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Supply chain resilience: how autonomous rovers empirically provide relief to constrained flight line maintenance activities

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Abstract

Purpose – The purpose of this research is to explore the utility of autonomous transport across two independent airframe maintenance operations at a single location.

Design/methodology/approach – This study leveraged discrete event simulation that encompassed real-world conditions on a United States Air Force flight line. Though the Theory of Constraints (TOC) lens, a high-demand, human-controlled delivery asset is analyzed and the impact of introducing an autonomous rover delivery vehicle is assessed. The authors' simulations explored varying numbers and networks of rovers as alternative sources of delivery and evaluated these resources' impact against current flight line operations.

Findings – This research indicates that the addition of five autonomous rovers can significantly reduce daily expediter delivery tasks, which results in additional expertise necessary to manage and execute flight line operations. The authors assert that this relief would translate into enhancements in aircraft mission capable rates, which could increase overall transport capacity and cascade into faster cargo delivery times, systemwide. By extension, the authors suggest overall inventory management could be improved through reduction in transportation shipping time variance, which enhances the Department of Defense's overall supply chain resilience posture.

Originality/value – When compared against existing practices, this novel research provides insight into actual flight line movement and the potential benefits of an alternative autonomous delivery system. Additionally, the research measures the potential savings in the workforce and vehicle use that exceeds the cost of the rovers and their employment.

Keywords Resilience, Mapping, Augmentation, Fling line

Paper type Research paper

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1. Introduction

Current research suggests that innovative organizations are more resilient to disruptions due to the development of advanced capabilities that help mitigate risk (Sabahi and Parast, 2020). Not surprisingly, innovation is occurring in all sectors of the military and civilian industry. In the military, the Air Force Research Laboratory's (AFRL's) experimentation office has taken crucial measures toward reducing the time it takes in the United States Air Force (USAF) to move technology into daily use (Cohen, 2020). In the civilian transportation sector, industry partners across the globe have incorporated autonomous systems to streamline processes like transporting packages, meals, groceries and solve the time-intensive "last mile" of delivery (Glaser, 2017). Consequently, these types of technological innovations allow supply chains to advance beyond a traditional linear model with one large central hub, to a smaller, more flexible "immediate" supply chain (Kay, 2016). Given that innovation occurs across both the public and private sectors, there are multiple opportunities where innovation mirroring and adoption can, and should, emerge. For instance, Air Force (AF) maintenance operations could benefit from the autonomous systems innovation occurring in the civilian transportation sector. Given the mismatch in national strategy demands and budgetary constraints placed on it (Bonds *et al.*, 2019), the military needs to seek new ways to attain the highest possible aircraft availability and military readiness, without the burden of overly expensive resources and perpetual sustainment costs. Moreover, the military requires advanced automated capabilities to increase its resiliency and guard against unexpected disruptions.

The purpose of this research is to determine actual flight line operations and then reveal if automated rovers can help increase flight line maintenance performance through the transportation of parts, people and tools in a cost-efficient manner. This analysis finds that AF maintainers can utilize their skill set more effectively when the logistical ferrying tasks are outsourced to rovers. We also found that multiple order effects ripple through the entire flight line operation. For example, maintainers, who historically waited for parts while sitting at the aircraft, can now work sooner due to reduced logistical queues. Additionally, tracking parts and tools become more manageable as each rover is electronically unlocked by an individual maintainer and accountability for the item is transferred to the individual. Absent the rovers, queues build in the processes, wasted time is accumulated, and consequently, aircraft are not appropriately repaired. This culminates into a reduction in transportation capacity which has a significant impact in overall inventory management where increased transportation variance adds to costs in parts stockage policies. Overall, the USAF experiences a reduction in its supply chain resilience posture.

The current AF maintenance process requires multiple steps to service an aircraft. First, the maintainer must determine the tools and parts they require (postdiagnosis); then call the expediter transport for pick up to be driven to the consolidated tool kit (CTK) or supply/Contractor Operated and Maintained Base Supply (COMBS); next, locate and check out the necessary parts and tools; then call transport for pick up; and finally, be driven back to the aircraft to begin repair. This process is rich for Theory of Constraints (TOC) type analysis, where bottlenecks are identified and subsequently relaxed to enhance overall system throughput; a call this research seeks to address.

Though autonomous delivery is relatively nascent, the literature in the field is growing daily. One study focused on autonomous delivery of items weighing less than ten pounds and located less than 12 miles away for consumer and enterprise utilization (Brar *et al.*, 2015). The authors found the limitations in drone use were restrictive battery life, which constrained the payload, range and preventative public sector regulations concerning drone use near people or aircraft. Other studies such as those of Li *et al.* (2020), focus on overcoming particular challenges of autonomous delivery, such as heavy traffic conditions (Li *et al.*, 2020). Still others study the potential efficiencies of moving freight via autonomous vehicles and the associated regulations that accompany such concepts (Jennings and Figliozzi, 2020).

The literature is much sparser exploring autonomous delivery in a military logistics setting. Examples from the literature tend to concentrate on aerial delivery scenarios, which are inappropriate in a flight line maintenance scenario due to personnel safety concerns. Once such study explored the use of K-Max, or Lockheed Martin's unmanned helicopter, to resupply troops in an operational environment (Peterson and Staley, 2011). Another conducted a cost-based analysis of unmanned aerial vehicles to provide logistical support in forward-deployed locations (Denevan, 2014). Our research offers a unique contribution by exploring autonomous rover utilization for logistical support of tools and parts to aircraft maintainers.

