An Agent Based Modelling and Simulation Framework to Support Strategic Cargo Airlift Evaluation

Master thesis Aerospace Engineering

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This document is completed on behalf of TU Delft in collaboration
with German Aerospace Center (DLR), Hamburg

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Image description: *A Tunner 60K Aircraft Cargo Loader loads ammunition onto a C-17 at Kobani Landing Zone (KLZ), Syria, Oct. 21, 2019. (U.S. Army Reserve photo by Staff Sgt. Joshua Hammock)*
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Preface

This thesis is the conclusion of my Master's degree in Aerospace Engineering at TU Delft in the Netherlands. It marks the final accomplishment of my studies, starting from my Bachelor's at TU Delft, to beginning my Master's in Power & Propulsion, to doing my internship at the German Aerospace Center (DLR), and now finally the thesis in collaboration with DLR and TU Delft within the Air Traffic Operations discipline. As a collaborative effort, this thesis has had its fill of scheduling difficulties and disruptions, especially due to myself living in Hamburg to work alongside DLR.

It is with the support of key people that this was possible. I would like to thank Prajwal Shiva Prakasha, my lead supervisor from DLR for firstly accepting my internship, setting the stage for thesis prospects. You have been very clear with communication, where we both understood the goals of each other and worked towards effective solutions and futures. Without you, this thesis would not have been possible and it is through you that this thesis was initially organized. Although it would have been ideal to have your physical presence more frequently along the thesis' development, the few words and discussions we had were core to its progression.

I would also like to give thanks to TU Delft supervisor Alessandro Bombelli. You have been my key communication and access point to TU Delft and the ATO branch. Not only this, you have been a very kind and caring supervisor, agreeing to have meetings online due to the circumstances and giving me useful tips for presenting, writing and discussing the thesis outside of the typical feedback. I wish we could have had more face-to-face meetings to better communicate with one another and improve interaction and friendliness, but I am appreciative of your attention-to-detail and extreme ease of talking to despite this. I am also very thankful for how you opted to accept this thesis, as by its nature it is not typical given its content and my background, and how you gave me and the topic a chance to evolve.

Lastly, and by no means least, I am thankful to Tobias Dietl. You were always my go-to for thesis discussions, with weekly (and sometimes bi-weekly) updates. Whether it was result discussion or troubleshooting you have always given me useful feedback and helped me to progress, even if you were already overloaded with your own work. I can assuredly say that especially towards the end, this thesis was greatly bolstered by your expertise with aircraft design and result tuning. On behalf of the DLR team, I would also like to express my gratitude to Nabih Naeem for guiding me through the DLR simulation tool in the very beginning, and it is through his, and others, past work that this thesis is could begin and be developed.

Thank you everyone and I hope to work with you in the future; else, let us use this as an excuse to celebrate altogether!

Nikolaos Kalliatakis
Hamburg, August 2023

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Nomenclature

ABM	Agent-Based Modelling
APOD	Aerial Port of Debarkation
APOE	Aerial Port of Embarkation
ASM	Aircraft Selection Model
BWB	Blended Wing Body
CONOPS	Concept of Operations
DARPA	Defense Advanced Research Projects Agency
DES	Discrete Event Simulation
DEVS	Discrete Event Systems Specification
DLR	*The German Aerospace Center*
DoE	Design of Experiments
DRAP	Disaster Relief Airlift Planner
FEI	Fuel Efficiency Index
FHA	Foreign Humanitarian Aid
HA/DR	Humanitarian Aid/ Disaster Relief
M&S	Modelling and Simulation
MoE	Measure of Effectiveness
MRE	Meals Ready to Eat
PPE	Pallet Position Equivalent
RERP	Reliability Enhancement and Re-engine Program
RToD	Required time of departure
SAC	Strategic Airlift Comparison [Tool]
SoSID	System of Systems Inverse Design [Tool by DLR]
TPFDD	Time Phased Force Deployment Data
UAV	Unmanned Aerial Vehicle
USAF	United States Air Force
VTOL	Vertical Takeoff and Landing [Vehicle]

Introduction

Cargo airlifts are an essential part of disaster relief missions and military campaigns. Due to their varied and unique mission requirements, the operational planning and optimal design of the aircraft are difficult tasks, yet crucial for success. This complexity is furthered considering that cargo airlifts are often distinguished into 2 separate parts: a strategic airlift, based on inter-continental travel, and a tactical airlift, which considers the last mile delivery to the final destination. The aircraft in strategic airlifts are designated with traveling great distances carrying as much cargo as possible, making their designs tailor made for these operations. Despite this, the time severity of airlifts and extreme cargo demands result in strategic aircraft being over-utilized. As years go by and the aircraft approach a hastened retirement; the cost of the aircraft makes them operationally infeasible, substantiating future aircraft design. Designing future aircraft to ensure that they are capable of withstanding the volatility of airlift environments is a difficult process. Most aircraft design loops do not consider the direct effects of the design parameters on the aircraft's expected operation. Subsequently, the aircraft outputted by these loops may be sufficient for standard operation, but may under-perform in other extreme operations. The likelihood of extreme airlift events, like natural disasters, is low, but the impact of these risks is significant enough to result in mission failure. Thus there is a need to evaluate aircraft fleet and operational resilience when faced by such black swan events.

To solve this problem, this work proposes a framework for coupling aircraft design, fleet planning and operational logistics to the airlift performance. This can be done by having an aircraft design tool's outputs be linked to the inputs for an airlift modelling tool, which can then be used to evaluate the aircraft's performance in its intended operational environment. Naturally, this requires a robust airlift model. Few airlift modelling tools are publicly available, especially ones that incorporates the potential extremities and captures the unpredictability of airlifts. As such, the goal is to develop a simulation tool which encapsulates the standard aspects of airlift in addition to uncommon events that can be mission compromising. Then, through measures of effectiveness (completion time, cargo throughput, cost, etc.) and measures of performance (utilization rate, travel distance, etc.), inputs corresponding to design can be directly linked to the output mission performance.

This work is done in part with the German Aerospace Center (DLR). DLR offers a python based simulation that can be expanded to include airlift operations and model aircraft as they carry cargo from origin to destination. By having a multitude of customizeable, parameterized tool inputs, the framework can be applied to a variety of scenarios subject to user input. Stochastically modeling unpredictable events offers users a holistic and robust analysis of different designs as they perform the airlift. To handle the resulting dynamic operation environment, the simulation employs agent-based modelling, easing the analysis of emergent behaviors and risk assessment within airlift system of systems. An illustration of the framework's capabilities is explored by varying the multiple inputs in a DoE so that a sample trade space is obtained. The desired prospect of this work is to provide a more definitive, experimental playground that exploits system of systems behaviors for the formulation of future top-level requirements.

This thesis is broken into three parts: a scientific paper in chapter 1, a literature study in chapter 2 and supporting work in chapter 3. The scientific paper is where the bulk contributions of this thesis can be found, detailing the methodology and evaluating results in hopes to answer the problem statement through relevant conclusions. The literature study is an extended analysis of the supporting literature used in the scientific report in the initial exploration of the thesis topic along with the derivation of the research problem and associated planning. The last section contains additional analysis of the thesis models, such as simulation verification through time step and sensitivity analyses.

Chapter 1

Technical Report

An Agent-Based Modelling and Simulation Framework to Support Strategic Cargo Airlift Evaluation

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Abstract

When there is a need to move cargo across the world in the fastest possible manner, airlift is the prime solution. Due to the potential extreme requirements of airlift, aircraft have to be capable of performing in a myriad of operational environments. To support future aircraft design loops, this work proposes a framework which couples aircraft design and operational effectiveness in an agent-based simulation, allowing a more direct evaluation of design choices. Aircraft are modelled with inputs akin to typical design tool outputs, and airlift operational objectives and events are parameterized to allow for user customization and mission tailoring. To deal with stochastic and unexpected events that occur within airlifts, such as aircraft servicing, cargo demand reformulation and airbase access restriction, the aircraft and cargo are modelled as agents and managed by a dispatcher. Aircraft bid for cargo with flights which are configured by the dispatcher, allowing cargo to choose its flight path according to the airlift objective. Through analyzing a theoretical disaster relief mission, the impact of disruptive events on airlift time, cost and cargo throughput is shown to be significant, motivating their inclusion in future analysis. An exploration of aircraft design and airlift objectives is also analyzed, which highlighted the variance in airlift performance due to changes in aircraft payload-range and operational logics. The results demonstrate the framework's ability to capture the varying complexities of the airlift system, exemplifying its utility in future airlift and aircraft design optimization and resilience testing.

Keywords: Strategic airlift, agent-based modelling and simulation, aircraft design, HA/DR

1 Introduction

In times of emergency, the rapid movement of cargo assets around the world is highly critical. Upon a natural disaster or other crises, foreign and domestic governments seek to offer prompt humanitarian aid and disaster relief (HA/DR) material to the afflicted area(s). Similarly, in wartime scenarios, militaries are responsible for the swift, international movement of supplies, vehicles and troops to support bases and operational areas. Despite the cargo sizing and content differences, both military and HA/DR missions have stringent time horizons and seek to minimize costs and maximize cargo throughput.

Cargo airlifts operate based on a hub-spoke delivery system to maximize cargo throughput whilst promoting fuel and cost efficiency. The transit of cargo between hubs across the world is termed strategic airlift, and the following delivery to the final destinations (spokes) is termed tactical airlift. Since strategic airlift requires aircraft to travel inter-continental distances with as much cargo as possible, the aircraft choice is constrained. Only aircraft with extraordinary payload-range capabilities are adapted to conduct these movements. Examples are the C-5 Galaxy and C-17 Globemaster [1]. Limited selection and the unpredictable requirements of each airlift can result in these aircraft being over-utilized, hastening their fatigue and inflating already high airlift costs.

Based on air frame structural fatigue projections, it is predicted that by 2040, the C-17, and by 2050, the C-5M, will be unable to satisfy airlift requirements [2]. Designing and manufacturing a future aircraft to replace the current fleet should be done before this time. To promote cost minimization whilst maintaining high reliability and utility, aircraft design loops should incorporate the impact of each aircraft design choice on the intended operational environment. Unfortunately, conventional aircraft design processes do not do this [3], often due to the difficulty of obtaining a reliable operational model which can be used to monitor the aircraft's performance Considering the multi-variate use case of strategic airlift, a robust model that is able to reflect different situations and environments is required. Few of such models are publicly available and they do not entirely capture the volatility of airlifts. Events such as aircraft servicing, the introduction of new cargo demands, or even sudden airbase unavailability, are examples that greatly change the operational environment and the corresponding aircraft performance. The problem is thus two-fold: the absence of a defined framework that couples strategic cargo aircraft design to its operational performance, and the development of an underlying airlift model.

The goal of this work is to therefore create a framework that allows for aircraft performance evaluation within a strategic airlift. This will be done by creating a strategic airlift modelling tool that incorporates airlift complexities and their resultant effects on aircraft operation. To holistically evaluate different aircraft designs in different airlift environments, the tool will also have user-customized inputs that dictate the operational logic for flight scheduling and planning along with airlift specific variables, such as detailing the aforementioned volatile events. The tool will then output several different mission effectiveness measures, such as total airlift time, cost and fuel usage and the total cargo delivered. Alongside this, aircraft performance measures such as scheduled flights, load factors and utilization rates can be compared. In such a way, modifications to aircraft design, fleet structure and operational parameters (assumptions and planning objectives) can be evaluated to determine optimal -or most resilient- designs in a myriad of circumstances. Through agent-based modelling (ABM), emergent behaviors and the complex effect of risks, like unexpected events, on the system of systems (SoS) is better captured. A visual representation of the proposed design framework is shown in Figure 1.1

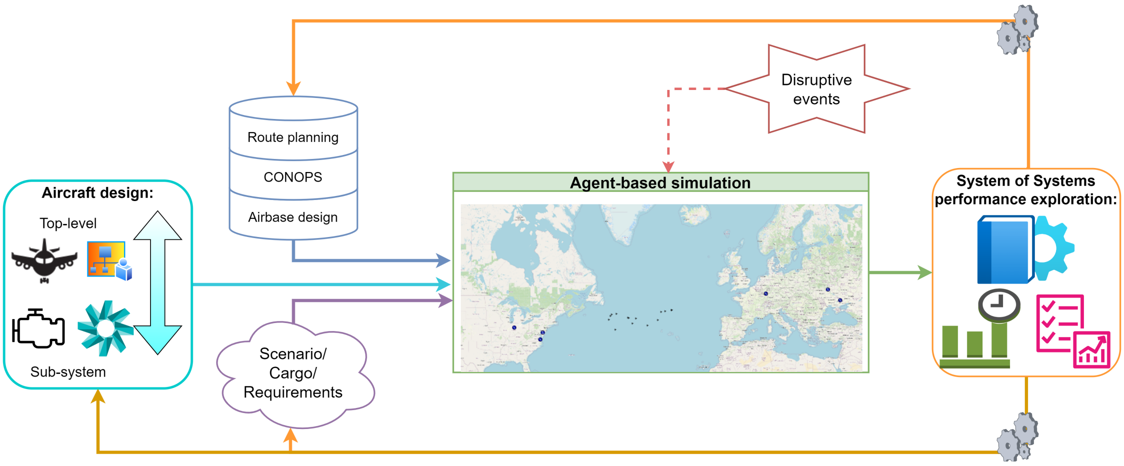


Figure 1.1: Framework overview

This report will first begin with a review of state of the art literature that developed airlift models to solve similar problems or can be used as a basis for this research. This is done in section 2. With this information, the methodology used in the creation of this research's airlift modelling tool and a definition of the analysis setups is defined in section 3. The setups are then evaluated and a trade-space including different aircraft designs is explored to demonstrate the tool's capabilities in section 4. Finally, concluding remarks on the research relevant to the problem statement is done in section 5.

2 Literature Review

Literature was filtered to focus primarily on strategic airlift model development, however tactical airlift models can be useful given the framework of aircraft design evaluation. Noteworthy airlifts in history, such as Operation Desert Shieldstorm (1990) in Iraq and Enduring Freedom (2001) in Afghanistan exposed issues with airlift planning and efficiency [4]. In Desert Shieldstorm, C-17's had not been fully acquired, resulting in reliance on C-5 aircraft. The over-utilization and large cargo demands on the aircraft delayed schedules and resulted in cargo pile-up [4]. Even with the C-17's introduction, aircraft servicing issues due to aging C-5's and redundant flight scheduling hindered Enduring Freedom's cargo throughput and inflated costs. These movements motivated airlift literature within the past 2 decades to focus on airlift planning, with mathematical models using different metrics to better plan aircraft choice, cargo allocation and flight routing.

Airlift planning literature is important as it governs how and which aircraft fly throughout the mission. A.D. Reiman [5] implemented nodal reduction heuristics to characterize different aircraft routing points (airbases) and then evaluated the different route combinations to determine optimal routing. Best routes were those with a high fuel efficiency index, which he defined as the ratio of cargo throughput to the fuel burn for a given distance [5]. An alternative formulation on route determination is proposed by P. Mogilevsky's Disaster Relief Airlift Planner (DRAP) [6]. DRAP is an integer linear program which considers the cost per flight and resource delay to determine the optimal flight path. Unlike Reiman's research, DRAP incorporates time effects, by aiming to prioritize timely or late deliveries as opposed to failed deliveries. The definition of cost per flight can be useful in this research as it was simplified to the fuel cost and cost per flight hour [6]. Additionally, despite modelling aircraft's payload-range capabilities as linear, sufficiently accurate results could be obtained[6]. Both of these route metrics can be expanded to allow user decision making in flight prioritization, preferring delivery time to fuel consumption for example.

M. Toydas [7] compared flight planning models with and without aerial refuelling, with the distinction being the inclusion of a rendezvous point for aerial refuelling which requires a detour. The planner uses great-circle distances to determine true flight distance between the areas and models fuel consumption with a non-linear function of airspeed, altitude, gross weight and flight distance [7]. By prioritizing earliest arrival times, results reflected a reduction of 160 hours by using aerial refuelling from an original time of 690.9 hours [7]. The inclusion of intermediate bases is also explored by R. Barwell [8], who created a set of discrete event models in a simulation to model a strategic airlift within the Canadian arctic. Airbases were modelled with GPS locations, and aircraft performance was based on a bulk speed and their available pallet position equivalent (PPE) spaces [8]. The work then compared several airlift scenarios which included an intermediate airbase between a set of origin and destinations and analyzed the impact of varying this intermediate base's location. By positioning the support base closer to the final destinations, airlift times were reduced, highlighting the importance of base location on airlift success [8]. Both aerial refueling and intermediate bases function similarly; they increase the payload-range of the aircraft by allowing for additional refuelling. Thus, at least one of these aspects should be incorporated in a robust airlift model.

