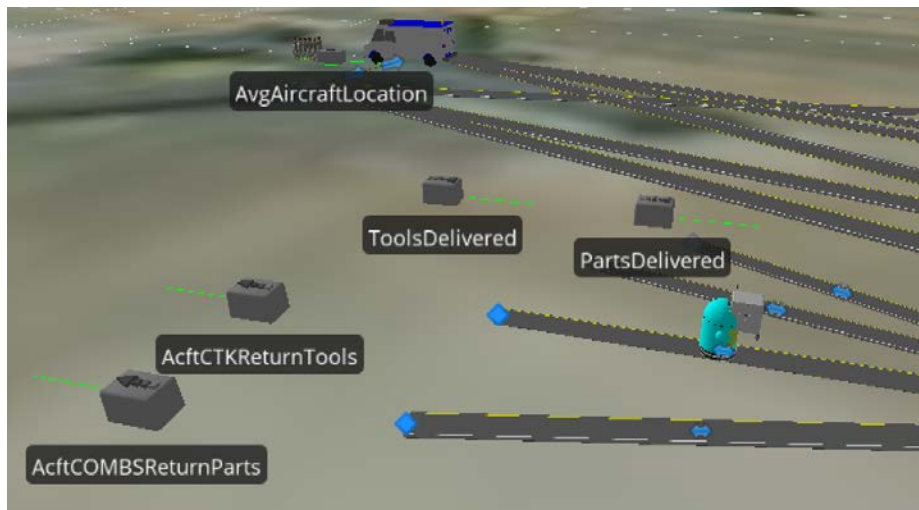


Figure 30. Rover Picking Up Tools From the Aircraft Location to Return to CTK, While the Expediter Vehicle is Dropping Maintainers Off At the AvgAircraftLocation Node in the Background. They Operate on Separate Network Paths on the Airfield.

The researcher defined the simulation rates by a random triangular distribution and subtracted or added .17 hours, or 10 minutes, either side of the average interarrival time for the minimum and maximum values, defining COMBS creation rates as a random triangular distribution (min, avg, max) of (.6155, .7855, .9555) and (.7103, .8803, 1.0503) for CTK. Additionally, the simulation needed a return rate of the rover picking up parts at the aircraft to return to COMBS, if the part was damaged or incorrect. The researcher set this rate as happening at a lower frequency or at a larger interarrival rate for the simulation definitions and added 2 hours to each interarrival rate for the return trip. As tools are not consumed in the maintenance process, the CTK return trips needed to equal the creation rates to ensure tool accountability. The simulation parameters were set as shown in Table 10 below.

Table 10. Ride-Along Observed Rates vs 1-Rover Simulation
Tool/Part Interarrival Creation and Return Rates

Routing	Ride-Along Rate	Simulation Interarrival Creation Rates	Simulation Interarrival Return Rates
Aircraft to COMBS	1.364/hour	Random.Triangular (.6155, .7855, .9555)	Random.Triangular (2.6155, 2.7855, 2.9555)
COMBS to Aircraft	1.182/hour		
Aircraft to CTK	1.000/hour	Random.Triangular (.7103, .8803, 1.0503)	Random.Triangular (.7103, .8803, 1.0503)
CTK to Aircraft	1.273/hour		

With the rate parameters set, the simulation produced the following numbers of each entity. In a 24-hour period, or during two shifts, 26 parts and 24 tools were taken to the aircraft, 7 parts were returned to COMBS, or a 27% return rate, and 23 of 24 tools were returned, a 96% return rate, to CTK as see in Table 11. The reason the return rate was not the required 100% for tool accountability was that the rover was unable to complete all the runs in the 24-hour period.

Table 11. 24-Hour Period in KC-10, 1-Rover Simulation:
Creation and Return Rates with Number of Parts and Tools Created and Returned

24-Hours	Simulation Interarrival Creation Rates	Number of Entities Created	Simulation Interarrival Return Rates	Number of Entities Returned
COMBS	Random.Triangular (.6155, .7855, .9555)	26 Parts	Random.Triangular (1.1155, 1.2855, 1.4555)	7 Parts (27%)
CTK	Random.Triangular (.7103, .8803, 1.0503)	24 Tools	Random.Triangular (.7103, .8803, 1.0503)	23 Tools (96%)

The above rates, and number of entities created, resulted in the rover's utilization to be 100% as seen in Table 12. However, the addition of the rover for the tool and parts runs slashed the Expediter's utilization 29.9% as seen in Table 13. The Expediter also drove 7.2 less hours and covered 107.4 fewer miles per 24 hour period. The throughput, or the number of times the vehicle moved an entity, was also cut 40.7% to a new total throughput of 210.

Table 12. KC-10 Simulation With 1-Rover:
Transporting vs. Waiting Rate, Hours, & Distances in 24-Hour Period

Simulation Vehicle	Utilization Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)	Throughput
Expediter	12.9%	3.1	87.1%	20.9	46.6	210
Rover - 1	100.0%	24.0	0.0%	0.0	85.3	80

Table 13. KC-10 Simulation Comparisons: Base vs. With 1-Rover:
Rates, Hours, & Distances in 24-Hour Period

Simulation Vehicle	Utilization Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)	Throughput
Expediter	42.8%	10.3	57.2%	13.7	154	354
Expediter with 1 Rover	12.9%	3.1	87.1%	20.9	46.6	210
Difference	29.9%	7.2	-30%	-7.2	107.4	144

Because rovers run on batteries, the rover would need an opportunity to recharge. A constantly running vehicle, like the rover with the 100% utilization rate, would have no time to sit and recharge its battery. The rover would need its battery replaced periodically when driving through the CTK to pick up or drop off a tool. The squadron would have to maintain several additional rover batteries to have on hand, charged and ready, for a quick pit stop swap out. The rover would also need time for maintenance, inspections, and repair. Although this model shows significant airfield transportation improvements, it is nevertheless impractical due to the limitations of the rover. Therefore, the researcher explored the following additional rover scenarios with two and three rovers on either a separate network configuration, with COMBS and CTK transporting only their own entities, or a shared network configuration, with a rover servicing either COMBS or CTK, on a first come, first serve basis.

Simulation: Model of the C-17 Expediter with One Rover

With the rate parameters set, as seen in Table 14, the simulation produced the following numbers of each entity. In a 24-hour period, 52 *ToolsBenchStock* were created and taken to the aircraft and 51 were returned to CTK, or a 98.1% return rate. The return rate was not the required 100% for tool accountability, because the rover was unable to complete its last return trip before the simulation time was complete.

Table 14. 24-Hour Period in C-17, 1-Rover Simulation:
Creation and Return Rates with Number of Parts and Tools Created and Returned

24- Hours	Simulation Interarrival Creation Rates	Number of Entities Created	Simulation Interarrival Return Rates	Number of Entities Returned
<i>ToolsBenchStock</i>	Random.Triangular (.3019, .5019, .6019)	52 Parts	Random.Triangular (.3019, .5019, .6019)	51 Parts (98.1%)

The rates, and the number of entities created, resulted in the rover’s utilization to be 46.9% as seen in Table 15. The Expediter’s utilization was 33.4%, or a 7.9% decrease, which equated to 1.9 hours saved, and 21.1 fewer miles driven, as seen in Table 16. The throughput was cut 17.6% to a new total of 280. The C-17 simulation view of the *Squadron* is seen in Figure 31.