The USAF cyclically faces maintainer manning shortages with gaps in skill levels coupled with decreasing aircraft mission-capable rates and operations tempo surges. These perpetual challenges drive the need for other solutions. Based upon our study, we believe current rover technologies can economically ease the daily maintenance routine, enabling more maintenance "touch time" with fewer personnel, and ultimately increase aircraft availability and mission capability rates. The results of this research will be vital for the future of USAF maintenance, as it will illustrate how the use of technologies, like rovers, can affect daily processes, decrease costs of transportation, reduce the number of hours waiting to perform critical path work tasks and ultimately increase the capability of the fleet. Finally, this research will illustrate the importance of autonomous vehicles in developing flight line resiliency. The research will address the following questions:

RQ1. Can autonomous rovers economically provide enhanced transportation capabilities for flight line maintenance operations?

RQ2. How many autonomous rovers and what kind of network would be needed during flight line maintenance operations to most effectively relieve transportation bottlenecks?

To appropriately address these research questions, we develop a suite of discrete event simulations that capture flight line operations for both KC-10 and C-17 maintenance activities in isolation of the other with up to five autonomous delivery vehicles split between the two operations (up to 3x rovers for KC-10 operations and up to 2x rovers for C-17 operations). The structure of this research paper is the following: First, the research methodology of the TOC is reviewed to provide the research basis for identifying the process constraints through spaghetti diagrams and process maps and set the basis for optimizing the system. Then, a discrete event simulation is constructed and run to identify the most efficient network of autonomous rovers. Finally, the findings are outlined with areas for future research.

2. Research methodology

2.1 Business Process Management

The Japanese word Kaizen combines "kai," translated as "change," with "zen," translated as "good" (Hys and Domagala, 2018). This "good change," also called continuous improvement, forms one of the foundations of Business Process Management (BPM), or a discipline that guides an organization to reflect and improve business processes (Dumas *et al.*, 2013). A business process is defined as a set of events and activities that cause an outcome or reach a goal when they are grouped together; events have no duration and can trigger subsequent activities, with activities ranging from a single, simple task, to multistepped work processes (Dumas *et al.*, 2013). Decision points lie among the events and activities, which can change the flow of the process and introduce different events or activities (Dumas *et al.*, 2013). The benefit, to both the customer and organization in improving business processes or creating a more efficient workflow, is that both customer satisfaction and organizational productivity improves (Ng, 2018).

In terms of the USAF, unit readiness status is, in part, reported through *mission capable rates* or a measure of the percentage of aircraft operating at a level sufficient to fulfill their mission set. In other words, the regular maintenance and inspections are current, and no components on the aircraft are inoperative or malfunctioning in a way that prevents completion of the mission. The USAF provides an annual report on mission capable rates, and detailed in 2021, a collective rate of 71.53%, which included a drop in rates across most fighter, mobility and bomber type aircraft (Everstine, 2021). To address mission capable rates, the business process of USAF maintainers was reviewed to implement the practices of Kaizen in a BPM study.

BPM often begins with the creation of spaghetti diagrams and process maps to provide an abstract view of the process. The Kaizen method recommends the spaghetti diagram because it is a single image of an entire workspace (Imai, 1986). The paths taken by the worker during a process are displayed as lines creating a visual “zero state” of movement through a process (Hys and Domagala, 2018). Repeated paths are easily seen as they combine to form a thick line, while infrequent trips remain single lines. Viewing these paths on the spaghetti diagram helps to eliminate waste and improves the value of the movement (Hys and Domagala, 2018).

2.1.1 Spaghetti diagram. First, we produced spaghetti diagrams utilizing the GPS tracker from the Cyclemeter Application (Version 10.9.12) to illustrate the expediter shuttling maintainers around the airfield during the shift. Cyclemeter provides an advanced application that includes maps, graphs, intervals and other data that overlay a tracked route on the Apple Maps’ satellite image of the airfield (Abvio, 2020). The subjects for this study were military members stationed at Joint Base McGuire-Dix-Lakehurst (JB MDL) performing daily routines with a ride-along observer recording the process. Typical weekday day shifts of 10 h for the C-17s and 12 h for the KC-10s were observed in March 2020.

The two squadrons sourced tools and parts through different processes. The C-17s maintain all 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 the separately located contractor warehouse, COMBS, issues some “calibrated” tools. On the other hand, the KC-10s sourced all their parts through COMBS, while the C-17s maintained “bench stock” parts in their centrally located CTK and only infrequently made trips to the separate Base Supply location when a large part was required. The C-17 storage of bench stock parts in their CTK permitted the greatest ease in procuring consumables, or frequently required smaller sized parts.

The KC-10 expediter vehicle shuttled the 35 maintainers on a shift from the squadron, to and from the aircraft, CTK and COMBS locations, while the C-17 expediter vehicle transported the maintainers from the colocated squadron/CTK building and the aircraft or Base Supply. The Cyclemeter application 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 route, the individual lines merged to form a thick blue band. The individual lines reappear when the image is zoomed in. The application 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. Figure 1 shows the route of the KC-10 expediter vehicle and Figure 2 displays the C-17 expediter vehicle.

Annotated on the maps are a one-mile scale, the main squadron buildings, CTKs with the tools, base supply with the C-17 parts, and COMBS with the KC-10 parts and calibrated tools. The numerous back-and-forth trips blurred to a thick line; therefore, various points are shown in closer zoomed images to show individual trips. For both squadrons, the CTK was the most highly trafficked area, shown by the yellow circle. While the C-17 main squadron area is colocated with a CTK, for the KC-10s, a CTK is positioned in an airfield hangar, located a 0.4-mile walk from the main building, or a 2-min drive. The drive takes 3–4 min if an airfield gate for wildlife is *not* open for other vehicular traffic. The process of driving through the gate