In terms of combining aircraft design with airlift models, there are few authors who researched this. For strategic airlift, C. Iwata et al. [9] made a strategic airlift comparison (SAC) tool for motivating C-5 upgrades as opposed to further C-17 acquisition. SAC relies on user inputs to model flight paths, but uses a developed payload-range diagram for each aircraft. The tool's results showcased that the re-engined C-5 (C-5M) can provide a higher cargo throughput whilst reducing fuel- reducing costs and bettering the airlift [9]. It was shown that the impact of airbase temperature and elevation on the aircraft was insignificant unless in extreme conditions [9], and thus will be neglected in this work. For tactical airlift, C. Weit et al. [10] made a discrete event simulation model for VTOLs delivering HA/DR supplies to Fijian islands. Within the work, the authors used a stochastic servicing model based on break rates to determine maintenance delays, but this only functioned to delay departure, meaning no checks were done to see if cargo could be shifted to an alternative aircraft. They also evaluated sensitivities in the VTOL design parameters, such as a 25% bulk speed increase[10]. The modifications were not evaluated on the design itself and seen as independent. Due to the smaller scale of tactical airlift, certain sensitivities were inconclusive, like fuel consumption increases [10]. In spite of this, the research offers a framework to develop this thesis' strategic airlift model, incorporating aircraft design into the operational effect and the utility of a stochastic servicing model.

Cargo allocation/ aircraft selection literature can be used in conjunction with route planning to better plan airlifts. J. Maywald et al. [11] created an aircraft selection model (ASM) which incorporated tactical airlift vehicles such as the C-130J-30 Super Hercules into an airlift along with C-5A's and C-17's to evaluate the effectiveness of smaller aircraft in the fleet. The loading algorithm prioritizes aircraft with the lowest pallet utilization relative to their maximum allowable [11]. This tool was then used with A.D. Reiman's [5] routing model in a sample airlift movement. Results highlighted that fleets comprised of Super Hercules had a reduced movement cost due to improved fuel usage [11]. That being said, the authors noted the importance of maintaining larger aircraft fleets with C-5's due to their unique ability to carry outsized and oversized cargo. This conclusion is shared in previous studies, like the RAND Corporation's [2]. Even the best theoretical future airlift fleets planned for introduction in 2050, which use commercial derivatives of Boeing 747's and blended wing bodies, require C-5M's to substantiate the transition and comply to airlift requirements [2].

To deal with unexpected disruptions in flight schedules and routing, authors have analyzed the effect of using a civil reserve fleet to support the main airlift fleet. G.A. Godfrey et al. [12] proposed an auction and bidding model aid in assigning different flights to a set of commercial airliners. By aiming to improve profits amongst commercial airliners, the model incentivizes their participation, which helps reduce the airlift costs and completion time by up to 50% [12]. The model also allowed for flight swapping between airliners when mutually beneficial. This aspect could be further expanded in this thesis, by using flight swapping when schedule disruptions occur, such as aircraft servicing. Sometimes in HA/DR and military missions cargo demand can vary from an initial estimation, which results in an sudden reformulation. This reformulation can lead to over-utilization and burdening planners with rescheduling. T.J. Leonard [13] aimed to deal with this by using forecasted demand based on monthly data for international airbase demands to determine when to request reserve fleet assistance. Despite aiding in planning and reducing costs, this formulation falters when airlifts feature black-swan events or natural disaster development, making it difficult to accurately predict new cargo changes. Thus, there is still a need for a work that features cargo reformulation and other disruptions and their effect on the airlift.

Overall, there is a gap in literature for the development of a framework that couples aircraft design to its operational effect in a strategic airlift, which also allows for objective-customization and disruptive event modelling. With the different techniques mentioned above, this thesis can adopt some of models for its methodology. Notably: the route planning models, such as nodal reduction techniques and route evaluation with fuel and cost efficiency and time delays; aircraft models, such as stochastic servicing, pallet capacity and cargo volume utilization and the use of a bulk velocity for aircraft performance; and operation models such as flight allocation with bidding models. A visualization of the conclusions of this literature review and the gap this thesis fulfills is shown in Figure 1.2.

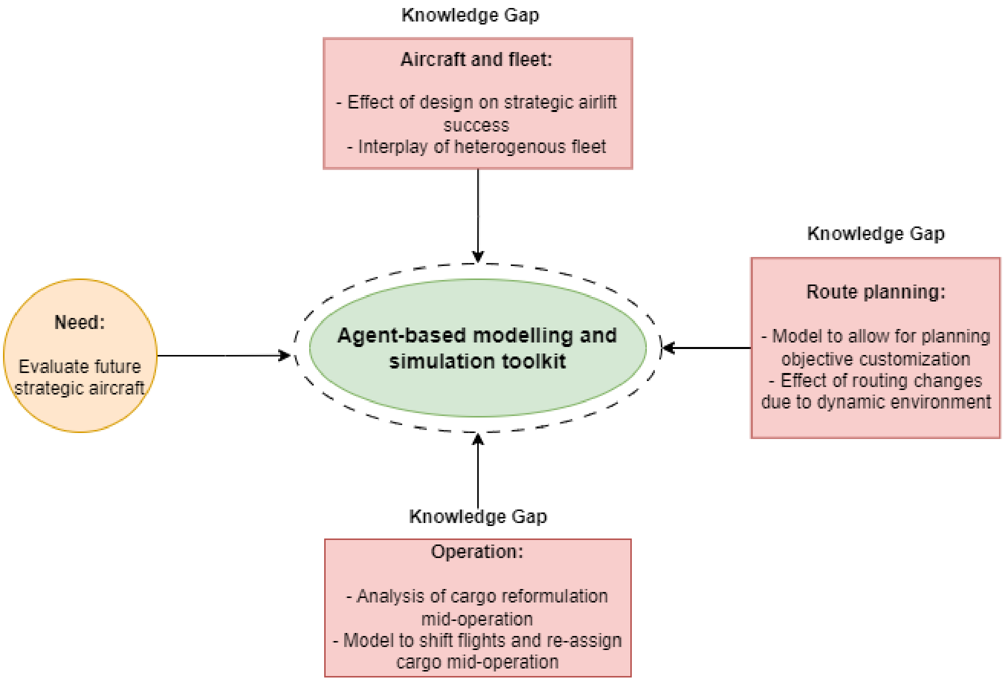


Figure 1.2: Thesis fulfillment of problem and knowledge gaps

3 Methodology

To provide a framework that couples aircraft and operational design directly to their mission effectiveness, the respective complexities of aircraft and operational design must be combined within the cargo airlift mission complexity. Encapsulating the multi-dimensional complexity of the cargo airlift operation is done through a modelling and simulation (M&S) approach. The benefit of M&S is the ability to have a ground-up development, where each detail and interaction can be defined between different systems, whilst allowing the user to visualize their inputs in the simulation. Moreover, agent-based modelling (ABM) can be employed, where entities or logic flows can be made independent, promoting automated thinking and response to simulated activities [14]. This chapter will detail the different methods employed in the creation of this framework, starting with the creation and development of the simulation model, then the operation modelling (including cargo creation and assignment and airbase modelling), and finally modelling of aircraft within the simulation.

3.1 The basics of the simulation

Within the tools provided by DLR, a python based simulation toolkit, System of Systems Inverse Design (SoSID), is present. SoSID, originally developed to simulate electric vehicles in use cases such as aerial wildfire fighting and urban air transport [15], functions by using ABM on several entities (aircraft, airbases, passengers, etc.). SoSID was chosen to be developed in this work, expanding it to larger use cases like strategic cargo airlift, using conventional, fuel-burning aircraft. Although not typically applied in this use-case, ABM benefits over other modelling schemes by offering a method to test risk management against a set of ”black swan” events, analyzing the emergent behaviors of the SoS. An example would be the development of an earthquake into a tsunami into a nuclear disaster as occurred in Japan in 2011. ABM also sets the foundation for future work in this framework, providing an intuitive and logical method for developing additional disruptions and airlift systems. The simulation functions by using mission time, map region and agent features (aircraft, airbase, cargo data) and providing a visual overlay displaying the airlift operation. Once the simulation is ended, an output file is generated, which details the overall airlift performance metrics (completion time, cost, fuel, cargo present/ missing, etc.) and aircraft data (flights, load factors, distance flown, cargo carried, etc.).

To develop the use-case for strategic cargo airlift, the SoSID model is upgraded to include:

1. the creation of cargo models which incorporate key cargo requirements:
   - Planned cargo- forecasted and created at mission initialization.
   - Spontaneous cargo- stochastically generated and is only created at specific time intervals; this represents cargo demand reformulation in lieu of unforeseen events.
2. the modeling of conventional aircraft which requires a defined fuel consumption model and servicing models
3. the modeling of airbases including a model for defining airbase accessibility changes due to ramp servicing or other effects
4. mission scheduling and route planning developments to allow for greater user customization and response to disruptive events.

These developments are further detailed in subsection 3.2 and subsection 3.3.

Since the simulation needs to model operations spanning several days, a time step is used to schedule the occurrence of events or agents actions. Per a real-time second, multiple time steps are taken depending on the computational strength of the machine. A default time step of 60 seconds is chosen as this offers consistent results while benefiting from a swift computation (further details can be found in chapter 3).

The time step and all other customizeable inputs are specified in an input file. This includes general simulation parameters (time step, map bounding box, maximum run time etc.) as well as mission specific parameters (objective weights, cargo loading time, airbase turnaround time between takeoffs, fuel cost per kg, etc.). Airbase and cargo information is also specified (see subsection 3.2. The aircraft are included in this input file, however to standardize design loops, the aircraft specification in simulation input file is limited to a file name containing the aircraft performance data (see subsection 3.3) and the locations of the aircraft with respect to the airbase definitions. Given the multitude of customizeable inputs, default values are instated in the simulation when the user does not include the parameter in the input file.

Several customizeable inputs pertain to stochastic elements. Since there are several stochastic elements in this simulation, such as aircraft servicing and cargo generation throughout the operation, each mission is run 15 times. This guarantees a convergence of less than 1% error in mean cargo delivery success. The analysis is associated with the time step analysis, found in chapter 3. Cargo delivery success is a Measure of Effectiveness (MoE) defined in this work and represents the percentage of cargo that has successfully arrived at its destination by the time the simulation ends. A delivery success less than 100% represents a 'failed' mission since not all cargo is able to be delivered by the end of the mission.

3.2 Operation modelling

The simulation operates via creating airbases, creating cargo and aircraft at airbases, creating flights with cargo and assigning them to aircraft, and then conducting said flights. This section discusses the details of airbase creation, cargo creation, and the important process of cargo assignment. To aid in individualized operation modelling, each aircraft, airbase and cargo is modelled as an agent in the ABM framework. The interplay between these different agents is monitored, controlled and initiated by a dispatcher agent, whose physical analogue would be an air traffic operator and flight planner.

3.2.1 Airbase implementation

One of the first parameters the user inputs into the simulation are the airbases. The airbases are the baseline for cargo and aircraft flight planning since they are the origins, destinations and refuelling/ service points. Each airbase input requires a name/ identifier and a corresponding GPS coordinate. The identifier is used for later reference when inputting cargo requirements and aircraft initialization. The airbases can also be expanded with information such as their available ramp space (how many aircraft can be there at a given time) and fuel pump rates. For this work, capacity is set to 10 aircraft for each airbase and fuel pump rates are set to 300 gallons/ minute (≈15.4 kg/s) which is a conservative estimate for air force bases [10].

The next detail of the airbase implementation is for new cargo generation throughout the simulation. The user can specify whether the airbase is able to generate or consume cargo, including the specific cargo type it can generate and/ or consume. When new cargo is generated in the simulation, the cargo is randomly created at one of the generator airbases and is assigned a destination corresponding to a random (different) consumer airbase. Lastly, the user can specify aircraft that are restricted from landing at the airbase. This capability is a simplification for when an airbase's conditions (elevation, field length, etc.) are not sufficient for the aircraft to land at. Restricted access can also be used dynamically, so that an airbase can restrict or enable new aircraft access in the middle of the operation. This allows for aspects such as airbase servicing where aircraft may not be able to land/ takeoff due to damaged runways or other afflictions.

3.2.2 Cargo creation

Within the basis of HA/DR or military airlift, cargo requirements are often detailed in time phased force deployment data (TPFDD) [16]. This denomination provides the identifier code for tracking purposes, the origin and destination airbase, required arrival data, the sizing classification (out-sized vs oversized vs nominal) and required pallets and load per cargo amount. A derivative of TPFDD is used in this work to detail the cargo for creation purposes and aid in user accessibility.

Cargo is initialized with an identifier string, which can be customized by the user. After, the origin airbase and destination airbase are specified. The cargo mass and pallet position equivalent (PPE) spaces that a single amount of that cargo occupies is also required. Since these values are quite significant for determining the payload-range capabilities of the aircraft, base values for common cargo types (food, water, generic armored vehicle, VTOLs, etc.) are provided for. The last aspect to initialize cargo is the required arrival time. This value is dependent on the different flight route times, which themselves are dependent on the aircraft performance capabilities and the airbase locations. To reduce the computational expense, the required time of departure (RToD) is employed. RToD is easier to verify with flight scheduling and is can be viewed as a simplified analogue to required arrival time.

An example of the cargo creation modelling input is shown in Table 1.1. The water and food information corresponds to a single case (amount) of the cargo.

Table 1.1: Cargo initialization model

Identifier	Origin	Destination	Mass	PPE	RToD
Food	Travis	Subang	500	0.25	4
Water	Travis	Subang	1000	0.25	3
...	...	..	...	...	...

Cargo can be created in three ways within the simulation. Planned cargo represents the cargo the airlift was originally created for and is present at initialization. Spontaneous cargo represents the reformulation of cargo requirements in lieu of a changing airlift environment. The last form of cargo is reinstated cargo, which is when already created cargo undergoes a scheduling problem that requires it to be reprocessed for a new flight path.

Spontaneous cargo is randomly generated, where each type of cargo has its own generation chance. If spontaneous cargo is generated, an origin and destination pair is selected based on the airbases labelled as generator and consumer (see subsubsection 3.2.1). The RToD is then assigned to be a random value between 2 and 5 days. Spontaneous cargo can be generated multiple times depending on the seed's RNG, giving each run a unique instance of spontaneous cargo. In reality, new cargo requirements will only be added to the airlift some time after it begins. To model this, a time interval is specified, which details the number of days from initialization that spontaneous cargo is created. By default this value is set to 3 days from the mission start.

Reinstated cargo is a result of scheduling problems like aircraft servicing delays- disrupting connecting flights- or from airbase accessibility changes- preventing aircraft from reaching the cargo. Reinstated cargo maintains the original cargo's requirements but has a different flight scheme from the point the scheduling changes take effect. In effect, the amount of reinstated cargo throughout the operation is a measure of scheduling disruptions that occur due to effects such as aircraft and airbase servicing.

3.2.3 Cargo assignment and route planning

When cargo is created and added to the simulation, it is processed by a dispatcher agent which determines optimal flight paths and presents the cargo different flight schemes that fulfill these paths. The cargo then chooses the best flight scheme that produces the earliest arrival time. Optimal flight paths are determined per aircraft type. Nodal reduction is applied to the airbases, using their GPS coordinates, upon which each set of available routes is looped through to find the flight path which provides the greatest mean Fuel Efficiency Index (FEI) (from A.D. Reiman's work [5]), shown in Equation 1.1, where n represents flight legs. This ensures maximum cargo throughput depending on the aircraft's payload-range capabilities.

$$FEI = \frac{\sum_{i=1}^{n} \frac{Distance_i[\text{km}]*Cargo_i[\text{tons}]}{Fuel_i[\text{tons}]}}{n} \tag{1.1}$$

Once the optimal routing is found, each leg of the route is bid for by aircraft, with the best flight winning the cargo. This process prioritizes scheduled flights instead of new flight creation. Doing so ensures that already scheduled flights (even deadheads) maximize their cargo/ fuel performance before creating new flights. If no scheduled flights are able to accommodate the cargo's required departure time, volume or mass, then new flights are checked for creation. Each aircraft proposes a prospective flight for the leg. To determine a prospective flight's departure time, the aircraft's flight schedule is looped to find the earliest time the flight can occur without compromising other cargo on the aircraft's schedule. Slotting in new prospective flights also considers any deadhead flights, with no cargo, that would be required to ensure that the prospective flight is connected to the preceding and succeeding cargo flights. In addition to the flight time, aspects such as refuelling time, taxiing, aircraft runway availability and loading and unloading times (assumed to be 15 minutes each) are considered. By the end of this, a set of viable flights (scheduled or prospective) which fulfill the cargo's demand and flight leg are collected. The last step is the determination of best flight, which is accomplished by discretizing the flight details into a value function so they can be compared.