Table 15 C-17 Simulation with 1-Rover:
Transporting vs. Waiting Rate, Hours, & Distances in 24-Hour Period

Simulation Vehicle	Utilization Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)	Throughput
Expediter	33.4%	8.0	66.6%	16.0	85.2	280.0
Rover - 1	46.9%	11.3	53.1%	12.7	31.3	103.0



Figure 31. C-17 Simulation: Multiple Sources, Servers, Sinks, Entities and Vehicles

Table 16. C-17 Simulation Comparison: Base vs. With 1-Rover Rates, Hours, & Distances in 24-Hour Period

Simulation Vehicle	Utilization Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)	Throughput
Expediter	41.3%	9.9	58.7%	14.1	106.3	340
Expediter with 1 Rover	33.4%	8.0	66.6%	16.0	85.2	280
Difference	7.9%	1.9	-7.9%	-1.9	21.1	60

Simulation: Model of the KC-10 Expediter with Two Rovers (Separate Networks)

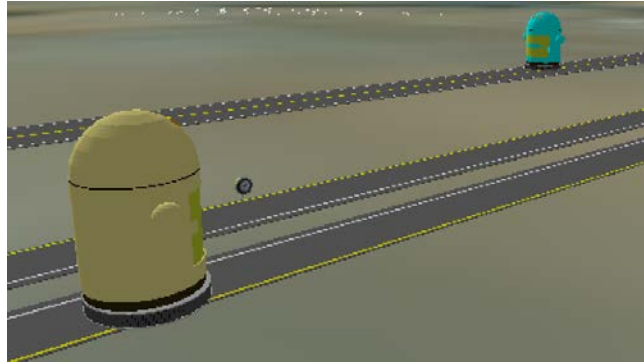


Figure 32. Yellow COMBS Rover Delivering an Aircraft Gauge Part to the Aircraft While Teal CTK Rover Travels Back to CTK to Pick Up a Requested Tool.

The researcher further altered the simulation to see the results if the model included two separate rovers, one rover for CTK and one rover for COMBS, to deliver and return their respective tools and parts, as seen in Figure 32. In this simulation design, each rover had its own bidirectional paths to deliver the respective tool or part as seen below in Figure 33. The 2-Rover simulation, with two separate rovers, maintained the rates from the 1-Rover simulation and the same number of tools and parts were created as in the 1-Rover simulation.

Table 17. KC-10 Simulation Results with 2-Rovers on Separate Paths: Transporting vs. Waiting Rate, Hours, & Distances in 24-Hour Period

Simulation Vehicle	Utilization Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)	Throughput
Expediter	12.9%	3.1	87.1%	20.9	46.6	210.0
CTK Rover	43.2%	10.4	56.8%	13.6	34.1	55.0
COMBS Rover	62.1%	14.9	37.9%	9.1	54.3	40.0

Having two rovers drops the utilization rate of each individual rover to 62.1% for the COMBS Parts Rover and 43.2% for the CTK Tools Rover, and distributes the hours

transporting to 14.9 hours for the COMBS Parts Rover and 10.4 hours for the CTK Rover. The COMBS Parts Rover also drives 54.3 miles/24-hour period, while the CTK Rover drives 34.1 miles. The Expediter has the same utilization rate, hours transporting, and distance driven as with the 1-Rover Simulation, because it is driving the same routes with the same number of entity workers. The results of the 2-Rover simulation in terms of transportation hours, rates, and distances are shown in Table 17.

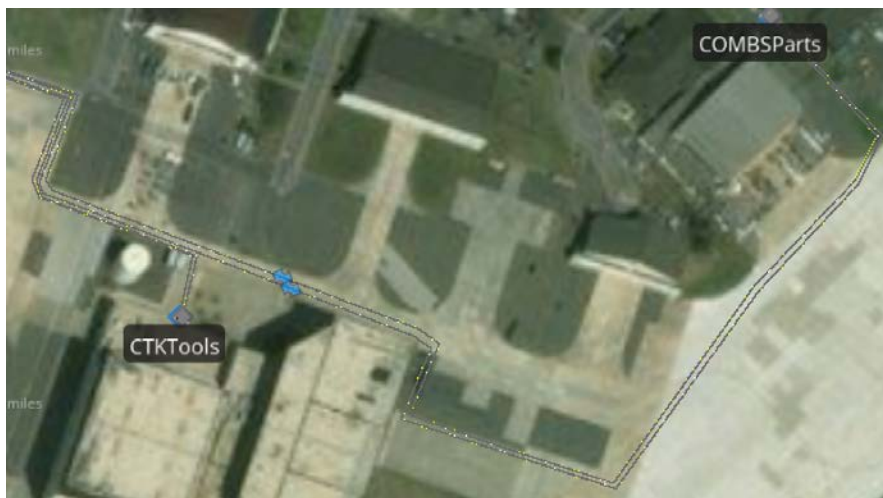


Figure 33. KC-10, 2-Rover Simulation:
Individual Bidirectional Paths for both CTK and COMBS Rovers.

Simulation: Model of the KC-10 Expediter with Two Rovers (Same Network)

The researcher further altered the simulation to observe the results if the model included two rovers that could service either CTK or COMBS and operated on one network of paths. In this simulation design, the network had unidirectional paths that either flowed towards the aircraft or back towards CTK or COMBS. The path would then branch at a transfer node to a bidirectional path leading to CTK or COMBS, as seen in

Figure 34 below. This design prevented a stoppage of rovers along any paths while transporting the tools and parts. The 2-Rover simulation, with two rovers on one network, maintained the rates of the 1-Rover simulation and the same number of tools and parts were delivered as in the 1-Rover simulation. Having two rovers on one network resulted in one rover having a 59.7% utilization and the other a 57.2%. That equated to 14.3 and 9.7 hours transporting respectively. The miles driven totaled 49 for the first rover and 46 for the second rover. The results of the 2-Rovers with the same network simulation in terms of transportation hours, rates, and distances are shown below in Table 18.

Table 18. KC-10 Simulation Results with 2-Rovers on Same Network: Transporting vs. Waiting Rate, Hours, & Distances in 24-Hour Period

Simulation Vehicle	Utilization Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)	Throughput
Expediter	12.9%	3.1	87.1%	20.9	46.6	210
Rover - 1	59.7%	14.3	40.3%	9.7	50.8	49
Rover - 2	57.2%	13.7	42.8%	10.3	48.8	46

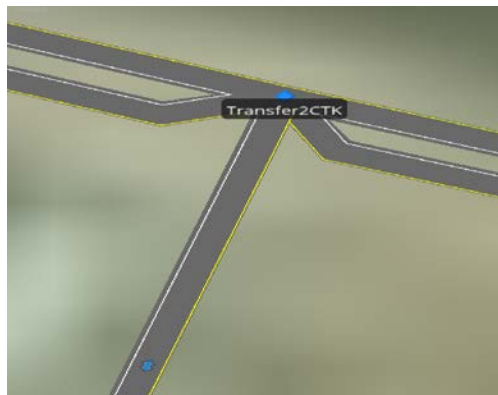


Figure 34. Unidirectional Paths Meet at Transfer Node for Bidirectional Path to CTK (and COMBS Not Shown).