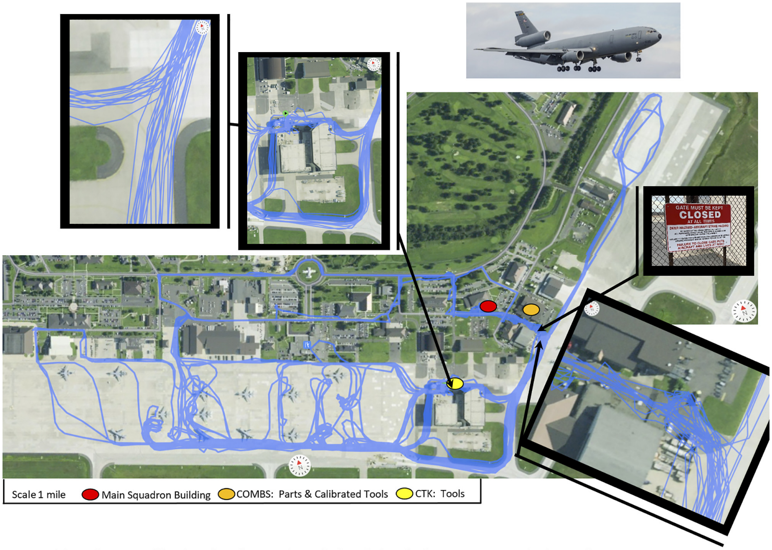

Figure 1.
Spaghetti diagram: GPS tracking of ride-along with KC-10 expediter at JB MDL, New Jersey (NJ)

Note(s): One mile is the length of the black box around the Figure Key

Source(s): (StaticFlickr (KC-10) 2020)

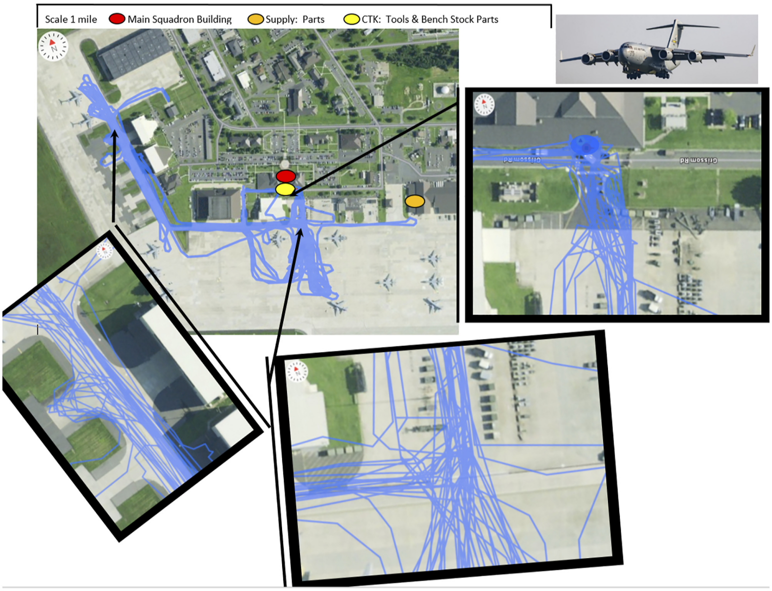

Figure 2.
Spaghetti diagram: GPS tracking of ride-along with C-17 expediter at JB MDL, NJ

Note(s): One mile is the length of the black box around the figure key

Source(s): (StaticFlickr (C-17) 2020)

involves someone getting out of the expediter van, dragging the gate open, the driver pulling forward, and the individual closing the gate and climbing back inside the van. There is no gate in the area of operations for the C-17s.

Due to the colocation in the C-17 process vs the extended layout of the KC-10 process, the miles driven by each respective expediter varied significantly. The KC-10 expediter drove 79 miles in a 12-h shift, or 158 miles per 24-h period. The C-17 expediter drove 37.5 miles in a 10-h shift, or 90 miles in a 24-h period. On average, the C-17 expediter drove 57% fewer total miles every 24 h. Additionally, the utilization, defined as the fraction of time that the expediter was actively transporting a maintainer, tool or part was measured, as was the idle rate, defined as the fraction of time the expediter is waiting to be called for a pick-up. The KC-10 expediter reported the day observed as an average day, while the C-17 expediter reported the day as less busy than normal. The total durations and distances drawn in the spaghetti diagram from the observation for both the KC-10 and C-17 expediters are listed below in Table 1.

Simulation process times to check out tools or parts or perform maintenance were modeled with a random triangular distribution. The time the maintainer waited to get picked up by the expediter, or the time spent in a nonvalue 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 steady state waiting time with the equation $L = \lambda W$, where $L =$ *average number in the system*, $\lambda =$ *average arrival rate* and $W =$ *average time in the system* (Kim and Ward, 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 and Ward, 2013). Further, the simulation was not run to steady state conditions, making Little's Law of little use for validating the model directly. The time-varying Little's Law is more appropriate for such situations. This is an area for future research as our study limited its scope to miles driven by and time spent by the expediter.

2.1.2 Process maps. Next, we created process maps using the software, Lucidchart, which provides an intuitive platform where process segments are selected and dropped into place (Content, 2019). Process maps vary in detail. While some provide a basic overview and others include detailed relationships between multiple sequences, some authors argue the importance of the completeness of the process map and recommend the inclusion of additional elements like actors, resources and data flow relations (Malinova *et al.*, 2015). This view of completeness is echoed by additional authors who argue for the higher degrees of detail (Heinrich *et al.*, 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.

Process maps are built using standardized symbols representing the events (circles), activities (rounded rectangles) and decision points (diamonds) through the sequence flow (arrows) (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, 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). We followed the Gemba Walk principle and conducted multiple visits to the

Aircraft	Utilization rate	Average miles per (#-hour) shift (observed)	Average miles per 24-h period (projected)
KC-10	43.8%	(12-h) 79 miles	158 miles
C-17	35.0%	(10-h) 37.5 miles	90 miles

Table 1. Utilization rates and total expediter miles observed on ride-along

CTKs to observe the operations and verified the routes with experienced maintainers. This culminated in a shift-long Gemba Walk, or expediter ride-along captured as the spaghetti diagram.