The function is shown in Equation 1.2, where B represents the user-defined weight and the ^ on each discipline indicates normalized values. Normalization is done based on the maximum value of each discipline amongst all the aircraft bids for the flight.

$$Bid = B_{time} * \hat{Time} + B_{utilization} * \hat{Utilization} + B_{fuel} * \hat{Fuel} + B_{cost} * \hat{Cost} \tag{1.2}$$

$Time$ refers to the difference in time (seconds) between the flight's departure time and the current simulation time. $Utilization$ refers to the change in flight hours the new flight incurs. $Fuel$ and $Cost$ refers to the fuel and cost changes due to the new flight plan. The best aircraft is then chosen by finding the bid with the lowest value, as each discipline represents a negative contribution. For example, a high $Time$ value means the flight's departure time is far in the future which is undesirable. If multiple aircraft have the same bid, the aircraft with the fewest scheduled flights is chosen.

$$AC_{best} = Min(Bid_{AC}) \tag{1.3}$$

The procedure is outlined in Figure 1.3. If cargo is present at an airbase that undergoes accessibility changes, cargo may be reinstated with its original requirements at a new generator airbase. If still no flights are possible, then the cargo is marked as a failure.

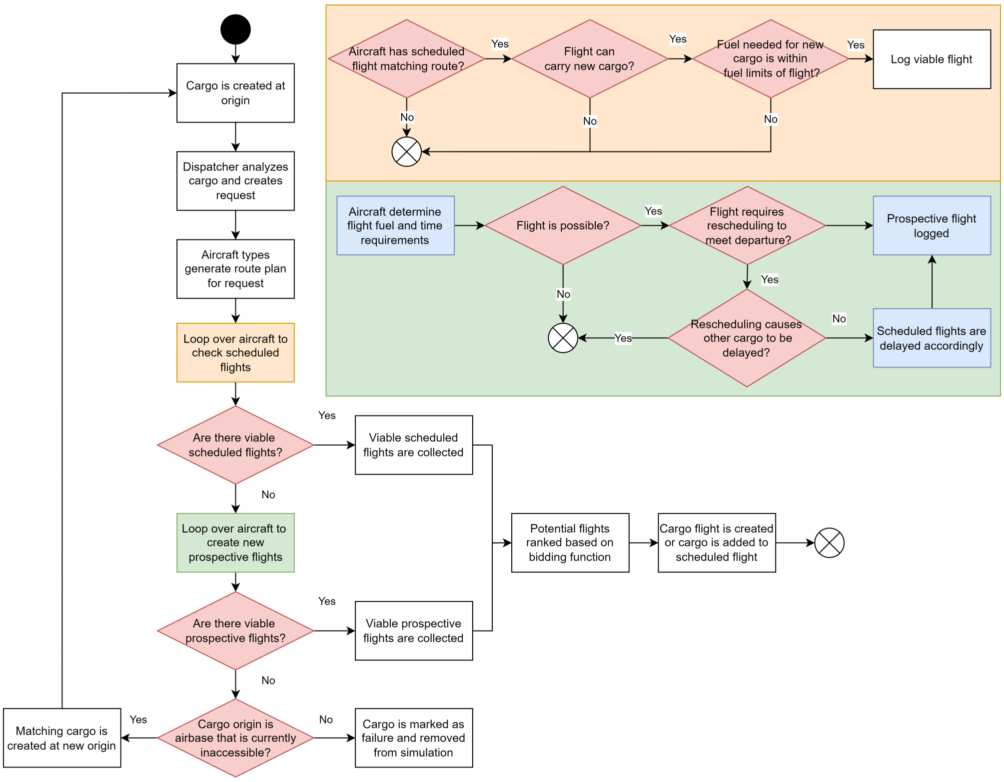


Figure 1.3: Process flow diagram for cargo assignment

3.3 Aircraft modelling

To model the aircraft accurately, there are several inputs that are required by the simulation. Since the function of the framework is to take inputs from an aircraft design loop, the aircraft model inputs should match to a corresponding output from a design tool (weights, aerodynamic and engine performances). Depending on the design tool, additional inputs may be required to allow for airlift performance modelling, such as pallet capacity, cost per flight hour, servicing chance (break rate). Within this section, the detailing of the aircraft modelling will be explained, as well as the outlining of the method for creating different aircraft designs without an official design tool.

3.3.1 Simulation implementation

The duty of the aircraft is to carry and transport cargo across the defined environment. Cargo carrying capabilities are based on the aircraft's maximum payload volume, represented by pallet position equivalent (PPE) spaces, the maximum payload mass and the fuel required for a flight [11]. Until any of these constraints are met, the aircraft can continue adding cargo to its flight. The pallet and payload capacity are easily checked for each new cargo addition, however to evaluate if the additional cargo mass results in an infeasible flight, the updated flight fuel needs to be determined. For a given route, the aircraft's fuel requirements can be computed based on a variant of the Breguet range equation (specified for jet engines), shown in Equation 1.4. The equation uses a cruise velocity (V), the thrust specific fuel consumption ($TSFC$), the lift-over-drag ratio ($\frac{L}{D}$) and the weight ratio, representing the change in weight from the beginning of the segment to the end.

$$R = \frac{V}{g_0 \cdot TSFC} \frac{L}{D} \log \frac{W_{i-1}}{W_i} \tag{1.4}$$

In using this variant of the Breguet, key assumptions are made:

- The aircraft flies at a constant velocity, specifically the cruise velocity.
- The aircraft flies at a constant L/D and $TSFC$.

The first assumption is feasible given the long flight distances, meaning the majority of the flight will be within the cruise segment. Given cruise conditions, it is also expected that the aircraft's angle of attack is relatively constant. The L/D and $TSFC$ can therefore be viewed as the average values across the flight, which are taken to be constant. Thus, the Breguet equation will provide a reasonable estimate for the total flight fuel assuming that the majority of the flight is conducted in the cruise state. Additionally, the equation can reflect the payload-range capabilities of the aircraft assuming the correct specific fuel and lift-over-drag ratio are used.

With the route and fuel determined, cost can be derived. The cost incurred by the aircraft whilst they operate is based on two factors: the cost due to fuel usage and the operational cost [6]. The fuel cost is a simple multiplication of the fuel consumed (measured at the end of the flight) and the cost of fuel (C_F), taken to be \$ 714 (US) per ton based on 2023 May jet fuel prices [17]. The operational cost is based on the cost per flight hour (CPFH) of the aircraft and the flight hours. The CPFH is variable and is affected by many factors such as aircraft age, required crew, maintenance frequency and cost and other complex factors [2]. For the C-5M and C-17 these values were taken based on a data set provided by the USAF in 2012 [18]. The C-5M's CPFH used is \$69328 (US) whereas the C-17's CPFH is \$ 23811 (US). The cost (C) for route i is thus defined as in Equation 1.5, where m_f is the fuel consumed in kg and T is the flight time in hours.

$$C_i = C_{fuel_i} + C_{op_i} \tag{1.5}$$

$$C_i = m_{f_i} \cdot C_F + T_i \cdot CPFH \tag{1.6}$$

Once the aircraft's routing is confirmed and it flies the assigned path, it may also require servicing. The occurrence of this event is modelled based on Iwata et al.'s [9] work where a vehicle has a probabilistic chance to require servicing at each landing. This is based on an input probability, the break rate. In this work, the servicing time is a random number of hours between 4 and 16 hours. When an aircraft is serviced, all of its planned flights are delayed by the service time and the aircraft cannot bid for new missions. If the cargo present on these flights has connecting flights with other aircraft, these flights are checked if they can still be caught by the cargo, including cargo loading and unloading times. If the cargo is unable to meet its subsequent flights or if the flight causes the cargo to not meet its RToD, the cargo will be reinstated so it can be bid for again by functioning aircraft.

Evidently, much of the aircraft's implementation relies on Equation 1.4, which requires aircraft specific data. For most top-level information, online data can be found. However, due to the nature of the aircraft being analyzed, specific fuel consumptions and aerodynamic characteristics are more problematic. Ordinarily the framework would be used in conjunction with an aircraft design tool which outputs these values, but currently, there is no available cargo aircraft design tool within DLR or publicly online. Yet the need for $TSFC$ and $\frac{L}{D}$ necessitates a method for their valuation. The absence of a detailed aircraft design tool also introduces issues with demonstrating the framework's ability to reflect design effects on the operation. These issues are solved by creating a simplified aircraft design tool, which is detailed in subsubsection 3.3.2.

3.3.2 Aircraft sizing and design tuning

The design of aircraft is a complex process composed of several design loops. Since this research focuses on a framework connecting aircraft design tools and operational effectiveness through a simulation environment, the aircraft design tool used and created in this work should not be regarded as a noteworthy result and therefore does not require a high fidelity. It must, however, at least capture the essential snowball effects that can occur within aircraft design, like how increasing design range increases fuel required, which increases the empty and takeoff weight of the aircraft, resulting in an increased fuel consumption again- a snowball effect. The Raymer conceptual design relations offer such utility [3].

To begin the design process, a design mission must be defined to which the aircraft must be constrained to. For this, the MIL-STD for cargo transporters under maximum range was used [19]. The mission entails a takeoff, climb, cruise, descent and 30 minute loiter and landing where 5% of the total fuel is kept as reserve. The mission profile is shown in Figure 1.4.

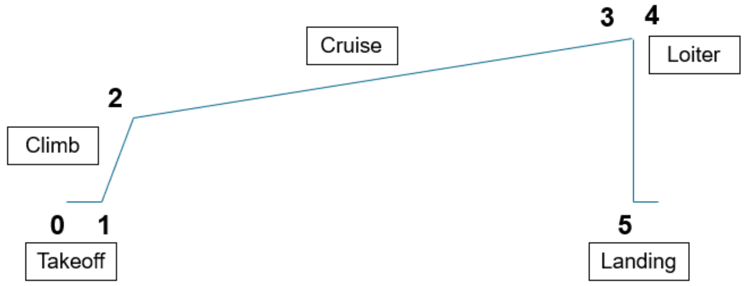


Figure 1.4: Sizing equations mission profile (based on MIL-STD [19])

With the mission defined, the fuel required for the mission is defined based on known values. Raymer details the typical weight ratios based on known, historical data [3]. This is detailed in Table 1.2, where the Breguet equations are used to estimate fuel usage and weight fractions in cruise and loiter. The endurance equation (Equation 1.7) uses the same variables as the range equation (Equation 1.4), however the L/D is replaced by the L/D_{max} and the $TSFC$ is replaced by the $TSFC_{loiter}$. They are linked to the design values of the range equation [3]: $L/D_{max} \approx 1.16L/D$ and $TSFC_{loiter} \approx 0.875TSFC$.

$$E = \frac{\frac{L}{D}_{max}}{g_0 \cdot TSFC_{l}oiter} \log \frac{W_{i-1}}{W_i} \tag{1.7}$$

Table 1.2: Raymer weight fractions based on historical data [3]

Segment	W_i/W_{i-1}
Take-off	0.97
Climb	0.985
Cruise	Breguet Range
Loiter	Breguet Endurance
Landing	0.995

R, V and E are often top level requirements, and $TSFC$ and $\frac{L}{D}$ are manipulable performance variables, meaning the $\frac{W_{i-1}}{W_i}$ is the focus. By re-arranging Equation 1.4 and Equation 1.7 for $\frac{W_{i-1}}{W_i}$ and including the ratios of Table 1.2, the ratio between the aircraft's post-mission weight W_{end} and its pre-takeoff weight W_0 is then given as:

$$\frac{W_{end}}{W_0} = \frac{W_{takeoff}}{W_i} \cdot \frac{W_{climb}}{W_{takeoff}} \cdot \frac{W_{cruise}}{W_{climb}} \cdot \frac{W_{loiter}}{W_{cruise}} \cdot \frac{W_{end}}{W_{landing}} \tag{1.8}$$

The weights shown are comprised of the aircraft empty weight, design payload, crew, usable fuel and fuel reserves. From this formulation, the difference in weight between W_{end} and W_0 is the total available fuel. The fuel fraction of aircraft (maximum fuel relative to maximum takeoff mass = $\frac{M_f}{MTOM}$) is then given in Equation 1.9 where $n_{reserve}$ is the reserve fuel multiplier (assumed to be 1.05).

$$\frac{M_f}{MTOM} = (1 - \frac{W_{end}}{W_0}) \cdot n_{reserve} \tag{1.9}$$

The next step according to [3] is to determine the empty weight fraction of the aircraft ($\frac{OEM}{MTOM}$), given an estimate of the $MTOM$. For this procedure, [3] provides an equation (Equation 1.10), which uses historical data to provide a statistical curve fit for different aircraft types. For a military cargo transporter with a fixed wing $A = 0.88$ and $C = -0.07$ and $K = 1.00$. A shift is applied to maintain the statistical trend line while providing the correct aircraft empty weight fractions (≈0.45 for the C-5M [20] and ≈0.47 for the C-17[21]).

$$\frac{OEM}{MTOM} = A \cdot MTOM^C K \tag{1.10}$$

Given both the fuel and empty weight fractions, the new $MTOM$ can be computed based on the summation of all weights at design conditions and re-arranging for $MTOM$. This gives Equation 1.11. The crew mass is estimated based on an assumed value of 85 kg per crew member and typical values for the crew size of the C-5 and C-17. Including spare crew, 12 members are assumed for the C-5M [22] and 8 for the C-17[21]. With a new $MTOM$, an iterative loop occurs between $\frac{OEM}{MTOM}$ and $MTOM$ until a convergence of 0.5% in $MTOM$ is obtained between steps [3].

$$MTOM = \frac{M_{payload} + M_{crew}}{1 - \frac{M_f}{MTOM} - \frac{OEM}{MTOM}} \tag{1.11}$$

With the sizing loop of Figure 1.5, changes in design payload and range are translated into the noteworthy masses of the aircraft ($MTOM$, OEM and M_f). To implement the C-5M and C-17 into the simulation, online data was taken when available. The L/D and $TSFC$ values however are not commonly tabulated and are dependent on several factors. Hence, to ensure that somewhat realistic values were obtained whilst fulfilling their design missions, the aircraft sizing tool was used to find suitable L/D and $TSFC$ values for the aircraft at design conditions. Effectively, a range of combinations for both the $TSFC$ and L/D were inputted into the process loop of Figure 1.5 such that a new fuel ratio was obtained for each combination based on the Breguet equations of Equation 1.4 and Equation 1.7. Since all other other parameters are constant and equal to the C-5M or C-17 specifications, the combination which yielded a converged $MTOM$ closest to the actual value was chosen as the design L/D and $TSFC$ for use in the simulation.

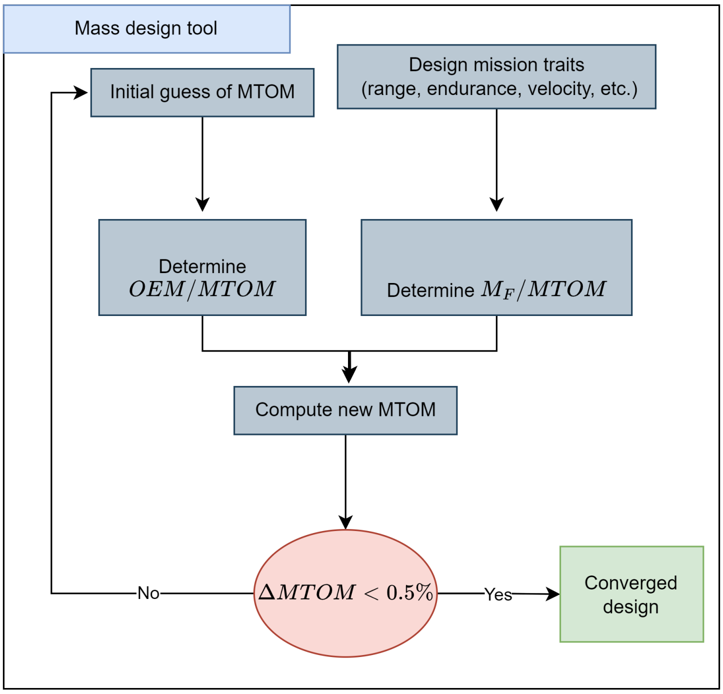


Figure 1.5: Mass design tool loop

The comparison between the tool outputs and available data for the aircraft are shown in Table 1.3, whilst the simulation inputs are shown in Table 1.4.