Simulation: Model of the C-17 Expediter with Two Rovers (Same Network)

The researcher observed the results if the C-17 model included two rovers on the shared network. The 2-Rover simulation, with two rovers on one network, maintained the rates of the 1-Rover simulation, and the same number of tools and parts were delivered as in the 1-Rover simulation. Having two rovers on one network resulted in one rover having a 30.9% utilization and the other a 14.5%. That equated to 7.4 and 3.5 hours transporting respectively. The miles driven totaled 71 for the first rover and 32 for the second rover. The results of the 2-Rovers with the same network simulation in terms of transportation hours, rates, and distances are shown below in Table 19. With such low utilization rates, no further rovers were added to the C-17 model.

Table 19. C-17 Simulation Results with 2-Rovers on Same Network: Transporting vs. Waiting Rate, Hours, & Distances in 24-Hour Period

Simulation Vehicle	Utilization Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)	Throughput
Expediter	33.4%	8.0	66.6%	16.0	85.2	280.0
Rover - 1	30.9%	7.4	69.1%	16.6	20.2	71.0
Rover - 2	14.5%	3.5	85.5%	20.5	9.7	32.0

Simulation: Model of the KC-10 Expediter with Three Rovers (Same Network)

Next, a third rover was added to the model with the same network of paths so that any rover could service any demand for tool or part movement. This network had the same unidirectional paths that either flowed towards the aircraft or back towards CTK or COMBS with the path branching at transfer nodes to a bidirectional path leading to CTK or COMBS. This design is critical with the additional rover and increased congestion on the paths, and it prevented the rovers from creating blockages along any of the paths. The

3-Rover simulation, with three rovers on one network, maintained the rates of the 1-Rover simulation and the same number of tools and parts were created as in the 1-Rover simulation. Having three rovers on one network resulted in their utilization rates as 1. 43.2%, 2. 41.1%, and 3. 22.7%. That equated to 10.4, 9.9, and 5.4 hours transporting, respectively. The miles driven totaled 34 for the first rover, 41 miles for the second, and 20 miles for the third. The results of the 3-Rovers with the same network simulation in terms of transportation hours, rates, and distances are shown below in Table 20.

Table 20. Results of Simulation with 2-Rovers on One Network: Transporting vs. Waiting Rate, Hours, & Distances in 24-Hour Period

Simulation Vehicle	Utilization Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)	Throughput
Expediter	12.9%	3.1	87.1%	20.9	46.6	210
Rover - 1	43.2%	10.4	56.8%	13.6	36.9	34
Rover - 2	41.1%	9.9	58.9%	14.1	34.0	41
Rover - 3	22.7%	5.4	77.3%	18.6	19.1	20

Simulation: Model of the KC-10 Expediter with Three Rovers (Separate Networks)

Finally, a third rover was added to the model with the two separate networks, one for CTK specifically, and one for COMBS specifically. The first simulation modeled 2 COMBS rovers and 1 CTK rover, and the second simulation modeled 2 CTK rovers with 1 COMBS rover. This 3-Rover simulation, maintained the rates from the 1-Rover simulation and the same number of tools and parts were created as in the 1-Rover simulation. Having three rovers on one network resulted in the rates displayed in Table 21, where the 2 COMBS with the 1 CTK rover allowed the most even split in utilization of 43.3% and 17.8% for the COMBS rovers and 43.2% for the CTK rover and equated to

10.4, 10.4, and 4.3 hours transporting, respectively. The miles driven totaled 55, 25, and 15 miles for the CTK and two COMBS rovers. The complete results of the 3-Rovers with separate networks in terms of transportation hours, rates, and distances are shown below in Table 21.

Table 21. Results of Simulation with 3-Rovers on Separate Networks: Transporting vs. Waiting Rate, Hours, & Distances in 24-Hour Period

Simulation Vehicle	Utilization Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)	Throughput
Expediter	12.9%	3.1	87.1%	20.9	46.6	210
CTK Rover - 1	41.6%	10.0	58.4%	14.0	32.9	53
CTK Rover - 2	1.6%	0.4	98.4%	23.6	1.2	2
COMBS Rover	62.1%	14.9	37.9%	9.1	54.3	40
Expediter	12.9%	3.1	87.1%	20.9	46.6	210
CTK Rover	43.2%	10.4	56.8%	13.6	34.1	55
COMBS Rover - 1	43.3%	10.4	56.7%	13.6	38.3	25
COMBS Rover - 2	17.8%	4.3	82.2%	19.7	15.1	15

Simulations: Compiled KC-10 Simulation Results with Various Network Designs

The compiled KC-10 Simulation Results with the various network designs and number of rovers is illustrated below in Table 22. The throughput column is included to show the number of items each vehicle moves, or represents each time a vehicle or rover moves an entity, i.e. the expediter can have a maximum of 6 in throughput on one departure to destination path, because that is the vehicle’s capacity.

Table 22. Results of All KC-10 Simulations on Various Network Configurations: Transporting Utilization Rate, Hours, Distances, and Throughput in 24-Hour Period

Network Structure	Simulation Vehicle	Ute Rate	Hours Trans	Wait Rate	Hours Idle	Total Distance (miles)	Thru
Simulation	Expediter	42.8%	10.3	57.2%	13.7	154.0	354
Simulation, 1-Rover	Expediter	12.9%	3.1	87.1%	20.9	46.6	210
	Rover - 1	100%	24.0	0.0%	0.0	85.3	80
Simulation, 2-Rovers Same Network	Expediter	12.9%	3.1	87.1%	20.9	46.6	210
	Rover - 1	59.7%	14.3	40.3%	9.7	50.8	49
	Rover - 2	57.2%	13.7	42.8%	10.3	48.8	46
Simulation, 3-Rovers Same Network	Expediter	12.9%	3.1	87.1%	20.9	46.6	210
	Rover - 1	43.2%	10.4	56.8%	13.6	36.9	34
	Rover - 2	41.1%	9.9	58.9%	14.1	34.0	41
	Rover - 3	22.7%	5.4	77.3%	18.6	19.1	20
Simulation, 2-Rovers Separate Network	Expediter	12.9%	3.1	87.1%	20.9	46.6	210
	CTK Rover	43.2%	10.4	56.8%	13.6	34.1	55
	COMBS Rover	62.1%	14.9	37.9%	9.1	54.3	40
Simulation, 3-Rovers Separate Network	Expediter	12.9%	3.1	87.1%	20.9	46.6	210
	CTK Rover - 1	41.6%	10.0	58.4%	14.0	32.9	53
	CTK Rover - 2	1.6%	0.4	98.4%	23.6	1.2	2
	COMBS Rover	62.1%	14.9	37.9%	9.1	54.3	40
Simulation, 3-Rovers Separate Network	Expediter	12.9%	3.1	87.1%	20.9	46.6	210
	CTK Rover	43.2%	10.4	56.8%	13.6	34.1	55
	COMBS Rover - 1	43.3%	10.4	56.7%	13.6	38.3	25
	COMBS Rover - 2	17.8%	4.3	82.2%	19.7	15.1	15

Simulations: Compiled C-17 Simulation Results with Various Network Designs

The compiled C-17 Simulation Results with the various numbers of rovers on the same network is illustrated below in Table 23.