From the ride-along, we constructed detailed process maps for both the C-17 and KC-10 operations. The process map captured the day in the life of a maintainer starting at the squadron for roll call and ending with the final drop back at the squadron at the shift's conclusion. The process map focused solely on the transportation aspect of the shift. Each process incorporated multiple decision nodes, including asking whether the expediter vehicle was immediately available to pick up the maintainer, if the maintainer needed tools or parts, if there was a delay waiting in a queue or for transportation, as well as various activity nodes of travel, tools, and parts check out, and the event of performing maintenance. We 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 the CTK to aircraft routing.

The start (oval), processes (rectangles), decisions (diamonds), delays (d-shaped) and the end (oval) are all connected through the flow lines for the expediter 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 pick up by the expediter van, walking due to an extensive delay waiting for the expediter, 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 expediter, 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 3 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 three- to thirty-five minute-wait as the expediter shuttles groups of six (the vehicle's capacity) to the CTK, and then to the flight line, and then shuttles maintainers to and from the aircraft to COMBS or the CTK depending on requirements for parts or tools. Figure 4 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 roll 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 expediter transportation to shuttle them to the aircraft.

2.2 Theory of constraints

The TOC, established by Eliyahu M. Goldratt, uses a systems-oriented process improvement tool following five steps (Chou *et al.*, 2012). The five steps outline the Process of On-Going Improvement (POOGI) (Wu *et al.*, 2020), and has found success in production line scheduling methods, like Drum-Buffer-Rope (Goldratt and Cox, 1984), and other production line methods, like the shifting bottleneck heuristic (Monch and DrieBel, 2005). Historically, the TOC has been popularized in the productions and operations management domain with strikingly little emphasis placed within the Logistics and Supply Chain Management literature (7.4% of all TOC publications) (Ikeziri *et al.*, 2019; Goldratt, 1988; Schragenheim and Ronen, 1990; Plenert, 1993). Consequently, we view this as a rich opportunity to employ this insightful theory into the USAF maintenance flight line operations context. In our flight line research, the main bottleneck for both aircraft, was found at the squadron, where 35 people arrive simultaneously for the start of their shift, and there is one expediter, driving a panel van with

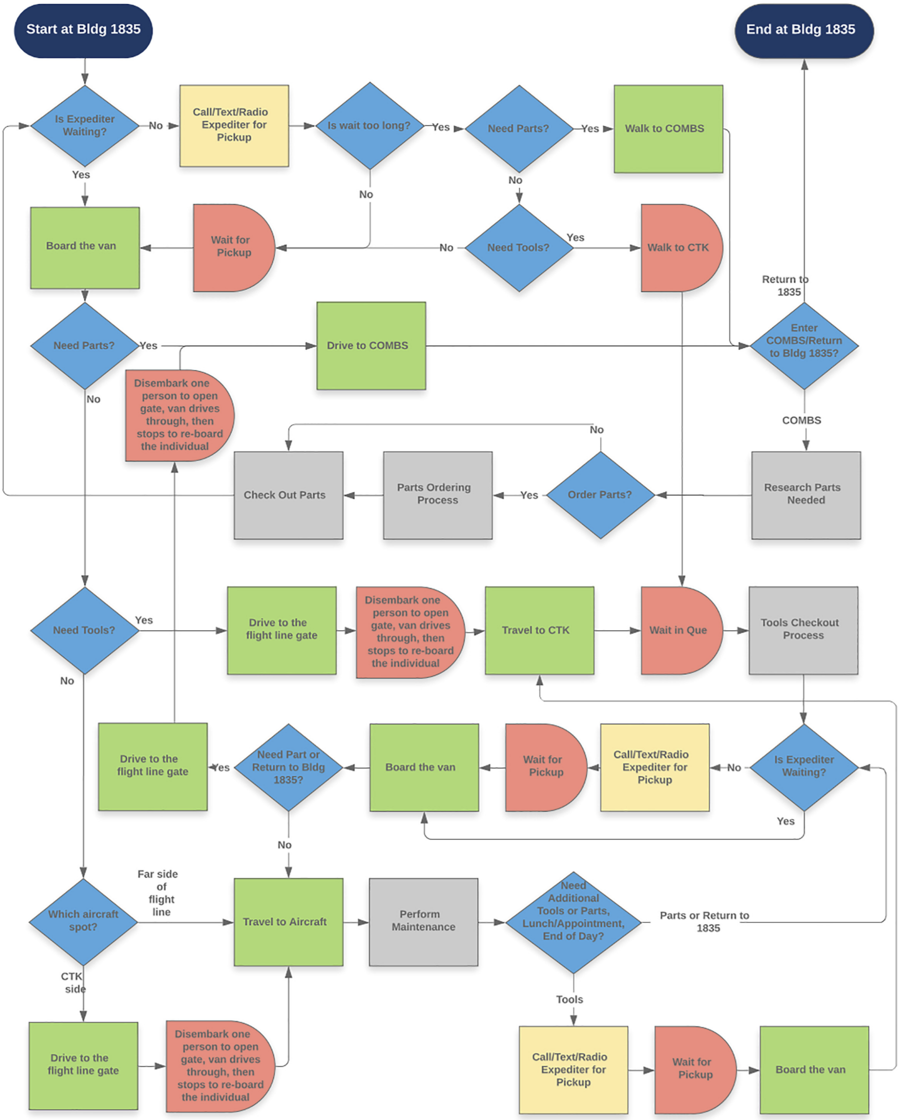

Figure 3.
Current KC-10 maintainer typical day process map

a six- or eight-person capacity (KC-10 and C-17, respectively), who is solely responsible for shuttling the maintainers to the aircraft and multiple locations on the airfield.

The maintainers' wait time is longest immediately following roll call waiting to get parts (C-17s) or waiting for transportation to the CTK and then waiting for parts (KC-10s). The next longest waiting occurs for transportation to COMBS or the CTK to pick up a part after diagnostic testing at the aircraft. To relieve both of these strenuous waiting times, this research proposes to replace trips to the CTK and COMBS/Supply with autonomous rovers that deliver tools and parts to the preprogrammed or requested aircraft parking spot.