Table 1.3: Sizing tool $TSFC$ and L/D computation analysis

Aircraft	TSFC $[10^{-5}$ kg /N s]	L/D [-]	$MTOM$ [tons]		M_f [tons]		OEM [tons]	
			Computed	Actual	Computed	Actual	Computed	Actual
C-5M	1.73	15.2	381.0	381.0	153.6	155.4	172	172.3
C-17	1.83	18.2	265.4	265.5	98.6	100.9	125.8	126.1

Table 1.4: Key simulation input data for different aircraft

Parameter	C-5M	C-17
MTOM [tons]	381	265.4
Max payload [tons]	129.3	77.5
OEM [tons]	172.0	125.8
Max fuel [tons]	153.6	98.6
Pallet capacity [PPE] [20][21]	36	18
Bulk/ cruise velocity [m/s] [20][21]	232.5	226
Design range [km] [23][21]	8890	8334
Design payload [tons] [23][21]	54	45.4
L/D [-] @ design	15.2	18.2
TSFC [kg / N s] @ design	1.73 E-5	1.83 E-5
CPFH [$] [18]	69328	23811

4 Analysis

The focus of this section is to demonstrate the framework's capabilities. To do so, an exemplary, theoretical mission set is created in subsection 4.1, where the use case is extended until a base mission is obtained. The missions and toolkit capabilities are compared in subsection 4.2, upon which a sample trade-space exploration is analyzed with the defined base mission in subsection 4.3.

4.1 Mission setups

The mission is defined as a transport of HA/DR material sufficient to supply 20'000 people in an Oceanic island area afflicted by a natural disaster. As this setup is for a proof-of-concept and theoretical, the destination for the airlift cargo is chosen arbitrarily to be Subang within Malaysia. A time scale of 6 days is chosen for the movement, since the first 5 days of the mission are most significant for human survival [10] (with water and food delivery) and subsequent days having a higher likelihood of sea and land effort assistance.

Humanitarian standards advise that each person is supplied with at least a gallon of water per day and roughly 2000 calories in food nutrition per day [24]. Given water and food requirements, treating 20'000 people requires roughly 80'000 L of water and 40 million calories per day. Using available information, water cases carry 980 L of water, occupying 0.25 PPE and weighing 1 ton [25], whereas food cases can store 576 Meals Ready to Eat (MRE's) which offer 1250 calories, occupying 0.25 PPE and weighing 0.5 ton [26]. To meet the requirement, 425 cases of water and 350 cases of food are required.

Although tactical airlift is not currently incorporated into the simulation, it would occur side-by-side to the strategic airlift. It is possible that strategic aircraft would also be responsible for carrying the tactical airlift vehicles so that they may be assembled and used to perform last mile delivery. The use case will therefore include the transport of 3 HH-60 VTOLs [27]. Finally, it is possible that other types of cargo such as blankets, tents or even Turtleback drone VTOLs, which act as single pallet tactical airlifters, are transported as well [28]. These cargo types will be categorized as "generic pallets" and will be treated as a single, fully loaded (maximum acceptable mass) pallet on the aircraft. A summary of the cargo present at initialization (planned cargo) is shown in Table 1.5.

Table 1.5: Use case cargo plan

Cargo type	Origin	Destination	Amount	RToD [days]	PPE	Mass [tons]
Water [25]	Travis	Subang	425	3	0.25	1.0
Food [26]	Travis	Subang	350	5	0.25	0.5
VTOL (HH-60) [27]	Travis	Subang	3	4	9	7.3
Generic pallet [29]	Travis	Subang	50	6	1	4.5

To conduct the airlift, a sample fleet of 4 x C-5M and 6 x C-17 will be used. The composition was based on current USAF fleet architecture and utilization [30][21]. The aircraft and cargo will originate at Travis airbase in the US. Several US airbases are present between the destination of Subang and Travis airbase- Barbers Point airbase Hawaii, Andersen airbase Guam and Kadena airbase Japan. These can be used to refuel and service the aircraft to aid in mission completion and increase cargo carrying capabilities. Since C-17 have greater landing versatility compared to the C-5M [21], only the C-17 are able to land at Subang.

The airbase and map setup is shown in Figure 1.6. A demonstration of the SoSID toolkit capabilities which also conveys the importance in modelling uncertainties can be done through a base mission development. Different aspects can be gradually included allowing for greater understanding of the effect of each uncertainty on mission success. The uncertainties in this context are of aircraft servicing, spontaneous cargo generation and airbase accessibility changes. Aircraft servicing will be done by applying a 5% chance of servicing for each aircraft upon landing. For spontaneous cargo, each of the cargo detailed in Table 1.5 will have a chance to be generated again and the cargo will be added 3 days into the simulation. This represents an updated cargo requirement instated by the Department of Defense to combat a theoretical worsened natural disaster. Airbase accessibility changes will be employed by making Kadena airbase inactive 2.5 days into the simulation. This represents a potential damaging of the runway due to excess utilization, prohibiting access.

Figure 1.6: Simulation airbase locations for mission setup.

For all of the aforementioned analysis, the bidding weight of time B_{time} and cost B_{cost} will be set to 1.0, whilst all other weights are set to 0. This is to emulate how the majority of the time, operators plan airlifts for the sake of fulfilling a time requirement or cost requirement [31].

A comparison between the missions is shown in Table 1.6.

Table 1.6: Mission and aspect comparison

	Cargo at initialization	Aircraft servicing	Spontaneous cargo	Airbase servicing
Mission 1	Yes	No	No	No
Mission 2	Yes	Yes	No	No
Mission 3	Yes	Yes	Yes	No
Mission 4 (Base)	Yes	Yes	Yes	Yes

With the combination of several different uncertainties, Mission 4 can be viewed as an off-design airlift with many disruptions. For this reason, Mission 4 is a suitable base mission to evaluate aircraft design resilience and test the operational contingency management. A sample trade-space exploration on aircraft designs and operational objectives will be done on this base mission, demonstrating the framework's main purpose to be combined with a design tool.

Within the trade-space, the C-5 will be the focal point of analysis. This is because most literature that develop future fleets [2] or alternatives to the current fleet [11] still stress the need for a C-5 similar aircraft to carry bulk cargo [32] despite its higher costs or reduced efficiency compared to smaller aircraft. Therefore, it would be beneficial to explore the different avenues that future C-5 like aircraft could develop to improve or maintain its airlift capabilities whilst improving its viability.

The design payload, design range, and pallet capacity of the C-5 will be incrementally varied and combinations of the three series will be generated. The new range and payloads will be used in the sizing equations of Figure 1.5 to produce the necessary empty-, fuel-, and maximum take-off weights for each design. The design payload will be incrementally varied from 35 to 75 tons, and the design range will be incrementally varied from 7000 km to 10’000 km. These changes result in aircraft designs that can be smaller than the C-17 to almost as large as the Antonov An-225. The pallet capacity will be incrementally varied from 30 to 42 PPE’s. This relates to cargo loading efficiency and available volume. Direct evaluations of volume are difficult, and thus the pallet capacity will be viewed in this analysis as an operational parameter. Given the same cargo bay (constant volume), it has been shown that improved loading techniques can produce up to a 25% increase in compartment utilization [33]. Since it is difficult to estimate the CPFH of such distinctly different aircraft designs, the bidding weight of cost will instead be swapped with that of fuel. Since fuel is a constituent of cost it can offer a similar, albeit different, analysis. Naturally, the change in aircraft designs can facilitate a different operational logic. Ergo, to capture this behavior, the bidding weights of time and fuel will be varied in this trade-space exploration, allowing each design to be analyzed for a medley of both time focused or fuel focused objectives.

The design of experiments (DoE) for the trade-space is shown in Table 1.7.

Table 1.7: Trade-space DoE setup

	Time/ Fuel Priority [1 = time, 0 = fuel]	Design Range [km]	Design Payload [tons]	Pallets [PPE]
[min, max] ~step	[0,1] ~0.05	[7500,10000] ~ 0.5	[35,75] ~5	[30,42] ~6
Bid ratio		x	x	x
Range	x		x	x
Payload	x	x		x
Pallets	x	x	x	
Runs per case	15	Total cases	3968	= 5935

4.2 Base mission development

The mission comparison for the main analytics is presented in Figure 1.7. Mission 1 is able to complete the airlift within a time of 4.5 days and a cost of $ 14 (US) million. The commonly used flight paths are shown in Figure 1.9a. The C-5M and C-17 fly directly to Kadena with cargo and then only C-17 fly to Subang.

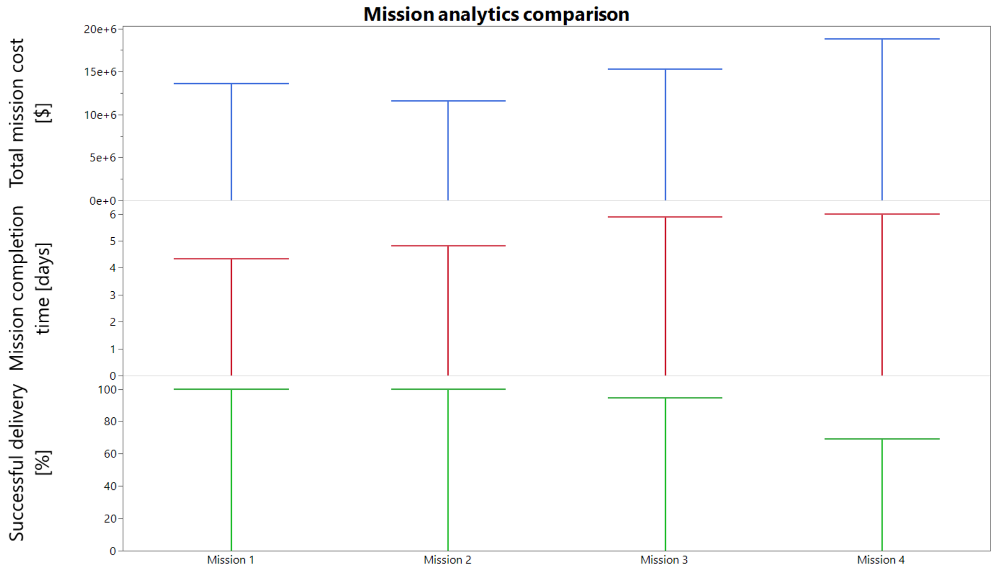


Figure 1.7: Mission setup comparison of key MoE’s

Due to the high cost of the C-5M flights, the C-17 win more cargo bids and fly more. By adding servicing, aircraft flights are arbitrarily delayed, extending the mission time to maintain the same cargo throughput. The addition of spontaneous cargo throughout the operation also extends the mission time, as more cargo is generated, resulting in more flights being scheduled, increasing airlift cost. For some runs, the simulation ends due to the time limit of 6 days, meaning not all cargo is able to reach the destination. The loss of access to Kadena airbase in Mission 4 orces aircraft to fly a less efficient route, as shown in Figure 1.9b, resulting in delayed departure/arrival times compared to those initially scheduled.

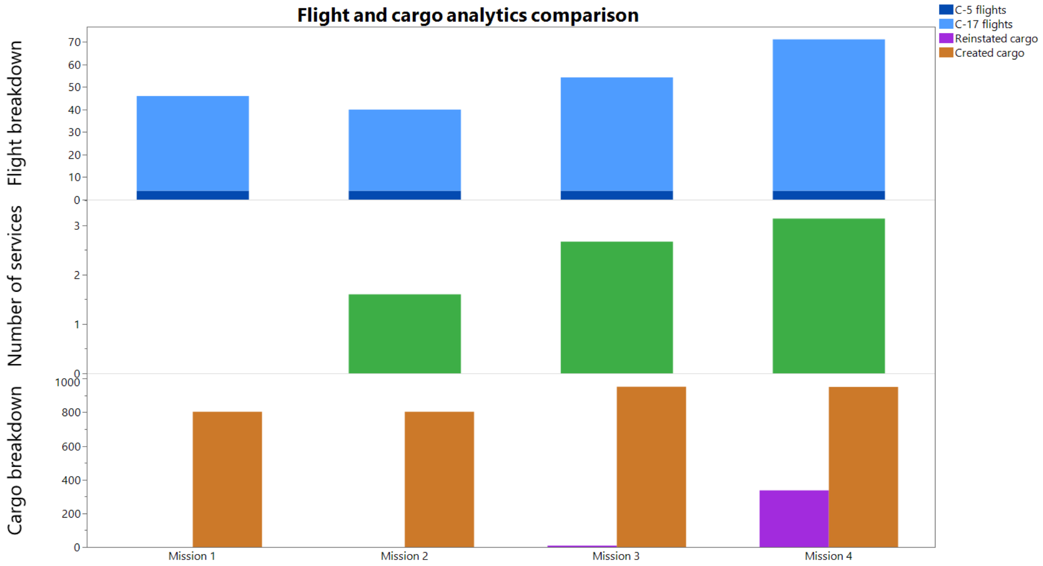


Figure 1.8: Mission setup comparison of flight and cargo analytics

Cargo at Kadena also has to be reinstated, exacerbating the already large cargo demands, as displayed in Figure 1.8. This increases the number of required flights and thereby increases servicing likelihood. These effects compound into a drop in successful deliveries and higher mission cost, as nearly all simulations ends by the time limit of 6 days.

Interestingly, the servicing delays can sometimes be beneficial to aspects such as cost. When the aircraft is serviced, flights scheduled towards the end of the simulation are often removed due to cargo no longer meeting its required RToD. This causes cargo reinstation, placing it on earlier flights, and the cancellation of the delayed flights. These earlier flights originally had a scheduled departure time that was later than the delayed aircraft's flight but they are now the best option for the cargo. Subsequently the number of flights is reduced, reducing cost, at the cost of delayed cargo arrival times. This phenomenon requires very specific conditions to occur and thus occurs infrequently with few cargo being reinstated. However, the impacts are significant as entire flights are removed, reducing cost.