Table 23. Results of All C-17 Simulations on Various Network Configurations: Transporting Utilization Rate, Hours, Distances, and Throughput in 24-Hour Period

Network Structure	Simulation Vehicle	Ute Rate	Hours Trans	Waiting Rate	Hours Idle	Total Distance (miles)	Thru
Simulation	Expediter	41.3%	9.9	58.7%	14.1	106.3	340
Simulation, 1-Rover	Expediter	33.4%	8.0	66.6%	16.0	85.2	280
	Rover - 1	46.9%	11.3	53.1%	12.7	31.3	103
Simulation, 2-Rovers	Expediter	33.4%	8.0	66.6%	16.0	85.2	280
	Rover - 1	30.9%	7.4	69.1%	16.6	20.2	71
	Rover - 2	14.5%	3.5	85.5%	20.5	9.7	32

Number of Rovers and Network Design on Wait Times

In Tables 24 and 25, the wait time the maintainer experiences for a particular tool or part item is compared to the network design and number of rovers operating. The charts are colored in shades of red; the darker the cell, the larger the number and thus the longer the wait or the higher the utilization rate. The lighter the cell, the smaller the wait or the lower the utilization rate. The tables become increasingly lighter as the additional rovers are added to the network. There are some instances when the wait or utilization is so low there is not color in the cell. For example, the KC-10 three rovers, on a separate network with two CTK rovers, has just a 1.6% utilization.

There are three average columns to explore the time; the minimum time, the average time, and the maximum time the item was in the system displayed in minutes.

For example, the ‘part’ being called for pickup at COMBS and the ‘part return’ call is from the aircraft back to COMBS. For the C-17s, the times averaged from 6 minutes to 16.5 minutes to get a tool or bench stock part delivered to the aircraft, and 6.6 minutes to 17.1 minutes waiting for the rover to pick up the item for return in the one rover configuration. The waiting times dropped to a maximum of 10.5 minutes for either wait if there were two rovers. Therefore, a 61.4% decrease in wait time with the additional rover for the C-17s. For the KC-10s, the times had an average range from 21 minutes to over 4 hours in the overtasked 1-rover model. The wait times were significantly decreased with the additional rovers. The configuration that kept the maintainer waiting the least was the 3-rovers, separate network with 1 CTK and 2 COMBS rovers. The waits ranged from 11.3 minutes to 28.7 minutes in that network configuration. The decision to incorporate an additional rover is based on costs, perceived advantages of lower waits, and utilizations rates that allow rover battery charging, maintenance, inspections, and repairs.

Table 24. C-17’s Average Time In Minimum, Average, & Maximum Minutes Waiting For Tools Or Parts From CTK & for the Rover To Return the Item.

Network Structure	Simulation Vehicle	Ute Rate	Min	Type of Entity	Avg	Type of Entity	Max	Type of Entity
Simulation, 1-Rover	Rover - 1	46.9%	6.0	CTK	6.9	CTK	16.5	CTK
			6.6	Return	8.4	Return	17.1	Return
Simulation, 2-Rovers	Rover - 1	30.9%	6.0	CTK	6.1	CTK	10.5	CTK
	Rover - 2	14.5%	6.6	Return	6.6	Return	10.5	Return

Table 25. KC-10's Average Time In Minimum, Average, & Maximum Minutes Waiting For Tools Or Parts From CTK/COMS & for the Rover To Return the Item.

Network Structure	Sim Vehicle	Ute Rate	Min	Type of Entity	Avg	Type of Entity	Max	Type of Entity
Simulation, 1-Rover	Rover - 1	100.0%	21.0	Parts	136.7	Parts	240.9	Parts
			42.1	P-Return	128.4	P-Return	211.3	P-Return
			41.6	Tools	140.0	Tools	241.7	Tools
			29.0	T-Return	134.7	T-Return	242.2	T-Return
Simulation, 2-Rovers Same Network	Rover - 1	59.7%	15.6	Parts	23.2	Parts	29.3	Parts
	Rover - 1		15.7	P-Return	15.7	P-Return	15.7	P-Return
	Rover - 2	57.2%	11.3	Tools	13.4	Tools	20.7	Tools
			11.4	T-Return	11.4	T-Return	11.4	T-Return
Simulation, 3-Rovers Same Network	Rover - 1	43.2%	15.6	Parts	23.2	Parts	29.3	Parts
	Rover - 2	41.1%	15.7	P-Return	15.7	P-Return	15.7	P-Return
	Rover - 3	22.7%	11.3	Tools	13.4	Tools	20.7	Tools
			11.4	T-Return	11.4	T-Return	11.4	T-Return
Simulation, 2-Rovers Separate Network	CTK Rover	43.2%	15.4	Parts	25.5	Parts	29.4	Parts
			15.3	P-Return	21.5	P-Return	43.8	P-Return
	COMBS Rover	62.1%	11.3	Tools	11.4	Tools	15.2	Tools
			11.3	T-Return	11.3	T-Return	11.3	T-Return
Simulation, 3-Rovers Separate Network	CTK Rover - 1	41.6%	15.4	Parts	25.5	Parts	29.4	Parts
	CTK Rover - 2	1.6%	15.3	P-Return	21.5	P-Return	43.8	P-Return
	COMBS Rover	62.1%	11.3	Tools	11.3	Tools	11.3	Tools
			11.3	T-Return	11.3	T-Return	11.3	T-Return
Simulation, 3-Rovers Separate Network	CTK Rover - 1	43.2%	15.4	Parts	24.0	Parts	28.7	Parts
			15.3	P-Return	15.3	P-Return	15.3	P-Return
	COMBS Rover - 2	17.8%	11.3	Tools	11.4	Tools	15.2	Tools
			11.3	T-Return	11.3	T-Return	11.3	T-Return

Costs and Cost Savings

There are several costs associated with the expediter. One cost is the expediter's time, and the other cost is the vehicle's operating expenses. There is a decrease, in both the expediter's hours transporting and the total distance driven by the vehicle, whether the system is augmented by 1 or 3 rovers. Looking at the operator costs, the Expediter is currently transporting 10.3 hours (KC-10) and 9.9 hours (C-17), but if augmented by a rover, the hours are decreased to 3.1 hours (KC-10) and 8 hours (C-17) in a 24-hour period, a total savings of 7.2 hours (KC-10) and 1.9 hours (C-17) as seen in Table 26.

Table 26. KC-10 and C-17 Hours Saved With Rover Augmentation

Simulation Vehicle	Utilization Rate	Hours Trans	Total Distance (miles)
KC-10 Expediter	42.8%	10.3	154
Expediter with 1 Rover	12.9%	3.1	46.6
Difference	29.9%	7.2	107.4
C-17 Expediter	41.3%	9.9	106.3
Expediter with 1 Rover	33.4%	8.0	85.2
Difference	7.9%	1.9	21.1

A search of [payscale.com](https://www.payscale.com) shows an average hourly rate for a USAF aircraft mechanic is \$16-39, with the average of \$25.45 (PayScale, 2020). With 7.2 and 1.9 hours saved, at the average mechanic rate, \$66,882.60 (KC-10) and \$17,649.58 (C-17) is saved each year, as seen in Figure 27. Looking at the vehicle costs, the expediter vehicle is driven 154 miles currently, and if one rover is added to the process, the miles driven decreases to 46.6 miles (KC-10) and 85.2 miles (C-17) per 24-hours. A vehicle cost

calculator estimates a cargo van, like one driven by the Expediter, gets on average 12 mpg at an average of \$2/gallon (Reliable Runners, 2020). The calculator also adds oil required for weekly mileage, normal maintenance (1%) and exterior maintenance (.13%). In the original simulation, the Expediter drove 1,078 miles (KC-10) and 744.1 miles (C-17) per week. This equates to \$179.67 (KC-10) and \$124.02 (C-17) per week in vehicle operating costs. With a rover, the expediter van mileage is decreased to 326.2 miles (KC-10) and 596.4 miles (C-17) per week at a lower cost of \$54.37 (KC-10) and \$99.40 (C-17). The savings in vehicle operating costs is \$125.30/week or \$6,515.60/year (KC-10) and \$24.62/week or \$1,280.24/year (C-17) as seen in Table 28. The personnel and vehicle savings together equals an annual savings of \$73,398.20 (KC-10) or \$18,929.82 (C-17) as seen in Table 29.