Figure 4.
Current C-17 maintainer typical day process map

In addition, a mobile ordering application would also streamline the supply chain. The proposed application 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. COMBS, supply or the CTK processes the order, and when the tool or part is picked and ready for transport, the processor would call a rover to their location for pick up and delivery, as long as the tool or part fits within the size or payload weight requirements of the rover. In order to deconflict with flight vehicles and aircraft, the rover would transit along the edge of the apron on a predefined route. The parking spot destination is included in the order, and the rover would wait at the spot to be unloaded by the maintainer that placed the order. To ensure tool accountability, the maintainer would have to unlock the rover with a unique card or have a unique pin number provided to be typed into the rover. Once the unique pin was entered, or the maintainer's card chip was read, the tool or part would be checked out to that specific maintainer.

To aid in calling the expediter for pick up, an Uber-type application could be employed. The feature to "schedule a pickup" could be used to set a future time and place for pick up or to request an immediate pick up. The streamlined supply chain ordering application, the Uber-type application and the use of the rovers culminate and relieve the binding expediter constraint. Figure 5 outlines the proposed process chart for the KC-10s that includes the rover. With the automation, the KC-10 decision nodes are decreased from twelve to nine, the delay nodes are reduced from eight to three and the transportation is halved from ten to five. In the C-17s, in Figure 6 below, there are nine decision nodes in the current process and seven decisions in rover model; the wait nodes are decreased from four to just one, and transportation nodes are reduced from seven to two. Consequently, the augmentation with the rovers and Uber-type application have streamlining effects for both processes.