(a) Mission 1

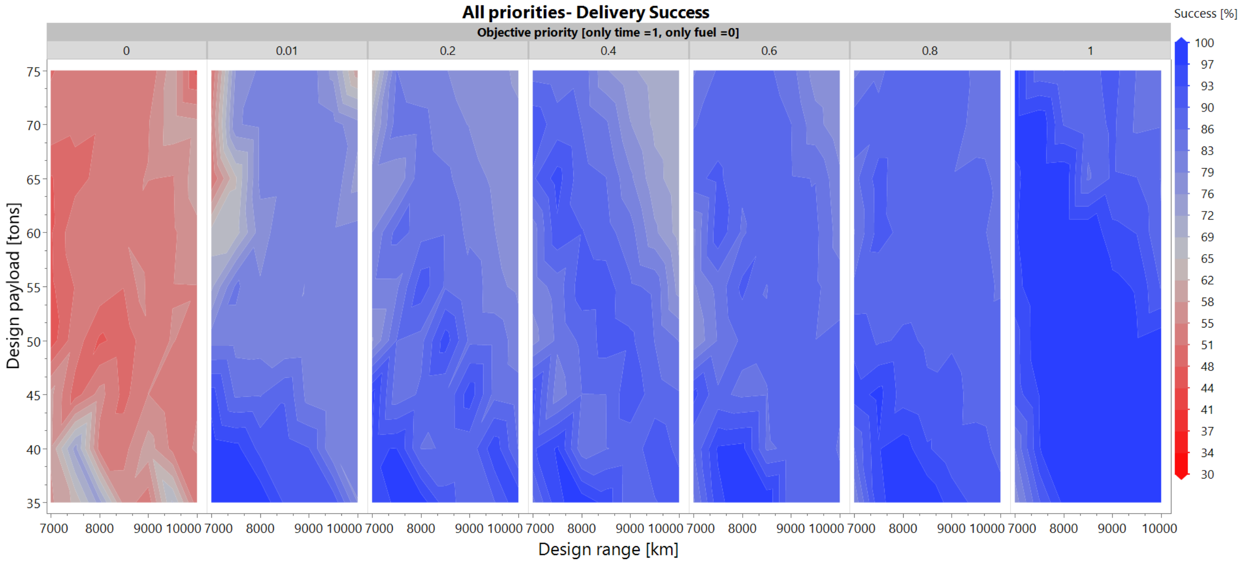
(b) Mission 4

Figure 1.9: Flight path heatmaps

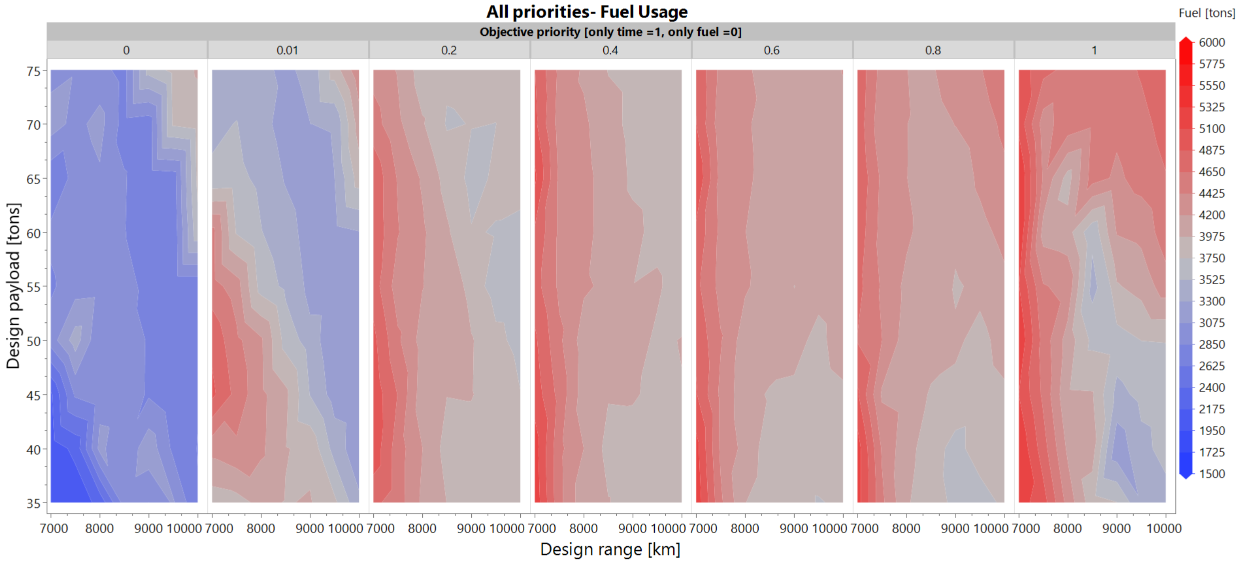
These results exemplify the importance of disruption uncertainties. Disruptive effects, such as aircraft servicing, spontaneous cargo generation and airbase accessibility changes, have significant impacts on airlift performance. In the studied airlift, omitting these uncertainties can underestimate costs by up to $ 4 (US) million, and overestimate cargo delivery throughput. The goal of this analysis is not to justify default application of these uncertainties; rather to motivate the inclusion of these aspects to better emulate the potential extremities of an airlift, which can aid in resilience testing and risk comparison.

4.3 Trade-space exploration

For the trade-space exploration, a total of 189 different aircraft designs were evaluated using 21 different airlift objectives. The results for delivery success and mission fuel usage across the different designs and objectives is shown in Figure 1.10. The objective priority brackets include that which is indicated until the next bracket. For example, ”Objective priority 0.8” includes the priority ratios of 0.80 to 0.99. The color gradients are used for qualitative comparison, providing a greater perspective of trend analysis.



(a) Delivery success comparison



(b) Fuel usage comparison

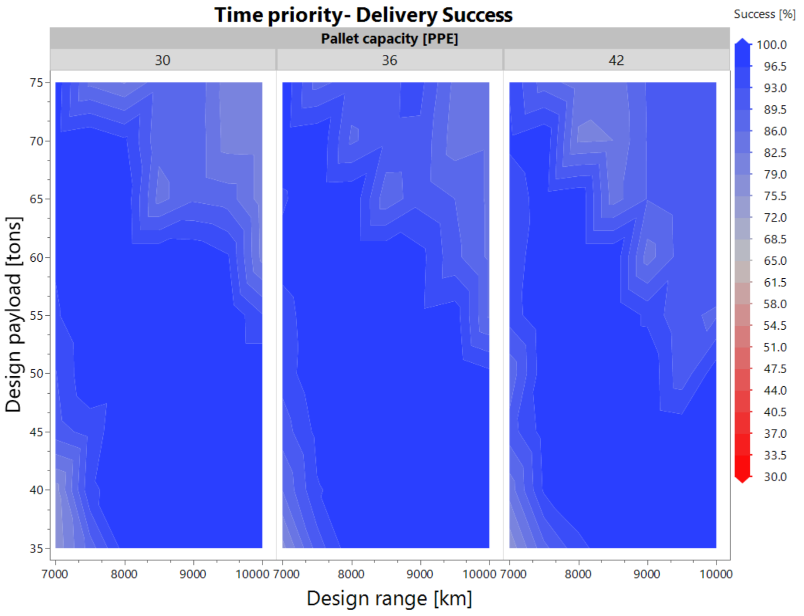
Figure 1.10: Trade-space MoE evaluation for all designs and bidding weights

As time priority increases, the delivery success increases, as larger designs become favored. Despite some missions having aircraft with high payload-range capabilities, missions with smaller aircraft tend to perform better than others, even at high time priorities. This is because of the fuel consideration, as the increased payload capabilities incur a higher fuel consumption. Prioritizing time puts less emphasis on fuel efficiency, increasing the fuel usage, as seen in Figure 1.10b. Higher success missions often complete the mission earlier, requiring fewer flights, which may result in a decreased fuel consumption despite high time priorities. When aircraft are designed with a high range or payload, the fuel considerations favor C-17 utilization. C-17 over-utilization extends mission time and inhibits delivery success, but reduces fuel usage for the same number of flights.

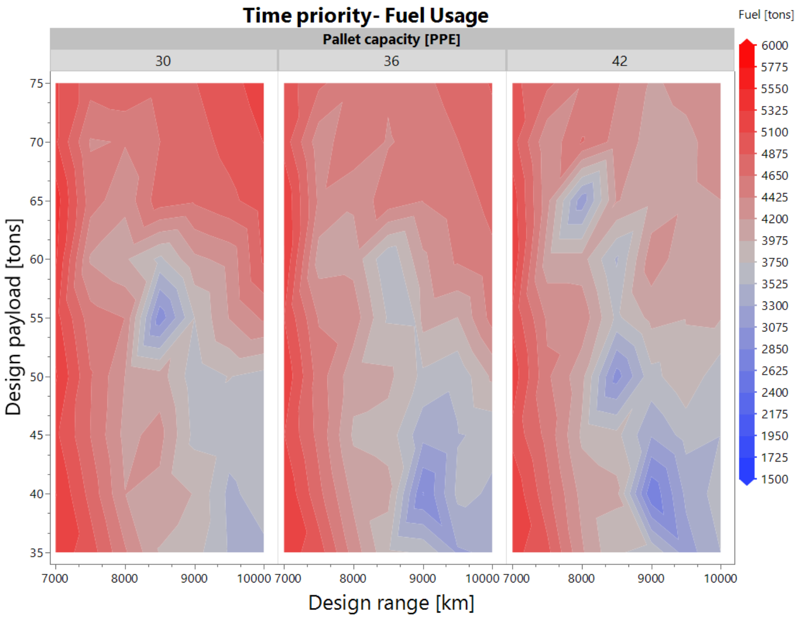
Aircraft with a relatively lower design payload range perform better than larger aircraft, though time priorities can alleviate this. Smaller aircraft tend to out-perform the C-17 in terms of payload capabilities, but can still have higher fuel usage- despite being more efficient than larger designs. When fuel priority is increased, either the aircraft should be designed as small as possible to be as similar or better than the C-17, or they should be designed with exceptional payload-range capabilities so that its low utilization offers great benefit. To further explore the trade-space, time focused (=1.0), fuel focused (=0.0) and mixed objectives (=0.50) were individually analyzed. Figure 1.11 shows the pure-time analysis.

Within the time priority, is a large band of designs that attain a 100% mission success, but the mission completion time can offer useful insight. The completion time and fuel usage present similar trends, with key designs performing missions better than others. There is a diagonal trend of aircraft designed with 42 pallet capacity that complete the airlift prior to the airbase even being destroyed (<2.5 days). These designs may seem distinct from one another, but due to the sizing method used to create the designs, they are with similar aircraft weight values. The minor variations highlight the potential for an optimization process to occur. Unexpectedly, these aircraft perform better than those designed with greater payload/ ranges.

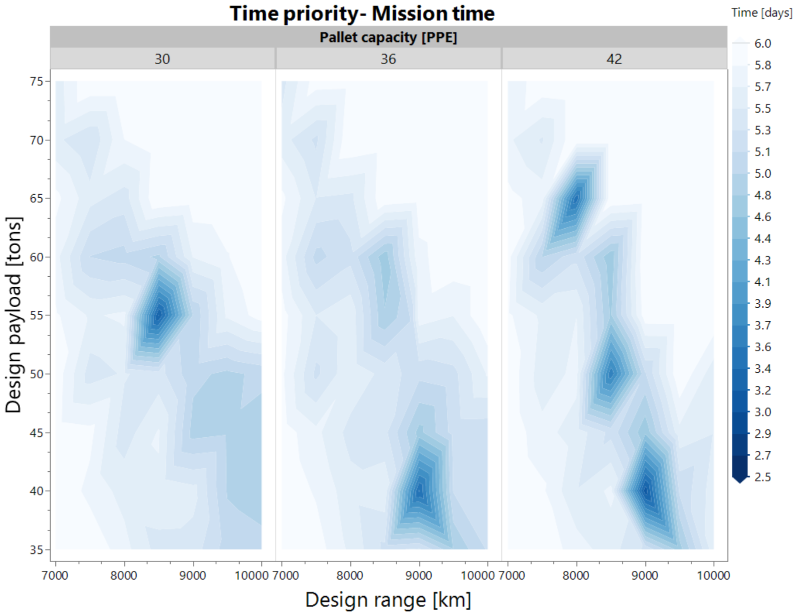
When time is the only focus, a flight's scheduled departure time is critical. Aircraft that designed for a higher range/ payload they have a higher empty weight and fuel capacity, meaning that they can carry more cargo, but also consume more fuel. The increased fuel consumption and capacity translates to greater refuelling times (70 mins), sometimes twice as much as the better performing aircraft. Despite this being a relatively short time difference, it may result the refueling time becoming the key constraint on ground operations as opposed to loading times and other events. This compounds into delayed departure and arrival times for future flights, resulting in increased C-17 utilization due to their faster turn-around times for cargo flights. The increased C-17 utilization is a drawback as it inhibits their ability to conduct the final leg of flight to Subang, extending the number of required flights and delaying mission time. The purpose of this conclusion is to highlight the drawbacks of a pure-time priority, guiding users to define operational objectives with several insights in mind.



(a) Delivery success comparison



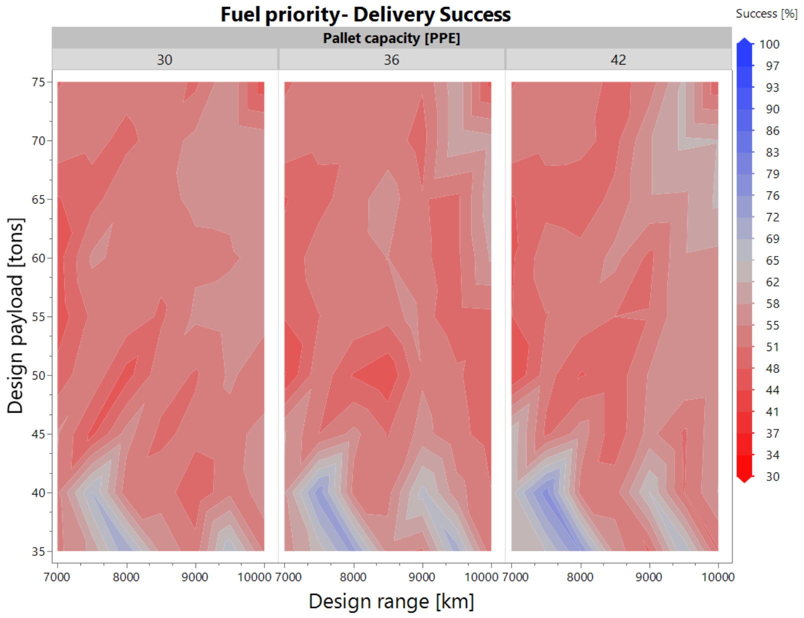
(b) Fuel usage comparison



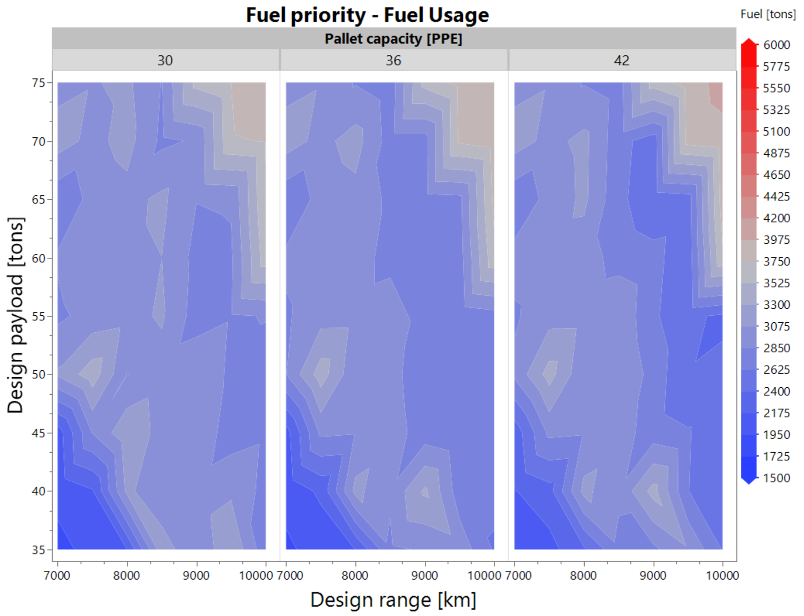
(c) Completion time comparison

Figure 1.11: Trade-space MoE evaluation for time prioritized missions

The same analysis can be done with a pure fuel focus. Aircraft design performance in only fuel prioritized missions is presented in Figure 1.12. When fuel is the sole priority, flight departure and arrival times are inconsequential. Aircraft which are designed with a lower range and lower payload consume less fuel than others and are favored in the bidding process. The reduced size also means the aircraft carry less cargo. When combined with the absence of departure time considerations, most of the missions within this objective bracket suffer from low success percentages, where commonly less than half of the total cargo is delivered. In fuel prioritized airlifts fewer flights are scheduled, as deadheads are disfavored. When the C-5 are designed with a low payload and range, they offer competitive or better fuel consumptions to the C-17, which can be favorable for fuel prioritized missions.