Table 27. Personnel Cost Savings/Year

Total Saved in Personnel Costs (Avg Aircraft Mechanic)	KC-10	C-17
Hourly Wage	\$ 25.45	\$ 25.45
Saved/day with Rover	\$ 183.24	\$ 48.36
Saved/year	\$ 66,882.60	\$ 17,649.58

Table 28. Vehicle Cost Savings/Year

Expediter	Weekly Mileage	Weekly Costs	Vehicle Savings/Week	Vehicle Savings/Year
KC-10	1,078	\$ 179.67	\$ 125.30	\$ 6,515.60
KC-10 With Rover	326	\$ 54.37		
C-17	744	\$ 124.02	\$ 24.62	\$ 1,280.24
C-17 With Rover	596	\$ 99.40		

Table 29. Total Personnel and Vehicle Cost Savings/Year

	KC-10	C-17
Total Saved/Year	\$73,398.20	\$18,929.82

The Maren-go, autonomous rover company, provided a quote for their Airfield Autonomous Rover, and between the software and hardware, the total cost for one rover is \$152,330, as seen in Table 30. If purchased, a rover of that cost, would be paid for in the savings of the Expediter operator and vehicle in just over two years (KC-10) and just over 8 years (C-17), as seen in Table 31. If two, or three rovers were purchased, the Return on Investments is listed in Table 31.

Table 30. Maren-Go Airfield Autonomous Rover Costs

Category	Item	Final pricing
Hardware	Modified Swincar	\$66,000.00
	Communication package	\$6,000.00
	Collision avoidance package	\$18,000.00
	C2 equipment	\$5,750.00
Software	Resupply software/Material Management	\$22,080.00
	Annual SW License (per user role)	\$1,380.00
	Specific navigation rules	\$7,360.00
	Insight AI	\$14,720.00
	IT integration	\$11,040.00
Total:		\$152,330.00

Table 31. Return on Investment (ROI)

ROI	KC-10	C-17
1-Rover	2.08 years	8.05 years
2-Rovers	4.15 years	16.09 years
3-Rovers	6.23 years	24.14 years

V. Conclusions and Recommendations

Summary of Findings

This study of utilizing rovers for autonomous delivery of tools and parts on the flight line is a unique application for autonomous vehicle usage in military logistics. Several studies reveal theories and applications for the use of autonomous systems in combat environments, but none exist, until now, for non-combat, flight line logistical utilization. Some studies include one Army report, which investigated autonomous resupply convoys, and two Navy theses which explored unmanned resupply aircraft for the Marines. Abbreviated findings from these studies, mentioned previously in Chapter II, included: automated vehicles provided reliable 24/7 re-supply in combat scenarios (Henry, 2018), and unmanned helicopters replaced dangerous manned convoy routes through enemy held territory (Peterson & Staley, 2011). Currently, UAVs fill surveillance and targeting roles, but there are numerous advantages of using UAVs for logistics (Denevan, 2014). This study expands the uses of autonomous systems, to the advantage of military personnel, with the integration of autonomous rovers on the flight line to facilitate the delivery of tools and parts for aircraft service and repair.

The United States of America's military has approximately 13,000 aircraft, as seen in Figure 35, and they all require maintenance. The scope of this research reaches beyond Air Mobility Command and beyond the USAF. It can potentially streamline maintenance operations for every one of the 13,000 military aircraft across the Department of Defense. As the 2018 Summary of the National Defense Strategy warns, we are currently living in a more complex and volatile global security environment than we ever have (M Mattis, 2018). China, Russia, North Korea, Iran, and non-state terrorist

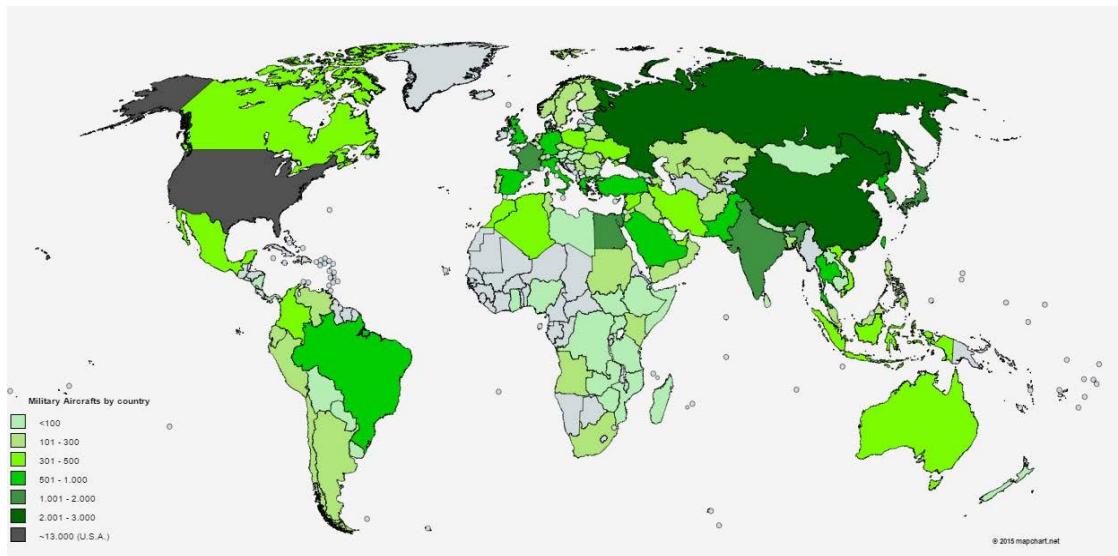


Figure 35. Global Map of Military Aircraft By Country: USA 13,000 (Bender, 2015)

groups are all named as threatening peace and security (M Mattis, 2018). The U.S. military aircraft are not operating at 100% mission capable rates. In the USAF, overall fleet wide readiness was 70.27% in fiscal year 2019, with the average grey-tail mobility aircraft mission capable rate at 71.75% (Everstine, 2020). Streamlining the process to inspect and repair the aircraft is critical, because there is currently a shortage of trained and qualified maintainers. The USAF maintainer staffing is currently undermanned with an overall loss

of 10% per year; a loss of 12% of personnel trained to a 5-level, and 10% loss of personnel trained to a 7-level (Losey S. , 2019). The USAF is losing those most experienced personnel at higher rates, and the United States does not have the leisure to be complacent (Mattis, 2018). Requiring highly trained personnel to ferry individuals around the flight line to get tools and parts is a non-value added task. It is time to adopt the right technologies for the right jobs. It is time to capitalize on autonomous capabilities to fill the tasks they are capable of performing, like ferrying tools and parts. It is time to release our highly trained personnel to do the job they are trained to do, to fix the USAF's aircraft, and to ensure U.S. security.