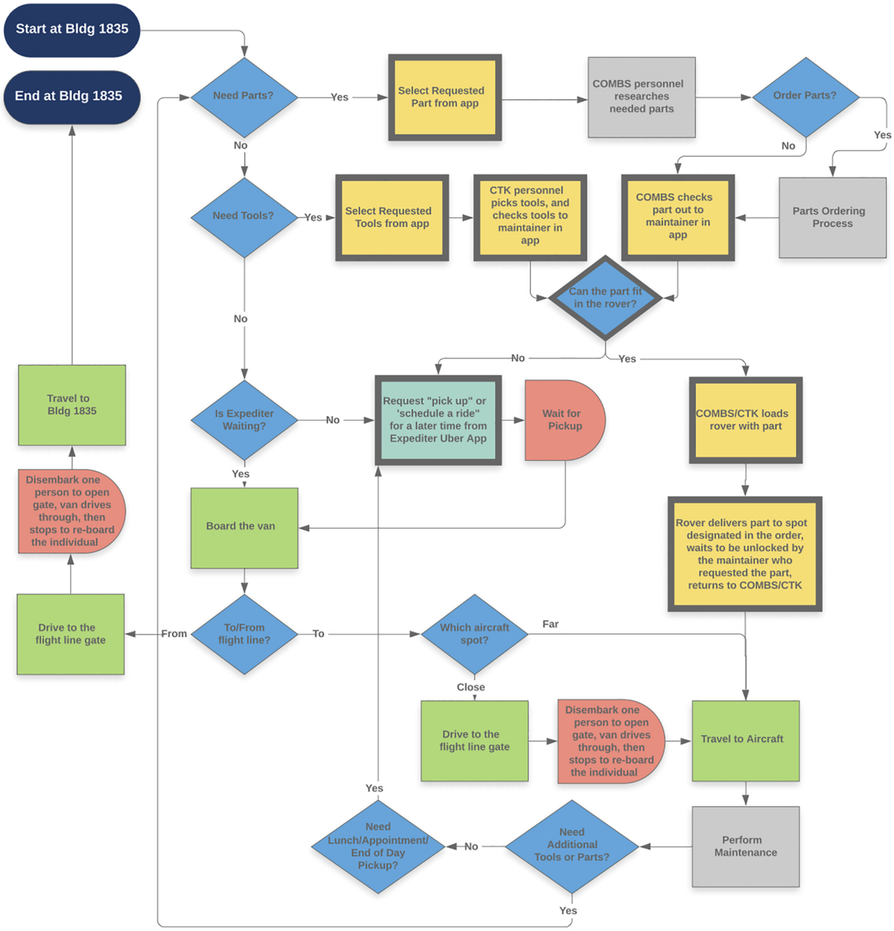

Figure 5.
Proposed KC-10 maintainer process map with rover and applications

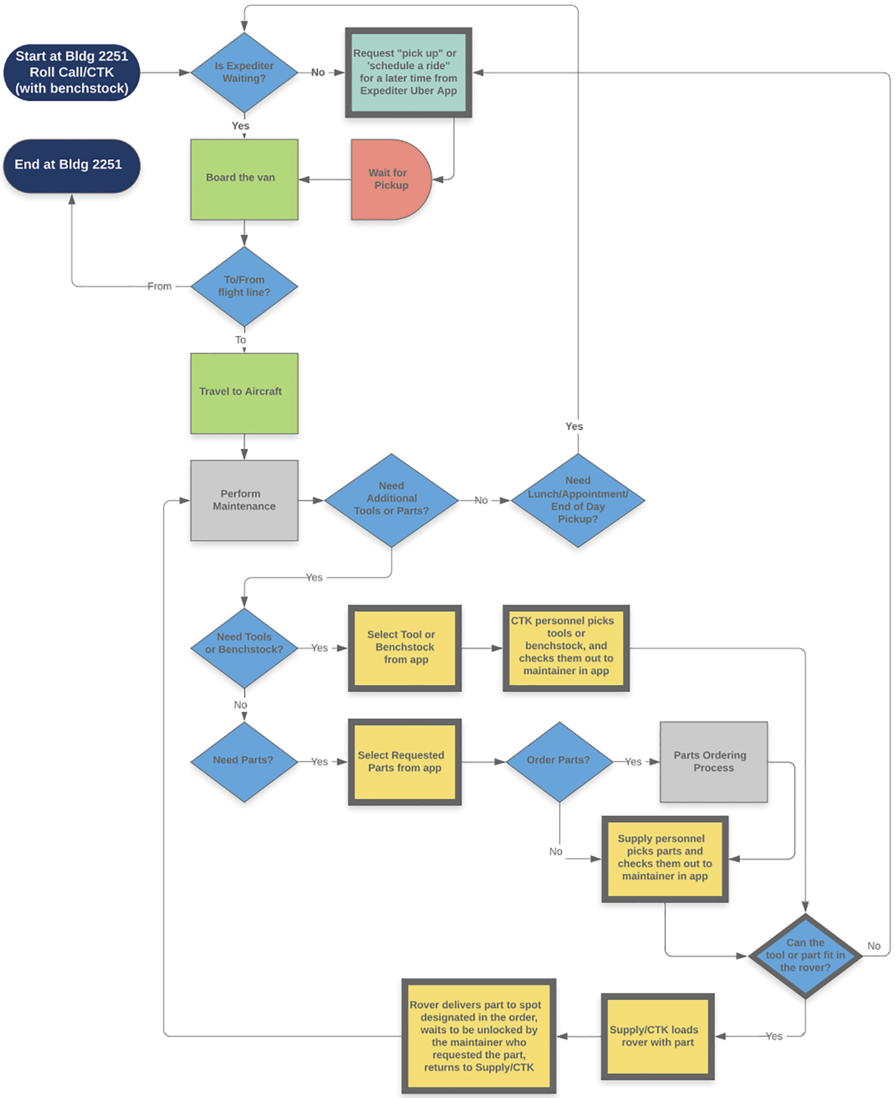

Figure 6.
Proposed C-17 maintainer process map with rover and applications highlighted

2.3 Theory of modeling

Finally, we used the Theory of Modeling with simulations to map, abstract and fit the processes into a model where variables can be changed to perform what if analysis and see various outcomes and explore innovative options. Modeling Theory upholds that models are a critical resource during scientific inquiry (Halloun, 2006). The creation of a model is accomplished in three steps: a map, an abstraction and a fit for purpose (Dumas *et al.*, 2013). The BPM tools of the spaghetti diagram and process map fulfilled the first step. The second step of building a model is to abstract relevant 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). By focusing on the efficiency of the maintainer tool and parts' transport process, our research concentrated on the transportation aspects of the maintainer's workday 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.

2.3.1 Simulation. We used SIMIO v14, which stands for **Si**mulation **M**odeling framework based on **I**ntelligent **O**bjects, to build the simulation both in a current-state model and a future-state with autonomous rovers. SIMIO is a Graphical user interface (GUI)-based simulation environment that facilitates the building of 2D and 3D simulations to analyze alternatives and improve processes (Simio, 2020). SIMIO provides animation that can quickly illustrate queues building and vehicles transporting workers to various stations, making it an ideal tool for analyzing the maintainer process.

To build a simulation, we 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, and imported as a symbol to the background of the facility window in SIMIO and sized to match the program's scale. The image map allowed us 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 actual roads. Additionally, this allowed us to define the vehicle's speed as a speed limit applicable to the scale of the airfield.

The baseline simulation modeled conditions as they currently exist. To explore the potential value of autonomous rover support to the operations, rovers in various quantities were added in alternative scenarios. Maintenance processes between the two aircraft types differed in that the KC-10 maintenance was split between organic and contracted capabilities, while the C-17 maintenance was strictly organic. Therefore, when rovers were added to the simulations, scenarios explored splitting the rovers dedicated to KC-10 maintenance operations between shared and split rover networks. Specifically, we developed a collection of discrete event simulations that capture flight line operations for both KC-10 and C-17 maintenance activities in isolation of the other with up to five autonomous delivery vehicles split between the two operations (maximum of 3x rovers for KC-10 activities and maximum of 2x rovers for C-17 activities).

When the rovers were added to the simulations, the properties of the vehicle were prescribed. The rover was required to park to load or unload, rotated in place for a network turnaround, followed the network path if possible, and avoided collisions. For shared rover network configurations, the rover was parked at the CTK. In the case of split network (KC-10 only), the COMBS-specific rover was parked at the COMBS parts source.

The values in Table 2 represent model parameters common to all simulation scenarios. These values were determined from observations of the actual operations collected during walk-throughs. The rover parameters were determined through proposed policies involving their potential employment.

2.3.2 Model validation. Baseline simulation results were compared to values observed during the ride-along and data gathering. Results were generated using 30 simulation replications, and results are reported at the 95% confidence level.

For KC-10 operations, the simulation's expediter vehicle had a mean utilization rate of 48.06 ± 2.55% and was actively transporting workers 11.54 ± 0.61 h. Comparing to the observed rates of 43.8%, the mean utilization produced by the model was higher than the observed rate, and the observed utilization was slightly outside the 95% confidence interval. Some of the difference can be explained because the simulation represents aircraft parking spots with an average parking spot vs every possible ramp and hangar location.

For C-17 operations, the simulation's expediter vehicle had a mean utilization of 46.34 ± 1.36%. This is in comparison an observed utilization rate of 43.8% observed on the ride-along. Again, the simulation results are slightly higher than the observed utilization and

Table 2.
Common model parameters

	KC-10 simulations	C-17 simulations
Average time between request for parts or tools (h)	Triangular (0.7103, 0.8803 and 1.0503)	Triangular (0.3019, 0.5019 and 0.6019)
Average time between return of parts or tools (h)	Triangular (0.7103, 0.8803 and 1.0503)	Triangular (0.3019, 0.5019 and 0.6019)
Average time between request for contracted parts (h)	Triangular (0.6155, 0.7855 and 0.9555)	N/A
Work crew size	Random discrete (3,0.05,4,0.12,5,0.3,6,0.7,7,0.88,8,0.95,9,1.0)	Random discrete (3,0.05,4,0.12,5,0.3,6,0.7,7,0.88,8,0.95,9,1.0)
Rover speed (mph)*	4	4
Rover load time (min)*	1	1

Note(s): * where applicable

slightly outside the confidence interval. Like the KC-10 baseline, part of the difference can be explained because the simulation represents aircraft parking spots with an average parking spot vs specific locations. The C-17 expediter reported that the observed day was uncharacteristically "slow" for what they normally accomplish.