(a) Delivery success comparison

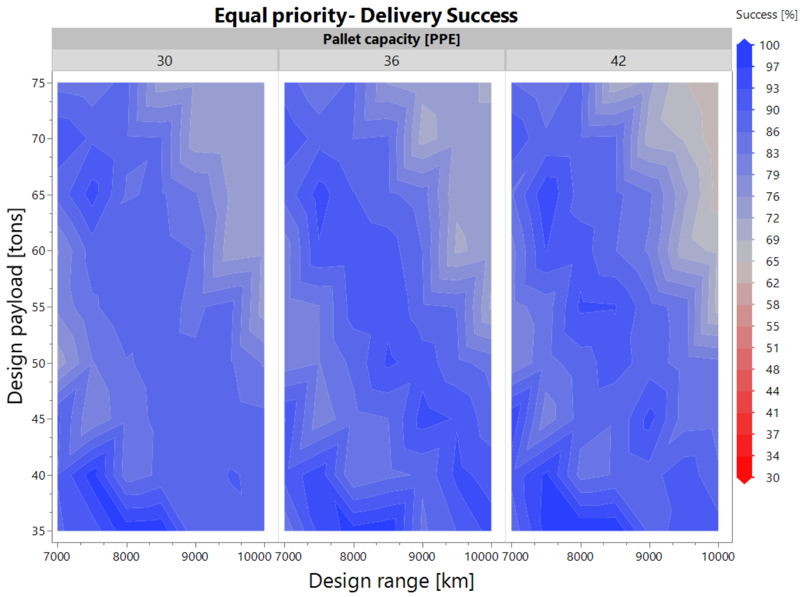


(b) Fuel usage comparison

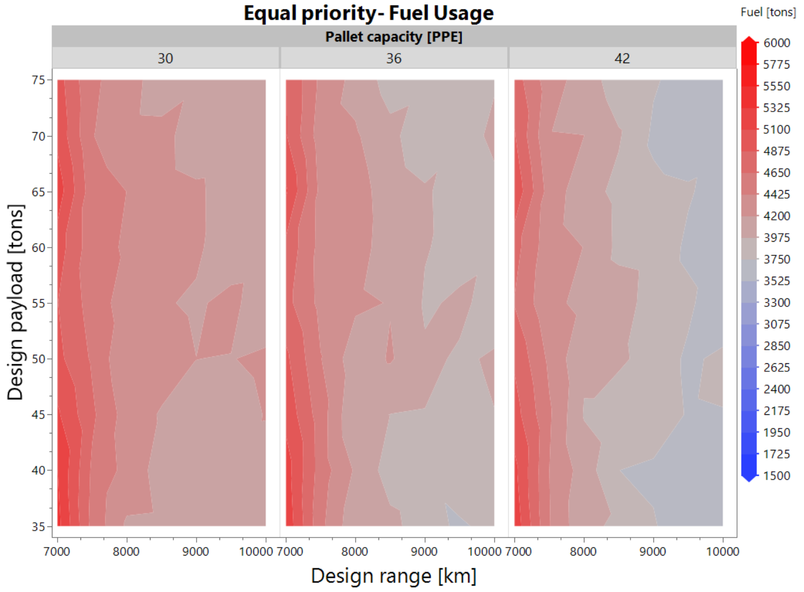
Figure 1.12: Trade-space MoE evaluation for fuel prioritized missions

Minimum mission fuel usage is obtained when the C-5 variant takes the majority share of flights, allowing a set of the C-17's to focus on conducting the last leg of flight, with some even remaining at the origin in the US. This can be beneficial for fuel usage, but diminishes mission success due to the reduced payload-range capabilities. Conversely, when the C-5 variant fuel usage is no longer competitive with the C-17's, over-utilization of the C-17 occurs once again, inhibiting success and increasing mission fuel usage. These analyses illustrate how the framework aids in assessing aircraft interactions within a heterogenous fleet.

Lastly, when the objective reflects an equal weighting of these priorities, the results of Figure 1.13 are obtained. The delivery success shows a blend of time prioritized and fuel prioritized trends; the time-priority trend for strong performing aircraft which trade-off payload and range and the fuel-priority trend of favoring of fuel efficient designs are present.



(a) Delivery success comparison



(b) Fuel usage comparison

Figure 1.13: Trade-space MoE evaluation for equally prioritized missions

By considering both time and fuel, the C-5 variants are favored when they either offer a competitive combination of a reduced fuel and departure time, or if they offer a greatly reduced departure time/ fuel usage despite an increased fuel usage/ departure time. The utilization decreases as range and payload is increased to high values, as the fuel consumption increases deter their usage. That being said, the increased payload capabilities can greatly reduce the required C-17 cargo flights, stabilizing the mission fuel usage. Surprisingly, when aircraft are designed with low fuel consumption (low payload and low range), the mission fuel usage is similar or worse to missions with larger aircraft designs. When aircraft are designed with a fuel consumption rivaling the C-17, the bidding departure time becomes determinant. This means that aircraft may win bids even if they schedule deadheads to reach the origin. The deadheads allow for a timely mission completion, but significantly increase mission fuel.

Deadheads are reduced when aircraft are designed with a higher payload/range as the disparity in fuel consumption becomes more significant, but then there is the recurring problem with C-17 over-utilization. The pallet capacity does not have a significant effect in this area, but can improve regions with high success or low fuel. By designing airlifts with an equal priority of time and fuel, aircraft design can be tuned such that high success rates rivaling that of a pure time objective whilst reducing fuel usages for the same situation.

One can determine the ”best” or most resilient aircraft design in the trade-space by finding the missions which result in a minimum mission fuel usage whilst achieving a 100% cargo delivery success. The framework allows for this by plotting the different mission designs across the MoE's, as shown in Figure 1.14. The two circles indicate optimal and near-optimal missions. The green circle highlights the best missions. All optimal missions are those designed with an almost pure time objective with relatively low payload and ranges. It may be bias to consider these designs as ”best”, as they are highly dependent on the scenario developed. This becomes evident when analyzing the mission completion time, where impact of the airbase accessibility is not present due to the completion before 2.5 days. The orange circle missions are all delayed because the airbase restriction caused the few remaining cargo at Kadena to be reinstated, extending mission time until the flights are conducted. These designs are very similar to the green circle's with slight changes, indicating an optimal design space or pareto front.

These results are not definitive and should be considered as an exploration of the framework's abilities and drawbacks. Thus, the framework can help identify desire-able aircraft and operational designs, but should be used for evaluation with a defined set of scenarios that are robust and fit the designer's goals.

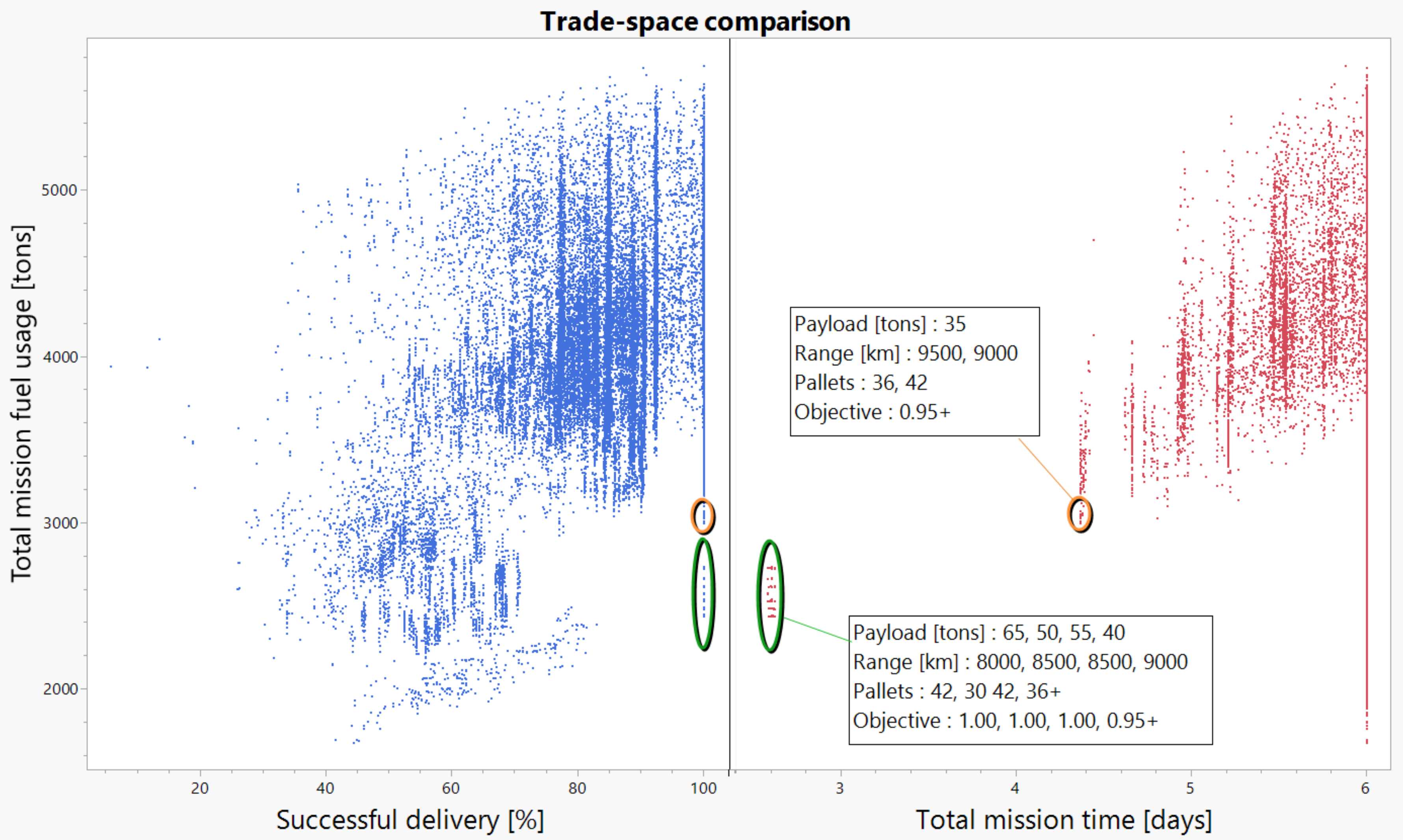


Figure 1.14: Trade space design comparison

5 Conclusion and Recommendations

The purpose of this paper was to design a framework that couples aircraft design and strategic airlift operational effectiveness for the sake of supporting future aircraft and fleet design. This was performed with an airlift simulation model that models aircraft, airbases, cargo and a dispatcher entity (mimicking an air traffic manager and flight scheduler) as agents. In doing so, the model can navigate through a dynamic operations environment, induced by events such as aircraft servicing, airbase access restriction and cargo requirement reformulation. Typical aircraft design tool outputs are used to model the aircraft along with a Breguet range equation to determine their payload-range capabilities. To allow for the modelling of various operation cases, the tool takes inputs to create its environment and determine its flight planning and cargo allocation logic. Information such as: the map size, cargo demand data, the airlift objective (a mixture of closing time, cost, fuel usage, etc.) and those relating to the aforementioned dynamic events are all customizeable inputs. The simulation then outputs important measures of effectiveness, such as total mission time, cost and fuel usage, and aircraft performance data for the different aircraft and the fleet. Heatmaps displaying the traffic network can be created to better visualize the system's operation.

The agent-based model employed allows for capturing of risk management and emergent behaviors when faced with black-swan events. When aircraft face schedule disruptions, they check each cargo to ensure its requirements and flight itinerary is maintained. If not, cargo is efficiently re-processed and a new itinerary is created that aligns with its requirements. This functionality combined with cargo generation mid-simulation (spontaneous cargo) sustains the flexibility and robustness of the airlift simulation model, allowing users to test aircraft and fleet resilience in a variety of extreme scenarios.

To illustrate the importance of including unexpected events, a sample HA/DR mission from Travis USA to Subang Malaysia was constructed. Within, a fleet of C-5M's and C-17's were tasked to move food, water, VTOL's and generic pallets in a 6 day time period. The mission was then incrementally developed to include aircraft servicing, spontaneous cargo generation and then airbase access restriction, which was applied to one of the intermediate bases. Since these events and their impact is stochastically modelled, the simulation is run 15 times per setup. Aircraft servicing delayed flights, extending mission time by half a day and sometimes resulting in better flight scheduling. Spontaneous cargo increased amount of cargo needed to be transported, increasing the total flights required and thereby increased mission time to almost 6 days and cost by almost $ 6 (US) million. When access to the commonly used airbase was restricted mid-simulation, the aircraft had to reschedule their flights to fly less efficient routes, extending total flight time and mission costs. The cargo present at the airbase at also had to be recreated, further burdening the aircraft. The impact of this restriction cause mission failure, with 30% of cargo not reaching its destination. Such results showcase the novelties of this thesis, and although these aspects may not plague every airlift, they can drastically compromise original airlift strategies and fleet plans, motivating their inclusion for proper airlift and aircraft evaluation.

Lastly, since this framework is to be used in conjunction with aircraft design, a demonstration of this interplay was done through a trade-space exploration of a C-5M similar aircraft using the fully developed sample HA/DR mission. The design payload and range was varied and using conceptual design sizing equations, the necessary inputs for the aircraft model were generated. Additionally, the impact of gradually varying the airlift objective from time to fuel priority was assessed. Noteworthy results from the exploration are that when prioritizing fuel, C-5 designed with a minimum payload and minimum range are optimal, but mission completion suffers, with the best delivery rates only achieving 70%. Conversely, when prioritizing time, most missions are successful, but to achieve a desirable fuel usage, the C-5's design range and payload must be within a certain threshold that does not compromise its refuelling time. When weighing both time and fuel equally, results incorporate the trends present in both time focused and fuel focused missions.

Despite the results being theoretical and situation specific, they representative of the framework's utility in determining aircraft and operational designs that offer the greatest resilience in extreme scenarios. Even for the same aircraft design, the multitude of inputs and different design objectives can produce different results, which can aid designers and operators alike in creating and determining limiting situations for each design. In conclusion, this work has fulfilled its purpose- coupling aircraft design to its operational effectiveness in a strategic airlift- whilst providing improvements to state-of-the-art airlift operational models (its environment and process logic). That being said, there are improvements that can be made to the aircraft model and the airlift model.

Aircraft modelling can be expanded in several avenues. Currently, aircraft data is parameterized into mean values (bulk velocity, L/D, TSFC, etc.) but ideally these should be based on flight altitude and thrust level and loaded mass. Weather effects are also missing in aircraft performance. Although the literature review indicated temperature data to be significant only in extreme scenarios, wind effects can greatly affect flight times, changing applicable cargo loads for the same fuel margin. These could be modelled stochastically per flight, but ideally a proper air current model would be overlaid depending on the flight trajectories. Aircraft cargo loading can be better defined as currently the cargo configuration within the aircraft and cargo geometries are not considered. The inclusion of aerial refuelling would also be essential to such operations, as it is already used in airlifts to extend payload-range capabilities, but was omitted in this work due to its complexity.

The airlift simulation model can also be further developed. Features such as having a side-by-side model for sea-lift and ground transports, like trains and trucks, can help better simulate the totality of cargo movements, expanding the system of systems nature. These could also be used to further benefit the airlift capabilities, since large sea-craft can double as cargo repositories which aircraft can help transport, essentially acting as moving airbases. This also brings the topic of airbase creation, where the airlift could transport resources to a location and ground agents use said resources to rapidly construct a simple airbase, offering an additional refuelling zone. Lastly, an incorporation of tactical airlift models which deliver the supplies directly to the afflicted areas would help to see the combined, subsidiary effects of strategic airlift decisions and aircraft design on the final operation. For example, larger aircraft could carry VTOLs which could then benefit the tactical airlift upon assembly, which could outweigh the fact that these larger aircraft expend more fuel and have increased refuelling times. In this regard, the total airlift, from beginning to end, would be simulated enabling better comprehension of design and operational changes on the greater mission success. The bidding model would have to be expanded in this regard to combine both strategic and tactical airlift vehicle bids and the resulting combinations of bidding pairs.

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Chapter 2

Literature Study

1 Introduction

When a disaster breaks out across the world, many large nations and militaries seek to provide immediate humanitarian aid and disaster relief (HA/DR) to the affected area. The cause of the disaster can be due to natural causes or wartime aid, however in any case due to the time urgency and hazardous environments, the required aid and provisions require an extraordinary movement of cargo. The solution is a rapid cargo airlift, whereby aircraft capable of flying for extended ranges with large payload are tasked with inter-continental sorties. The unpredictable nature of the airlift requirements often leads to inefficient and costly operations. Additionally, the high utilization of cargo aircraft during a movement can result in design flaws to be magnified and maintenance issues, further encumbering the airlift. As such, there is a need to improve airlift missions, from the perspectives of both operations and aircraft and fleet design.

This literature study therefore aims to investigate how airlift missions have been, and can be further, improved. This will be answered by analyzing several different, established approaches- under the branches of: aircraft and fleet design, load planning and route scheduling, and operations and airbase design. Each of these disciplines will be discussed in this paper so that gaps in knowledge can be identified for the purpose of defining a research question, and subsequent sub-questions, for a thesis project.