Conclusions and Significance of Results

Mileage Reduced

From the observation ride-along, the annual mileage driven by each aircraft's expediter was calculated. Figure 36 shows the annual mileage driven by the KC-10 expediter vehicle, 57,670 miles, the C-17 expediter vehicle, 32,850 miles, and the average American citizen, 13,476 miles, as reported by the U.S. Department of Transportation's Federal Highway Administration (FHWA, 2018). When compared with the average annual miles driven by an American, the expediter vehicle is driven almost four times as many miles. Although not an apples-to-apples comparison, as the expediter vehicle is operated by two to three different people in a 24 hour period; nevertheless, it highlights the sheer number of short, repetitive trips that must be made in a small area. In fact, the area of operations for the KC-10 expediter is a 1.5 square mile area, and for the C-17 expediter, it is within 0.375 square miles. This is in comparison to the 8,729 square

miles within the state of NJ. Then again, the consolidated areas of operation are an ideal environment for incorporating autonomous rovers to fulfill the short, repetitive trips back and forth for tools and parts.

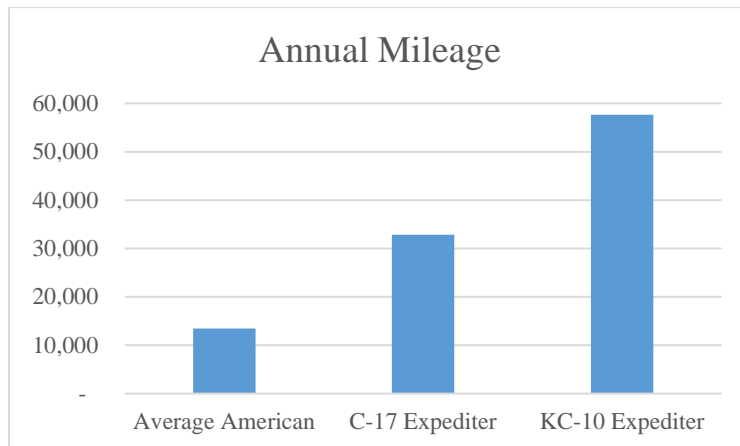


Figure 36. Comparison of Annual Mileage Driven

Autonomous vehicles are a solution to aid undermanned maintainers and to increase aircraft availability and mission capable rates (Saunders, 2015). Industry partners across the U.S. have incorporated the use of autonomous systems to streamline processes like transporting packages, meals, and groceries, and tackle the time-intensive ‘last mile’ of delivery (Glaser, 2017). These rovers navigate sidewalks and walking paths on college campuses such as George Mason University, Northern Arizona University, University of Pittsburgh, and Purdue University (Hawkins, 2019). The rovers can scale curbs to deliver payloads weighing up to 20 pounds (Hawkins, 2019). Given the shortage of maintenance personnel, rovers on the flight line would reduce the time the maintainers are waiting for tools and parts, or for themselves to be transported to or from the aircraft. In the simulation of the current expediter-only model, the expediter is spending 64.3% of the shift transporting maintainers. When a rover is added to the model, as seen in Table

32, to replace the trips to get tools and parts, not only does it reduce the expediter's throughput by 40.7% (KC-10) and 17.6% (C-17), but the time driving is reduced by 7.2 hours (KC-10) and 1.9 hours (C-17), and the miles driven is reduced 69.7% (KC-10) and 19.8% (C-17).

Table 32. Change In Expediter's Utilization With Rover In Model

Simulation Vehicle	Utilization Rate	Hours Trans	Total Distance (miles)	Throughput
KC-10 Expediter	42.8%	10.3	154	354
Expediter with 1 Rover	12.9%	3.1	46.6	210
Difference	29.9%	7.2	107.4	144
C-17 Expediter	41.3%	9.9	106.3	340
Expediter with 1 Rover	33.4%	8.0	85.2	280
Difference	7.9%	1.9	21.1	60

Time Gained

The expediter gains 7.2 hours (KC-10) and 1.9 hours (C-17) of value added time, to be used for other productive tasks, in the models with the rover. While there is a cost savings from the reduced time driving, the expediter's cost savings may be moot; the expediter would still presumably be on-shift for that duration. However, those extra hours could be consumed in productive work, or it could translate to more idle time and lower productivity. The following will explain why the additional time will translate to higher productivity. Of note, the KC-10 expediter was the rank of MSgt, 75% of the way through a 20-year career and the C-17 expediter was a senior TSgt, 70% through his career. The expediter is an important position, the director for all the repairs of the fleet. As he drives the maintainers around the flight line, he talks to the maintainers and is

updated on the repair status of the aircraft, the required parts, or any issues that arise, including personnel issues like managing appointments or illnesses. This MSgt or senior TSgt has accumulated, on average, 15 years of training, experience, and knowledge about the Maintenance Career Field and USAF; and yet, is spending 42.8% (KC-10) or 41.3% (C-17) of his shift performing ferrying tasks. The ferrying work is both important and necessary, but hardly commensurate with his attained skill level. If the ferrying of the tools and parts, could be performed by technology, like a rover, the expediter could contribute more value added time to the process. With those 7.2 and 1.9 hours each day, the expediter could interact more with the personnel as they perform maintenance and better oversee the training of the next generation of maintainers. More time focused on resolving maintenance issues could prompt the mission capable rates to move in a positive direction.

How Many Rovers?

If one rover is added to the maintenance process with the above mentioned value added benefits, the question becomes how many rovers, and in what network configuration, are the most advantageous for the process.

Because rovers, with the current technologies, run on batteries, the rovers would need an opportunity to recharge their batteries. In the 1-rover simulation for the KC-10s, the rover runs constantly with a 100% utilization rate. In such a situation, the rover would have no time to dock and recharge its battery. A rover would also not be able to continue transporting for the entirety of its 100% charge. For example, Maren-go, reports their rover needs to be re-charged when the battery reaches 20% battery life remaining. Then there is an associated battery charging rate and whether the entire rover needs to wait

while the battery recharges, or if there is a removable battery. An option would be to ensure CTK or COMBs maintain extra batteries in a fully charged or actively charging docking station. The personnel loading the rover with tools or parts would need to ensure the batteries are replaced periodically when driving through the CTK or COMBs for a quick swap out. Additionally, the rover would need time for maintenance, inspections, and repairs. Thus, having only 1-rover is impractical for the KC-10.

The C-17s showed one rover as a more practical option for their transportation needs. The rover's utilization was 46.9% and the expediter's was 33.4%. This configuration caused the maintainer to wait a maximum of 17.1 minutes. When adding two rovers, the utilization of the rover drops to 30.9% and 14.5% and the maximum wait is only reduced by 6.6 minutes to 10.5 minutes. The additional 6.6 minutes is not worth the cost of the second rover; thus the C-17s would most benefit from one additional rover.

When adding two rovers to the KC-10s, whether on a separate or same network configuration, their utilization rate drops and becomes more evenly split. The two rovers on the same network is the most even split in utilization with 59.7% and 57.2% for the two rovers utilization. This model allows the rovers to have periodic times to recharge batteries and have minor repairs or inspections completed. However, there is little to no room for a complete removal from the system for major maintenance or repair. Therefore, the most robust system would include three rovers.