Given these results, and in consultation with the project subject matter experts, the results were determined to be reasonably close to support scenario exploration and comparison.

2.3.3 Experimental parameters. The experimental parameters defining the differing scenarios were based on the number of rovers available and, in the case of only the KC-10 maintenance, the concept of employment as either a shared resource or split between organic and contracted functions. The scenarios explored by this research and their respective parameter settings are shown in Table 3.

The baseline and all rover scenarios were simulated with 30 replications, and results are reported at a 95% confidence level.

2.3.4 Results. Two metrics were computed through the simulation runs. First, the results for utilization of the expediter vehicle are shown in Table 4.

Table 3.
Experimental parameter settings for simulation scenarios

		KC-10 Sim Network		C-17 Sim Network
Scenario	Number rovers	Shared	Split	Shared
Baseline	0	N/A	N/A	N/A
A	1	1	0	1
B	2	2	0	2
C	2	1	1	
D	3	3	0	
E	3	2	1	
F	3	1	2	

The results clearly indicate that the addition of autonomous rovers significantly reduces the utilization of the expediter. Perhaps more interestingly, the reduction in expediter utilization achieves no greater reduction beyond the addition of a single rover to the maintenance system. Therefore, while the rover alleviates much of the tool and part delivery functions required from the expediter vehicle, the expediter retains requirements that the rover cannot replace, e.g. manage flight line operations and transport people.

Second, the utilization of the rovers in each scenario is shown in Table 5.

The rover utilizations statistically differ from scenarios A-F. The rovers assigned to the KC-10 operations require more rover services than one rover alone can deliver. However in Table 5 Scenario B, two rovers operating simultaneously are capable of handling all rover tasks with sufficient utilization to spare. Unfortunately, the simulation does not account for required rover service, charging or other scheduled downtime. The implications of this omission are further explained in the findings.

Finally, the average and maximum times spent waiting for parts and/or tools delivery by the rover assets were assessed from the simulation. While there are no corresponding baseline numbers for comparison, the results highlight potential trade-offs with differing numbers of rovers in the system. For instance, in the KC-10 maintenance network, the number of rovers has a drastic effect on the wait time for parts and tools. With a single rover, the mean wait time for parts is 140.78 ± 0.08 min, and the mean wait time for tools is 138.83 ± 0.073 min. For scenarios with more than a single rover, the mean wait times are no worse than 25.33 ± 0.002 min and 16.45 ± 0.008 min, respectively. Alternatively, in the C-17 maintenance network, the number of rovers does not have such a profound effect on the mean wait times. From a single rover to two, the mean wait times decrease from 7.39 ± 0.003 min to 6.08 ± 0.001 min. While statistically significant, the difference is not practical.

	KC-10	C-17
Baseline	48.06 ± 2.55%	46.34 ± 1.36%
A	12.94 ± 0.00%	33.71 ± 0.26%
B	12.94 ± 0.00%	33.71 ± 0.26%
C	12.94 ± 0.00%	
D	12.94 ± 0.00%	
E	12.94 ± 0.00%	
F	12.94 ± 0.00%	

Table 4.
Expediter vehicle utilization

	KC-10			C-17	
Scenario	Rover 1	Rover 2	Rover 3	Rover 1	Rover 2
Baseline	N/A	N/A	N/A	N/A	N/A
A	100.00 ± 0.00%			46.55 ± 0.46%	
B	58.81 ± 1.04%	57.13 ± 0.84%		32.57 ± 0.80%	12.50 ± 0.84%
C	44.08 ± 0.57%	61.83 ± 0.34%*			
D	43.07 ± 1.12%	39.17 ± 1.10%	27.00 ± 1.79		
E	35.09 ± 2.09%	8.15 ± 2.13%	61.83 ± 0.34*		
F	44.08 ± 0.57%	44.13 ± 0.53*	16.19 ± 0.48*		

Note(s): *split network rover

Table 5.
Rover utilization

3. Findings

From the observation ride-along, the annual mileage driven by each aircraft's expediter was calculated: the annual mileage driven by the KC-10 expediter vehicle working 24 h/365 days is 57,670 miles and the C-17 expediter vehicle operates 32,850 miles. The annual mileage highlights the sheer number of short, repetitive trips that are made within the confines of a flight line and ramp area. The area of KC-10 operations is a 1.5 square mile area, and the area of C-17 operations is within 0.38 square miles. Consequently, the consolidated areas of operation are an ideal environment for incorporating autonomous rovers to fulfill the short, repetitive trips ferrying tools and parts.

In the baseline simulation of the current expediter-only model, the expediter is spending 48.06 (2.55)% (KC-10) and 46.34 (1.36)% (C-17) of the shift ferrying maintainers. When a rover is added to the model to replace the trips to retrieve tools and parts, the time driving is reduced by 8.43 h (KC-10) and 3.03 h (C-17), and the miles driven is reduced by 126.44 miles or 73.07% (KC-10) and by 32.49 miles or 27.34% (C-17) as seen in Table 2. Those hours and miles saved translate to value-added time (see Table 6).