A background on cargo airlift will first be presented in this paper, which proceeds into a review of the publicly available literature concerning airlift missions, ensuring that research targeting the different aspects of airlift missions (aircraft and fleet design, route planning and airlift operations) is covered. Once the literature review is conducted, the research question and supplementary sub-questions can be derived based on existing knowledge. This section will also highlight pertinent research objectives and a preliminary research plan. Finally, a concluding section of the literature study will be presented.

2 Background on Rapid Cargo Airlift

Cargo airlift is divided into 2 types: strategic and tactical. Strategic airlift is the longest phase of the airlift and deals with the inter-continental travel between an embarkation hub where the bulk cargo is originated, and a debarkation hub, where said cargo is unloaded [1]. Tactical airlift is the proceeding travel between the debarkation hub to a forward operating base or to the final recipient [1]. This portion of airlift is commonly referred to as “the last mile” delivery. Distinguishing airlift into these two legs allows for aircraft specialization. Strategic airlift is conducted by very large aircraft which have large volumes and extended ranges. Examples are the C-5 Galaxy and C-17 Globemaster [2]. The need for landing and takeoff capabilities in austere locations limits larger aircraft from conducting tactical airlift, which is relegated to C-130 variants and VTOLs [3]. Due to the larger number of capable aircraft for tactical airlift and reduced load requirements, strategic aircraft are often regarded as the primary airlift vehicles and secured by militaries.

Although the rapid airlift of cargo is often associated with the military domain and HA/DR missions, the distinction between these two operations is minimal. Both airlifts require a fleet of considerably large aircraft to transport the bulk cargo from the origin hub to a debarkation hub, where the cargo is then sortied to the final destinations using a batch of smaller aircraft or VTOLs [4]. In either case the time and cost of the missions are sought to be minimized and the compounding effect of delays can be detrimental to the mission’s success. The greatest difference between the two deals with the cargo to be transported; military missions often will transport a combination of pallets and rolling stock such as vehicles and other outsized cargo whereas HA/DR missions often will transport food and water provisions along with occasional airlifts of VTOLs [5]. Due to the similarities between the mission types, literature review will deal with both use cases as the same aircraft fleet that carries out military missions is often used for HA/DR missions and vice versa.

The literature review will be segmented into 3 different branches concerning the different disciplines that comprise an airlift operation: the aircraft and fleet discipline, the route planning discipline and the operations discipline, which will also include some infrastructure design. Aircraft design and fleet operations in airlift will be discussed first, following will be the literature review concerning the creation of route planning and optimization, and finally airlift operations dealing with airbase and mission operations will be overviewed.

3 Aircraft and Fleet Design

In terms of airlift aircraft design, there is limited literature focusing directly on the aircraft parameters, instead the fleet design is commonly analyzed.

J. Maywald et al. [6] are authors who advocate for a change in traditional cargo aircraft fleet design and operation. Airlift for military and HA/DR operations is conducted using a hub-and-spoke delivery system, where mass aggregation of the cargo is performed at major aerial port hubs and then delivered to the smaller port hubs or recipients. The delivery system allows for efficiency maximization but conversely results in a segregation of aircraft into those applicable for the inter-continental travel [6]. With the modernization of aircraft technology, smaller aircrafts that were originally ignored for strategic airlift are more capable to perform longer distance travel with heavier payloads. To improve the system the authors suggested a more holistic analysis whereby all aircrafts, strategic and tactical, would be incorporated into airlift planning [6]. To illustrate the potential benefits, the authors created an Aircraft Selection Model (ASM) which allowed for smaller, tactical aircraft to be considered for longer sorties by using "hopping" or intermediate stops between major hubs for refueling [6]. Such a procedure increases the maximum payload allowable on the aircraft due to the reduced fuel requirements. The ASM was then applied to a month-long cargo movement with daily sorties with the goal of optimizing the movement's costs. Results showed several replacements of airlift sorties which were originally conducted by C-5A's, a traditional strategic airlift aircraft, with a set of smaller C-130J-30 Super Hercules, a traditional tactical airlift aircraft [6]. The substitutions reduced sortie costs by up to $65,000 adjusted to inflation and total sorties reduced since larger aircraft were more available when required instead of being utilized on smaller cargo sorties [6]. An example of the improved planning approach leading to greater utilization is provided in Figure 2.1.

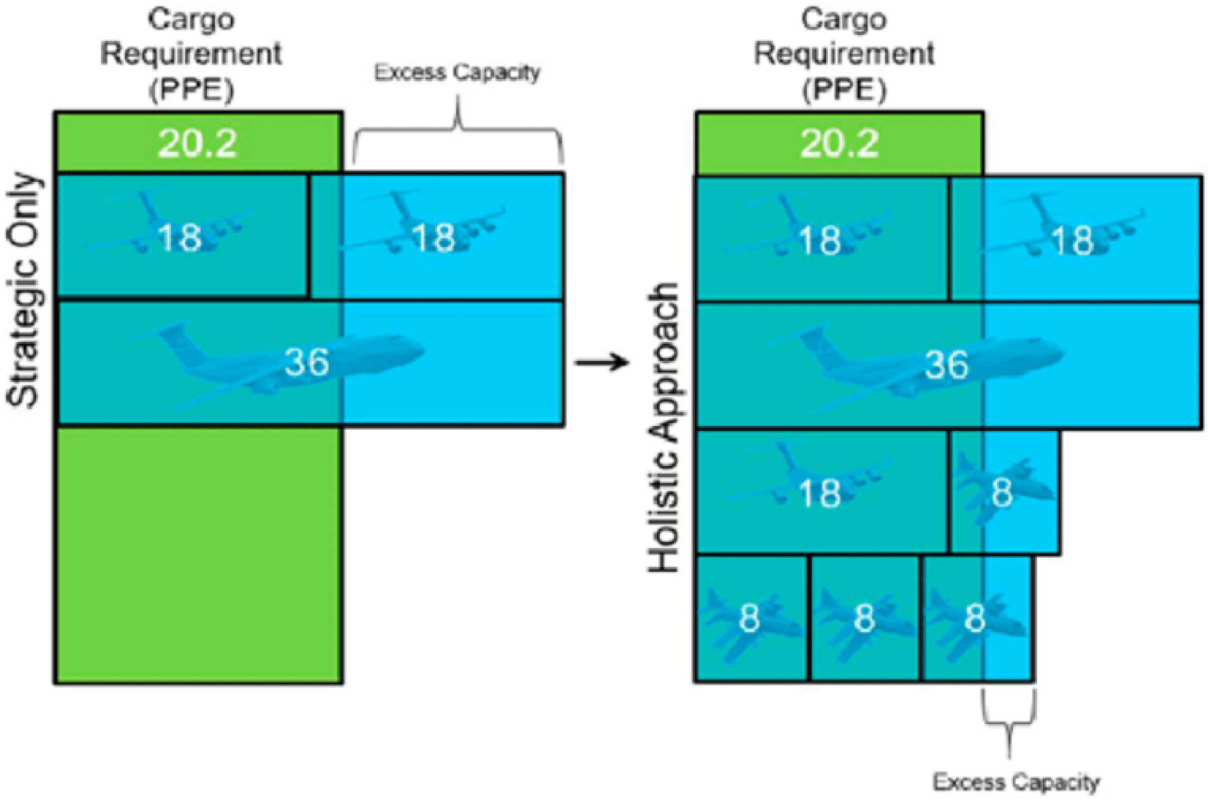
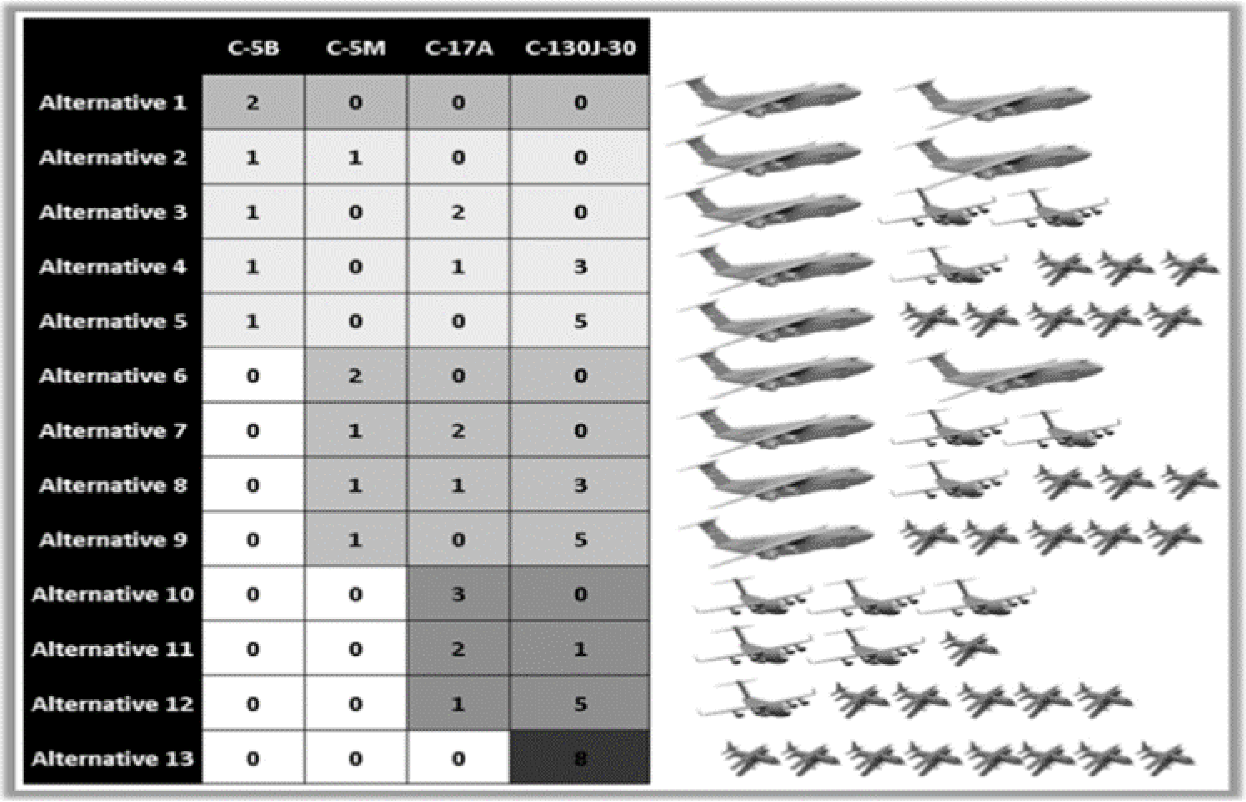


Figure 2.1: Improved cargo utilization with all-inclusive planning (from [6])

Due to the prospects of these results, J. Maywald et al. continued with a further analysis on the same movement but expanded upon the ASM, using multi-step heuristics, and loading model, using an iterative algorithm [7]. The heuristic algorithm is used for the ASM, and allows for the user to input constraints on the available routes, cargo requirements, aircraft availability and aircraft's required payload characteristics-such as outsized cargo only being loaded in C-5 and C-17 aircrafts [7]. The ASM outputs a set of alternatives that minimize the objective function, chosen to be the fuel consumption of the fleet in the sample movement. The set of alternatives is presented in Figure 2.2.



	C-5B	C-5M	C-17A	C-130J-30
Alternative 1	2	0	0	0
Alternative 2	1	1	0	0
Alternative 3	1	0	2	0
Alternative 4	1	0	1	3
Alternative 5	1	0	0	5
Alternative 6	0	2	0	0
Alternative 7	0	1	2	0
Alternative 8	0	1	1	3
Alternative 9	0	1	0	5
Alternative 10	0	0	3	0
Alternative 11	0	0	2	1
Alternative 12	0	0	1	5
Alternative 13	0	0	0	8

Figure 2.2: Aircraft alternatives for inter-theater airlift (from [7])

Following this, each alternative is loaded with cargo using the loading model, which equitably distributes the pallets amongst the aircraft based on the lowest utilization rate (the ratio of loaded pallets to maximum allowable) [7]. The loading order prioritizes pallets with the highest mass and the model ensures the sizing requirements of the payload and aircraft are met. Figure 2.3 visualizes the loading algorithm.

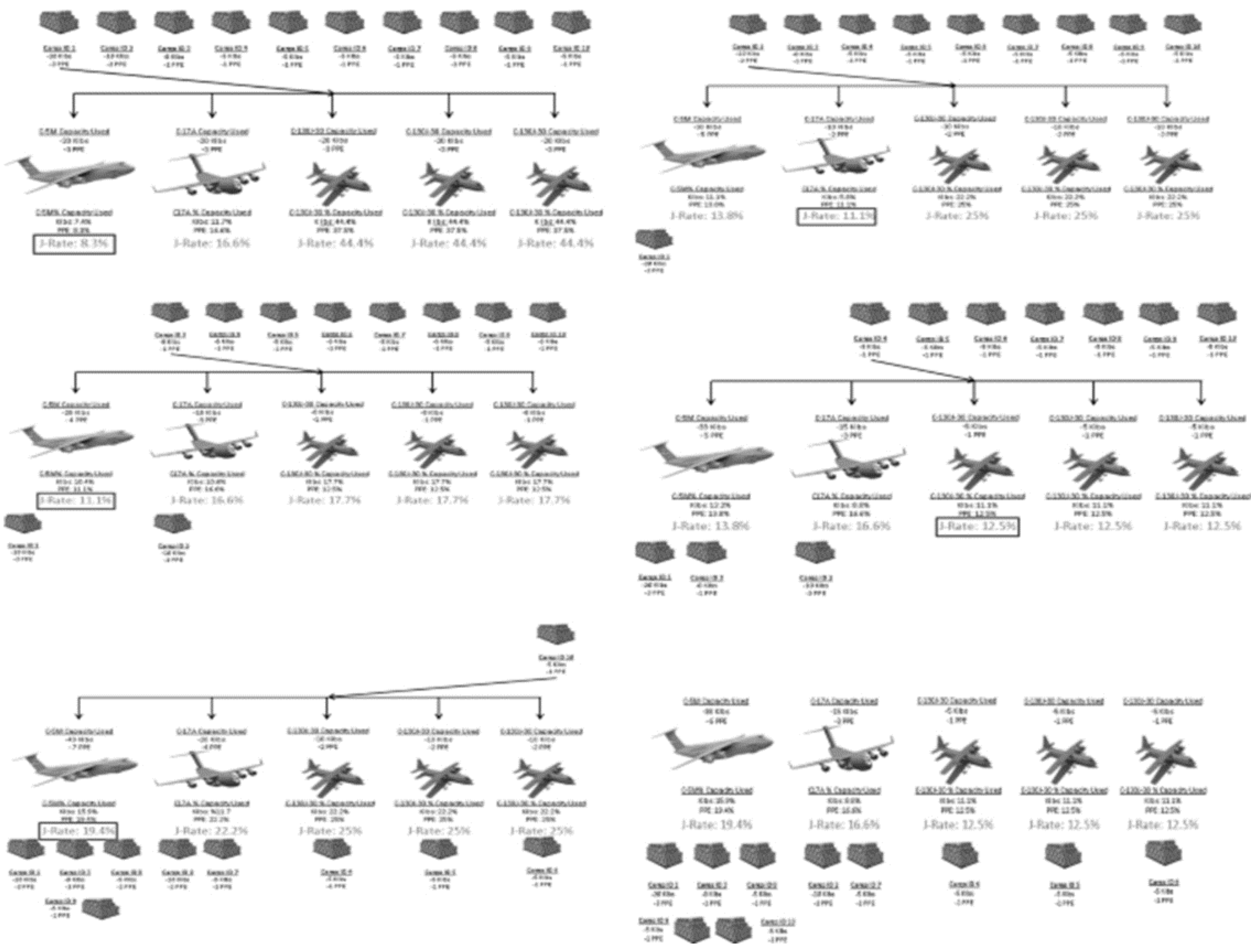


Figure 2.3: Cargo loading algorithm visualized (from [7])

Aircraft routing is done based on nodal reduction techniques from A.D. Reiman [8], which uses the aircraft's range constraints and regression equations for the fuel consumption in the climb, cruise and descent segments to determine optimal flight paths. Lastly, assumptions such as only analyzing cargo (excluding passenger) sorties in the movement and having all loaded cargo within the aircraft share the same destination were made to limit the problem definition [7]. The authors concluded that the selection model used the Super Hercules for several sorties, once again reducing the total movement fuel and operation and logistics cost savings by more than $6M for the month [7].