When adding the third rover, the network configuration greatly influences the utilization rates. There are two models that would allow for an almost complete removal of a rover from the system, because both report their utilization rate below 18%. This

occurs in the three rovers on the separate networks. On the same network, three rovers have the following utilization rates, 43.2%, 41.1%, and 22.7%. The three rovers on the same network would create the most redundant and flexible system. Because the rover removed is not specific to COMBS or CTK, it becomes available for maintenance or inspections, while leaving two rovers to continue their scheduled deliveries of either tools or parts. The system easily flexes to a 2-rover, same network configuration. Also when the three rovers are maintained by one entity, CTK in this model, there is centralized command and control (C2) for the technology.

Finally, the researcher explores the efficiency of the three rovers in the same network configuration as compared to the other configurations. When looking at Table 33, the 3 rovers on the same network deliver the item just 0.6 minutes slower than the 3 rovers on the separate network, 2 COMBS and 1 CTK. This is a negligible delay for the added benefits of the centralized C2, redundancy, flexibility, heightened efficiency and shortest wait times. The researcher recommends the 3 rovers on a same network configuration for the KC-10s.

Table 33. KC-10 2-Rover & 3-Rover (Same Network) Vs. Separate

Network Structure	Simulation Vehicle	Ute Rate	Hours Trans	Total Distance (miles)	Throughput
2 Rovers, Same Network	Rover (1)	59.7%	14.3	50.8	49
	Rover (2)	57.2%	13.7	48.8	46
3 Rovers, Same Network	Rover (1)	43.2%	10.4	36.9	34
	Rover (2)	41.1%	9.9	34.0	41
	Rover (3)	22.7%	5.4	19.1	20
3 Rovers, Separate Networks: 2 COMBS/1 CTK	COMBS Rover (1)	43.3%	10.4	34.1	55
	COMBS Rover (2)	17.8%	10.4	38.3	25
	CTK Rover	43.2%	4.3	15.1	15

Table 34. Lowest Wait Times For Maintainers

Network Structure	Simulation Vehicle	Utilization Rate	Max Min Time in System (Min)	Max Avg Time in System (Min)	Max Time in System (Min)
3 Rovers, Same Network	Rover (1)	43.2%	15.7	23.2	29.3
	Rover (2)	41.1%			
	Rover (3)	22.7%			

Recommendations for Future Research

The researcher observed the maintainers' process through the eyes of an expediter and focused solely on the transportation aspect of the tools and parts process. When the one-time cost for the rover is \$152,330, if the annual cost savings is the sum of the personnel savings and the vehicular savings, a total of \$66,882.60 (KC-10) and \$17,649.58 (C-17), the return of investment is 2.07 years/rover (KC-10) and 8.05 years/rover (C-17). While there are cost savings in man-hours and expediter vehicle costs, the biggest multiplier of impact is on the actual maintainers' time.

An area for future research would be capturing the process through the lens of a maintainer. If a maintainer can order a part on an app, there is not the accumulated wait time of calling the expediter, driving to COMBS, waiting to get the part issued, calling the expediter, driving back to the aircraft, and having the other maintainers waiting at the aircraft for the one part. The additional people waiting for the one runner who went on the errand serves as a steep multiplier for the wait time, and could serve as a greater impetus for incorporating the rovers.

Additional questions include what is the distance the rovers can drive with what weight or in what environmental conditions limit or prevent their use, or their maintenance costs. These are all other areas for future exploration. Most importantly, is how this model addresses tools or parts too big or too heavy for the rover to transport. Autonomous rover technologies are continuing to evolve and improve. The payloads and capabilities of the rovers today, will pale in comparison to those of tomorrow. In the intermediate timeframe, the expediter would continue to make those few transportation runs for the oversized items, and future researchers can explore additional solutions. Finally, this research stops at a simulation. Future research can further study the research of employing actual rovers in a proof-of-concept trial.

There are two types of process improvement projects (Renata, 2018). One type of project includes Kaizen, Total Productive Maintenance (TPM), Lean, and Six Sigma (using DMAIC or Define, Measure, Analyze, Improve, Control process) (Renata, 2018). These are types of projects mentioned in the recommendations for intermediate action that can be implemented at a squadron level. It is a type of improvement that is implemented by the employees themselves by incorporating incremental innovations

(Renata, 2018). A second type of project incorporates Design for Six Sigma (DFSS) methodology and requires an involved, upper-management to provide critical support, supervision, structure and communication (Renata, 2018). This support would come from higher than a squadron level. The higher level would be required to ensure the goals of the base agencies are aligned and the benefits to the maintainers and the AF's aircraft are not lost sight of in the churn of a change and a new process.

Recommendations for Intermediate Action

Listed here are several immediate improvement actions that the researcher recommends. The incoming shift is comprised of 35 people arriving at the same time for a roll-call briefing at the squadron, before being given their daily assignments. Staggering arrival times, even by 30 minutes, would reduce the bottleneck at the beginning of the shift, while still allowing leadership eyes-on time with all personnel. There could also be a pre-recorded morning briefing, which is viewed by all personnel coming on shift. Adding additional vehicles aids the initial dispersal of the personnel from the squadron to the aircraft as well. The squadrons, currently, do implement an additional driver, but not every maintainer is flight line driver qualified. Often, the expeditors do not have excess personnel to even assign as an additional driver. Additional to the trained and qualified back-up driver, an extra vehicle needs to be present. Due to the number of miles driven, the vehicles frequently require maintenance themselves and are unavailable. Finally, the squadrons could consolidate their supply chain and relocate the supplies and tools to a centralized location, closer to the aircraft. The C-17 squadron models this technique because their bench stock parts were kept at their CTK. Conversely, the KC-10s kept

their bench stock with their other parts at COMBS, 0.4 miles away from their CTK. To further complicate the supply chain, COMBS also maintained 'calibrated' tools. Some maintainers would request expediter transport to CTK to find that the tool they were looking for was not a regular tool, but a calibrated tool, and had additional time spent being further transported to COMBS.

When the recommendation for the three rovers on a same network configuration is realized, implementation should be a graduated implementation approach. The researcher recommends choosing a single squadron unit, at an airfield where construction is not planned in the area of operations, and implementing the project in the early spring to avoid complications from environmental factors. The recommendation is for a moveable path, not a fixed route like a train rail, to allow for greatest flexibility around airfield construction projects, new or dynamic parking spots, and for use in undefined contested environments. The maintainers should be readily involved in the implantation of the rovers and routinely asked for feedback as to their positive or negative interactions with the technology. Once the rover concept is proven in a small-scale level, lessons learned can be incorporated to then take the technology fleet-wide, across AMC, into combat areas, and across the Department of Defense.

Final Thoughts

The AF faces a severe maintainer shortage and a mission capable fleet-wide average rate of 70%. There is a shortage of expediter vehicles, and the high mileage driven with the vehicles requires their constant removal for repairs. The simulations demonstrated the constraint of the expediter and van for the tool and parts deliveries. As

the USAF's fleet ages, the aircraft will need increasing amounts of repair, and the need to remove the constraints in the maintenance process is of increasingly concern. The researcher demonstrated the differences in efficiency between the current maintainer tools and parts transport process to one with a combination of an expediter augmented with autonomous delivery rovers. The KC-10's expediter saw a 29.9% reduction in utilization, gained 7.2 hours, and drove 107.4 miles less each 24-hours. The C-17's expediter saw a 7.9% reduction in transportation, gained 1.9 hours, and drove 21.1 miles less each day. The simulations demonstrated how rovers, as an emerging technology, can address the flight line constraint, and augment the expediter to significantly reduce time and transportation costs. In the intermediate, tools and parts need to be located as close to the aircraft parking as possible, with bench stock parts and all tools co-located to best streamline the process. Once the rover delivery is successfully demonstrated in a proof-of-concept, the technology can be incorporated fleet-wide and has potential valuable impact across the Department of Defense.