While there is a cost savings from the reduced time driving, the expediter would still be on shift. The KC-10 expediter was a master sergeant (midlevel manager), and the C-17 expediter was a senior technical sergeant (midlevel manager). Together, these professionals had an average of 15 years of training, experience and knowledge concerning the maintenance career field in the USAF. Yet 43.8% (KC-10) and 35% (C-17) of the shift was consumed performing ferrying tasks hardly commensurating with their attained skill level. With a rover performing the ferrying task, the expediters and senior maintainers can utilize those 8.43 and 3.03 h each day to instruct and oversee training of the next generation of maintainers or any other multitude of important tasks. Ultimately, more time focused on resolving maintenance issues could prompt the mission capable rates to move in a more positive direction, which enhances transport capacity to deliver critical cargo.

Because rovers are constrained by current battery and technological limitations, the rovers would need opportunities to recharge or have batteries periodically replaced. In the 1-Rover KC-10 simulation, the rover runs constantly with a 100% utilization rate. In such a situation, the rover would neither have time to dock and recharge its battery, nor have the ability to continue transporting for the entirety of its 100% charge as some batteries require recharging when reaching 20% battery life remaining. There is also an associated battery charging rate and whether the entire rover needs to remain stationary during recharging or if there is a removable battery that can be quickly exchanged. An option would be to ensure the CTK or COMBS to 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. Additionally, the rover would need additional time for maintenance, inspections and repairs. Having only one rover is, thus, impractical for the KC-10.

When adding two rovers to the KC-10s, whether on a separate or same network configuration, their utilization rate drops significantly. This two-rover 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

Table 6.
KC-10 and C-17 expediter savings (per 24 h) with rover augmentation (1 per airframe)

Aircraft	Expediter	Add 1 rover	Hours and miles saved	Total hours and miles
KC-10	11.54 ± 0.61 h	3.11 ± 0.00 h	8.43 h	11.46 h and 158.93 miles (per 24 h)
	173.03 ± 9.18 min	46.59 ± 0.00 min	126.44 min	
C-17	11.12 ± 0.33 h	8.09 ± 0.06 h	3.03 h	
	118.83 ± 3.54 min	86.34 ± 0.92 min	32.49 min	

major maintenance or repair. Therefore, the most robust system would include three rovers for KC-10 operations. Three rovers on the same network would create the most redundant and flexible system, allowing a rover to be removed for maintenance or inspections and operations continuing in the two-rover configuration (assuming implementation allows the sharing of rovers regardless of network configuration). Additionally, when the three rovers are maintained by one entity, the CTK in this model, there is centralized command and control (C2) for the technology. See Table 3 for the results of the simulations on various network configurations. Additionally, this same logic applies to the ideal two-rover model for C-17 operations. Collectively, the two independent maintenance operations could potentially augment the other with rovers during programmed and unprogrammed rover sustainment activities.

4. Conclusions

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 noncombat, flight line logistical utilization to facilitate the delivery of tools and parts for aircraft service and repair. Furthermore, this is the first research effort that mapped the flight operation process and validated it empirically through the application process. This will serve as an important springboard for future research efforts that evaluate flight line maintenance and logistics operations.

We observed the maintainers' process through the eyes of an expediter and focused solely on the transportation aspect of the tools and parts delivery process. Current quotes from the industry price a delivery rover at $152,330 for the first rover, and $47,000 for each additional rover totaling $340,000 for our recommended five rovers for the KC-10s (3x rovers) and C-17s (2x rovers) combined (Thobaben, 2020). 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), both operations see a combined savings of $84.532.20 annually; the cost of the five rovers would be realized in four years and one month. While this calculation only accounts for cost savings in man-hours and expediter vehicle costs, the biggest multiplier of impact is on the actual maintainers' time which is not captured in this computation. However, we would anticipate this result to translate into enhancements in aircraft mission capable rates, which could increase overall transport capacity and cascade into faster cargo delivery times. By extension, we believe overall inventory management could be improved through reduction in transportation shipping time variance, which enhances the Department of Defense's overall supply chain resilience posture.

An area for future research would be capturing the individual maintainer's time. If a maintainer can order a part on an application, 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 time factor is steeply multiplied because of additional maintainers waiting for the one performing the tool or part retrieval and could serve as a greater impetus for incorporating the rovers.

Additional areas to be explored further include the rover's maintenance and repair costs. Additionally, tools or parts too big or too heavy for the rover to transport could continue to be transported by the expediter, and the percentage of trips made by these oversized parts could be gathered. Finally, this research stops at a simulation. Future research can also employ actual rovers in a proof-of-concept trial. Future research should also consider the different distributions set against each simulated parameter or variable. This effort would allow for greater resolution to the efficacy of rover use.

As operations on flight lines demand greater resilience to ensure higher aircraft availability, this research provides a roadmap that can help mitigate disruptions. For example, flight line operations cease once lightning or hazardous weather is within the vicinity. Rovers would still be able to operate during this time and could potentially alleviate this disruption. In addition, physical attacks also minimize the footprint on the flight light to alleviate potential harm to exposed personnel. Conversely, rovers depend on networks and greater technology that may make them more vulnerable to cyberattacks.

The current technologies have demonstrated abilities to process databases of over 20,000 stock-keeping units (SKUs) and could identify all the items in a COMBS and/or CTK. The rovers today have no environmental limits and have proven operations in all seasons of weather and across all terrain. While the individual rovers have avoidance awareness to navigate around any popup threats, the technologies require a premapping “walk-through” of their areas of operation to define allowable and avoidance areas. Some rovers have internal cellular readers and others navigate through WiFi, driving the requirement for the military to ensure the system is not vulnerable to cyberattack before incorporating it into downrange locations. The proof-of-concept trial would further identify limiting factors for rover use in military logistical fulfillment.

In gestalt, the simulations demonstrated the efficacy of rover technology and how it can effectively address flight line constraints, augment human-driven vehicles, and save scarce human technician time. Furthermore, by decreasing the expediter’s queue wait time to nearly zero, the expediter could be employed in other more beneficial ways such as technical repair oversight and flight line managerial functions. This autonomous resource could provide the additional resilience that USAF flight lines need in times of labor shortage, especially with unique skill sets.

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