Appendix 1. Storyboard



Simulations at JBMDL found annual savings: 2,628 hours/89,201 miles for the KC-10 expeditor and 694 hours/7,702 miles for the C-17 expeditor.

Autonomous Rovers: Flight Line Delivery of Maintenance Tools and Parts

The maintenance expeditor shuttles maintainers to and from the aircraft to get tools and parts.

The Air Force could streamline its flight line tools and parts delivery by incorporating autonomous rovers to perform the runs.



Abstract

The AF faces severe maintainer shortages and a fleet-wide mission capable rate of 70%. As the USAF's fleet ages, aircraft will need increasing amounts of repair, and the need to remove constraints in the maintenance process is a concern. The expeditor was identified as the constraint, and autonomous rovers as a solution. The researcher demonstrated through simulations of the maintenance process at JB MDL, the differences in efficiency between the current expeditor transport process, to one augmented with autonomous delivery rovers. In 24 hours, the KC-10's expeditor saw 29.9% reduction in utilization, gained 7.2 hours, and drove 107.4 miles less, while the C-17's expeditor saw 7.9% reduction in transportation, gained 1.9 hours, and drove 21.1 miles less.

The simulations demonstrated how rovers, as an emerging technology, can address the flight line constraint, and augment the expeditor to significantly reduce time and transportation costs. In the intermediate, tools and parts need to be colocated as close to the aircraft as possible, with bench stock parts kept with the tools to create the most streamlined process. Once rover delivery is successfully demonstrated, the technology can be incorporated fleet-wide and has valuable impact across the Department of Defense.

Advisor: Lt Col Jason R. Anderson, PhD
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Air Force Institute of Technology

Maj Mary Ashley Stanton

Studies in Military Logistics

This study is a unique application for autonomous vehicle usage in military logistics. Several previous studies reviewed the use of autonomous systems in combat environments, but none exist, until now, for non-combat, flight line logistical utilization. The studies include one Army report (Henry, 2018), which investigated 247 autonomous combat resupply convoys, and two Navy theses (Peterson & Staley, 2011) and (Denevan, 2014), which explored unmanned resupply aircraft, like the K-MAX, to replace convoys to remote bases for the Marines.

Research Question

The research question is to find differences in efficiency between the current maintainer tools and parts transport process using a single expeditor, with that of a process augmented with an autonomous rover delivering supplies to maintainers working on C-17s and KC-10s at JB MDL with respect to time and cost.

Methodology

The results of the study were obtained through the observation of both the C-17 and KC-10 maintenance expeditors at JB MDL. To explore the differences in the current processes, with that of a process utilizing autonomous rovers, Kaizen principles and Business Process Management were used. Gemba walks defined the steps in the current process, and spaghetti diagrams illustrated the expeditor's day. Then process maps were developed to represent the process flow through various events, activities, and decision points. Combining the spaghetti diagram with the process map, the Theory of Constraints works to optimize the limitations outlined in the system. Finally, the Theory of Modeling uses simulations built in the 'Simio' multi-paradigm modeling program to map the processes, change variables, see different outcomes, and to explore innovative options.

Results

In the 1-rover simulation for KC-10s, the rover runs constantly with a 100% utilization rate. In addition to either needing time to dock and recharge a battery, or the ability to quickly replace the battery, the rover would need time for maintenance inspections and repairs. With two rovers, the KC-10s show an even split in utilization with 59.7% and 57.2%. There is no room for removal from the system for major repairs. The most robust system would include three rovers. On a shared network, three rovers have the following utilization rates: 43.2%, 41.1%, and 22.7%, and would create the most redundant and flexible system. Because the rover removed is not specific to parts or tools delivery, it becomes available for maintenance or inspections, while leaving two rovers to continue their scheduled deliveries of either tool or parts. The researcher recommends the 3 rovers on a shared network configuration for the KC-10s, resulting in a max wait for tools of 11.3 to 20.7 minutes and 15.6 to 29.3 minutes for parts.

Future Research

The researcher observed the maintainers' process through the eyes of an expeditor, and focused solely on the transportation aspect of the tools and parts process. When the one-time cost for the rover is \$152,430, and if the annual cost savings is the sum of the personnel savings and the vehicle savings, which is a total of \$68,822.80 (KC-10) and \$17,649.50 (C-17), the return of investment is 2.07 years/rover (KC-10) and 6.05 years/rover (C-17). While there are cost savings in man-hours and expeditor vehicle costs, the biggest multiplier of impact is on the actual maintainers' time. Once the rover delivery is successfully demonstrated in a proof-of-concept, the technology can be incorporated fleet-wide and has potential valuable impact across the Department of Defense.



Simulation Vehicle	Use Rate	Min	Type of Entry	Avg	Type of Entry	Max	Type of Entry
C-17 Simulation, 1 Rover	46.9%	6.0	Return	6.9	Return	15.5	Return
			CTK	8.4	Return	17.1	Return
C-17 Simulation, 2 Rovers	30.9%	6.0	Return	6.1	Return	10.5	Return
			CTK	6.6	Return	10.5	Return
KC-10 Simulation, 1 Rover	59.7%	14.5%	Parts	23.2	Parts	29.3	Parts
			Tools	11.7	Tools	13.4	Tools
KC-10 Simulation, 2 Rovers	57.2%	14.4	Parts	11.4	Parts	11.4	Parts
			Tools	11.4	Tools	11.4	Tools
KC-10 Simulation, 3 Rovers	41.2%	15.6	Parts	23.2	Parts	29.3	Parts
			Tools	11.3	Tools	15.7	Tools
KC-17 Simulation, Same Network	22.7%	11.8	Parts	13.4	Parts	20.7	Parts
			Tools	13.4	Tools	13.4	Tools

Research Question

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			CTK	6.6	Return	10.5	Return
KC-10 Simulation, 1 Rover	59.7%	14.5%	Parts	23.2	Parts	29.3	Parts
			Tools	11.7	Tools	13.4	Tools
KC-10 Simulation, 2 Rovers	57.2%	14.4	Parts	11.4	Parts	11.4	Parts
			Tools	11.4	Tools	11.4	Tools
KC-10 Simulation, 3 Rovers	41.2%	15.6	Parts	23.2	Parts	29.3	Parts
			Tools	11.3	Tools	15.7	Tools
KC-17 Simulation, Same Network	22.7%	11.8	Parts	13.4	Parts	20.7	Parts
			Tools	13.4	Tools	13.4	Tools

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14. ABSTRACT The AF faces severe maintainer shortages and fleet-wide mission capable rates of 70%. The simulations at JBMDL found the expediter as the constraint in tools/parts delivery. As the USAF fleet ages, aircraft need increasing repairs, and there is a need to remove constraints in the maintenance process. The researcher demonstrated differences in efficiency between the current maintainer transport process, to one augmented with autonomous delivery rovers. KC-10's expediter saw 29.9% reduction in utilization, gained 7.2 hours, and drove 107.4 miles less every 24-hours. C-17s also saw improvement. Once rover delivery is demonstrated, technology can be incorporated fleet-wide, and has valuable impact across the DoD.					
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