The conclusion of J. Maywald et al.'s [7] work is that future airlift movements should seek to incorporate smaller strategic aircraft that bridge the gap between tactical and strategic airlift. The availability and serviceability of such a fleet is an aspect not discussed, as it was assumed all the aircraft were available and present at a given time [7]. J. Maywald et al.'s [7] models for cargo allocation based on lowest utilization rate may be worthwhile to include in future research so as to evaluate the effects of changing the objective of the cargo model, seeing if lowest utilization rate is the most effective manner of distribution depending on the mission objective.

For tactical airlift fleet design, A.J. Sugalski [9] examined different VTOL fleets for conducting a HA/DR supply mission in a hurricane disaster of Puerto Rico. Models for the daily cargo demand were made to recreate the disaster of 2017 and then the movement was carried out using different VTOLs and Unmanned Aerial Vehicles (UAVs). The VTOLs selected, MV-22B and the HH-60W, were compared to a UAV, the FLI: Turtleback. Despite the Turtleback only being able to carry 1 cargo pallet at a time, up to 4 UAVs could be managed by a single operator at a time [9]. In the fixed demand model which recreated the scenario, results found that both the MV-22B and the HH-60W only required 1 unit to conduct the daily sorties, with the MV-22B having a reduced utilization- beneficial for service life and faster delivery times [9]. The Turtlebacks required 3 units to complete the daily sorties, and suffered a high utilization of 15.4 hours for the day [9]. The benefits of the Turtlebacks become apparent when increasing the units per day; to complete the mission in the same time as the MV-22B (6.7 hours), 7 Turtlebacks would be in operation, but half the number of operators is required compared to the MV-22B [9]. The daily utilization of assets with increasing Turtleback use is presented in Figure 2.4.

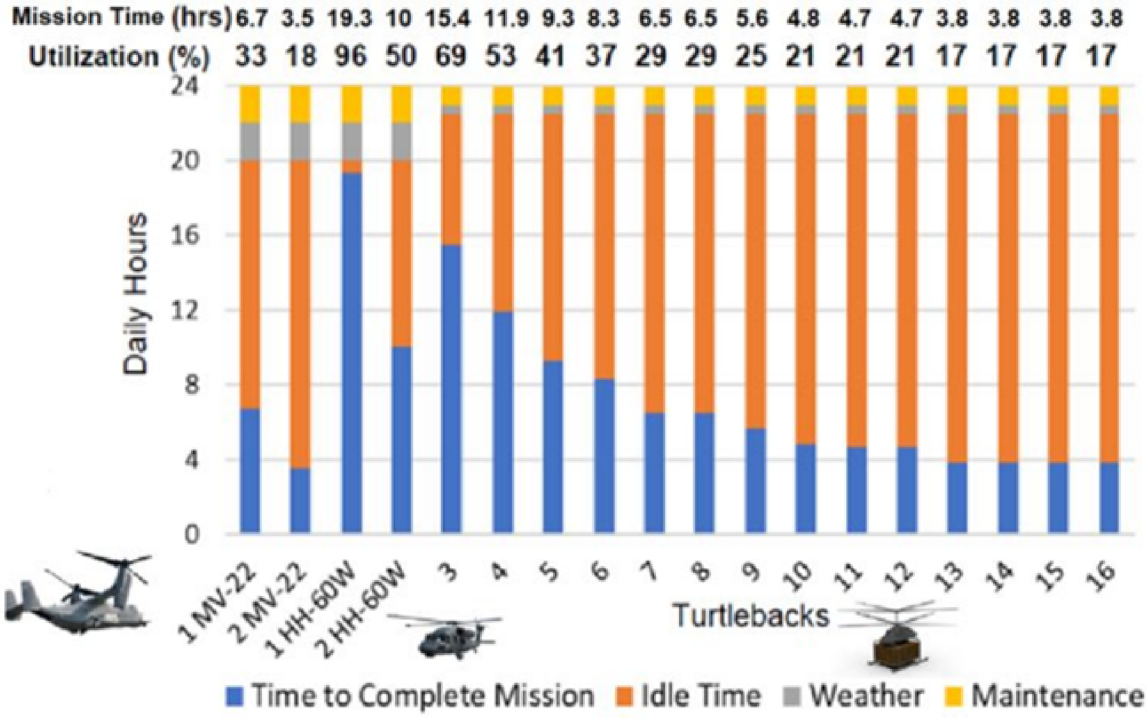


Figure 2.4: Daily utilization of VTOL assets (from [9])

The author then created another model for a varying demand scenario in which the number of people requiring aid is increasing and the distance between the cargo base and the affected region is increased. This model reflected similar points to the first model but allowed for planner to tailor the demand to match their own situation to obtain an optimal fleet analysis [9]. One key conclusion from the planner was that the Turtlebacks offer a greatly reduced cost and timely completion but if a more effective and faster response is required, then using the MV-22B is still optimal [9]. Although the author included operation costs, personnel requirements and the ability to fly longer in bad weather for the UAVs, they assumed an unlimited ramp space or airbase capacity for UAV storage and servicing, meaning the feasibility of the fleet may be unrealistic [9]. As well as this, the on-ground operations and complications for loading up each Turtleback frequently was discussed but not incorporated [9].

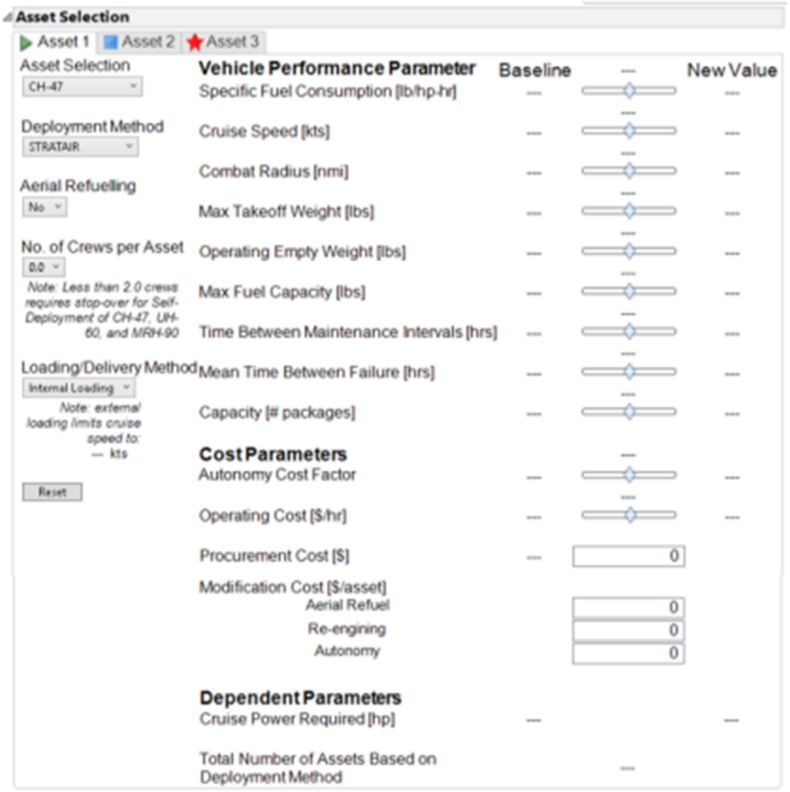
This research is an ideal analysis of how asset type variation can have significant effects on the airlift speed and cost. Further research can be done on fleet heterogeneity in finding a robust solution to different airlift scenarios where both cost and mission time are minimized. The cost modeling regarding operations (crew cost) from this work and the idea of analyzing a fleet's performance under a different set of demand locations and number of requests can be adopted for future research on fleetwide analysis.

One of the few attempts to investigate the effects of specific aircraft design parameters on the operation's success can be found in the work of C. Weit et al. [5]. The authors evaluated VTOL vehicle design (take-off weight, cruise speed, fuel consumption, combat radius, etc.) and operating parameters (aerial refueling and autonomy capabilities) on a discrete event simulation of a Fijian humanitarian aid mission [5]. For the operation, the Fijian islands were aided by Australian military, which meant that if VTOLs were incapable of the long-haul flight to Fiji, they were disassembled, flown by strategic aircraft such as the C-17, and then re-assembled at a nearer port [5]. The delivery of supplies was performed such that areas with larger population density were treated equally to areas of lower density under the assumption that each area would distribute the parcels amongst the afflicted area [5]. The different technology improvements were reflected into reductions in takeoff weight, fuel consumption and storage requirements, cruise speed and the required servicing time [5]. The conversions of different technologies onto the aircraft design used by the authors is presented in Table 2.1. Despite the implications on subsystem design that would occur due to technology improvements, the authors emphasized that the goal was to benchmark new subsystem requirements for their eventual design [5].

Table 2.1: Technology modifications and their physical analogs (from [5])

Parameter Group	Technology Group	Aircraft Parameters
Vehicle Parameters	General Airframe Technologies	Maximum Take-off Weight
		Empty Weight
		Maximum Fuel Available
		Cruise Speed
	Reduced/Zero Maintenance Technologies	Mean Time Between Failure
		Mean Scheduled Downtime
	Engine Core Technologies	Cruise Specific Fuel Consumption
		Combat Radius
Operating Parameters	Deployment Technologies	Aerial Refuel
	Autonomy Technologies	Autonomous Operations
		Semi-Autonomous Operations
		Teleoperations

Cargo and crew loading were simplified to a dispatch center where present vehicles were placed in a pool, indicating availability. Pooled aircraft are loaded as required and unloaded upon mission completion, re-entering the pool [5]. Vehicle delays due to flat tires, rotor power-train breakdowns and other afflictions were modelled as a 15% chance of a 3-hour or 5-hour delay during a mission [5]. To simulate the constrained operation environment, fuel pumps were limited to 300 gallons per minute [5]. By conducting a design of experiments (DoE) along with a constituent surrogate model, the different parameter variations and combinations were evaluated to create a design space [5]. The authors then created a dashboard (Figure 2.5), with toggles and sliders of simulation parameters for easier user operation.



Asset Selection: CH-47

Deployment Method: STRATAIR

Aerial Refuelling: No

No. of Crews per Asset: 0.0

Note: Less than 2.0 crews requires stop-over for Self-Deployment of CH-47, UH-60, and MRH-90

Loading/Delivery Method: Internal Loading

Note: external loading limits cruise speed to: --- kts

Procurement Cost [$]: 0

Modification Cost [$/asset]
Aerial Refuel: 0
Re-engining: 0
Autonomy: 0

Figure 2.5: Simulation environment input panel (from [5])

Results indicated that VTOLs which were capable of self-deployment (no strategic airlift assistance) and aerial refueling had higher utilization rates than those requiring strategic airlift and conventional fueling, meaning more areas were visited and packages were delivered. The high utilization rate conversely led to higher maintenance chances, meaning a greatly increased operations cost, which can outweigh the higher effectiveness [5]. In terms of vehicle design parameters, increasing the cruise speed by 15% leads to improved mission effectiveness- more packages/ cities/ sorties delivered- and a slightly reduced cost and fuel use due to the faster mission time [5]. The same analysis was done on a 15% decrease in specific fuel consumption, however in terms of mission effectiveness, no benefit was apparent and only in the operation performance was there a reduction in required fuel by 15% [5].

The work did not include heterogenous fleets or other mission types and the inclusion of strategic airlift vehicle design was absent. Nonetheless, C. Weit et al [5]'s contribution offers a robust framework for future research, allowing for the evaluation of strategic airlift. Aircraft design parameters, operations planning and the potential inclusion of fleet architecture can all be analyzed for mission effectiveness using the above framework. As well, smaller details such as fuel pump rates, servicing times and probabilities and initial design parameters for sensitivity analysis can be extrapolated from the work.

The RAND corporation [10] analyzed different prospects for future airlift fleet design based on the retiring fleet requirements. This study evaluated currently available military cargo aircraft, commercially acquirable aircraft as well as future concepts, such as blended wing bodies (BWB). Based on the airlift requirements set by the US government, multiple aircraft fleet combinations were created with a preference of homogenous fleets unless heterogeneity was required for cargo sizing demands [10]. As of 2012, the USAF inter-theater fleet consisted of only C-17A and C-5 aircraft, whereby C-5 variants are undergoing a Reliability Enhancement and Re-engine Program (RERP) to become C-5M's [10]. The motivation for the study was based on the high utilization and low availability rates for the aircraft increasing the fatigue, resulting in a faster retirement profile than desired [10]. It was predicted that by 2050, most of the C-17A's and C-5M's would retire, resulting in a need for a replacement, either by upgraded aircraft of a new fleet [10]. The predicted retirement profile from the RAND Corporation is presented in Figure 2.6

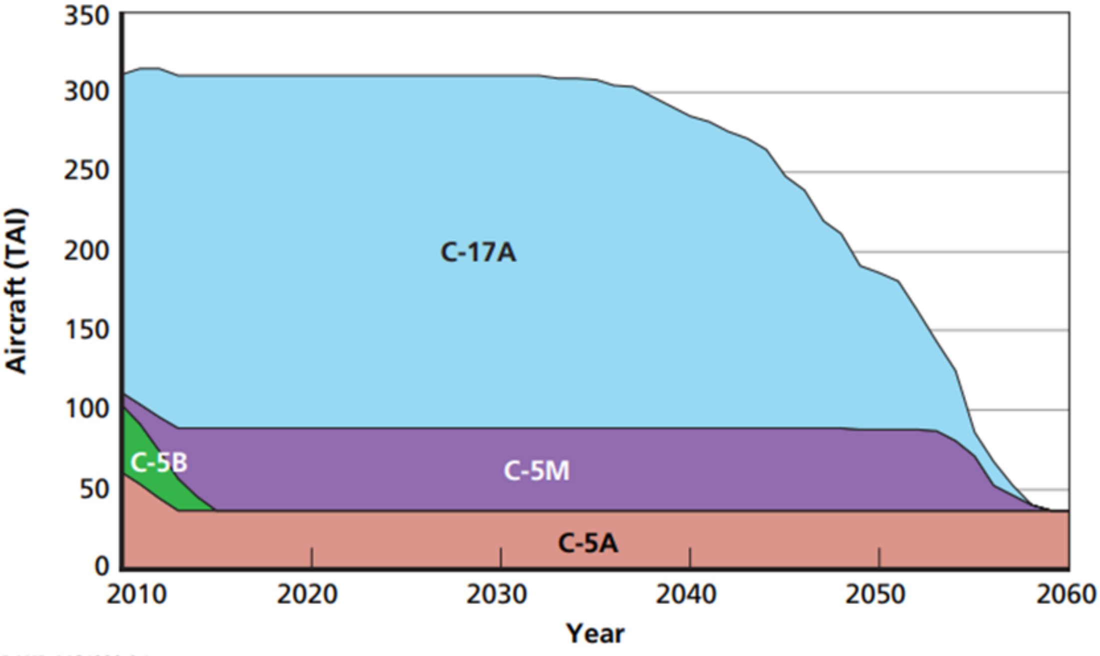


Figure 2.6: Projected retirement profile for current airlift fleet (from [10]

15 different aircraft alternatives were analyzed for the future fleet, including 2 C-5 variants and an upgraded C-17A variant with better fuel consumption and short-field capabilities, as well as 3 commercial-derivative aircraft based on Boeing aircraft, 3 foreign military aircraft (A400M, An-124-100M-150 and Il-

76MF), 3 future designs (2 BWB's and 1 box-wing aircraft), and 2 aircraft (C-59X and C-84X) which share performance capabilities with the C-17A and C-5M respectively [10].

Each aircraft was adjusted to become the sole aircraft for the future fleet unless they were incapable of carrying oversized and outsized cargo (helicopters, cranes, howitzers, large containers, etc.) in which case several new C-5M's would be registered into the fleet to make it robust [10]. The number of aircraft procured was then computed based on the airlift requirements released in MCRS-16 Case 1 [10], where 2 large-scale land campaigns and 3 homeland defense consequence management events must be conducted simultaneously. The performance of each alternative would then be compared to the C-5M, which would allow for a procurement profile (how many need to be introduced per year), until the majority of C-5M's are retired, in which case one of the sufficient alternatives would be used [10]. The resulting number of each alternative procurement's requirement is presented in Figure 2.7.

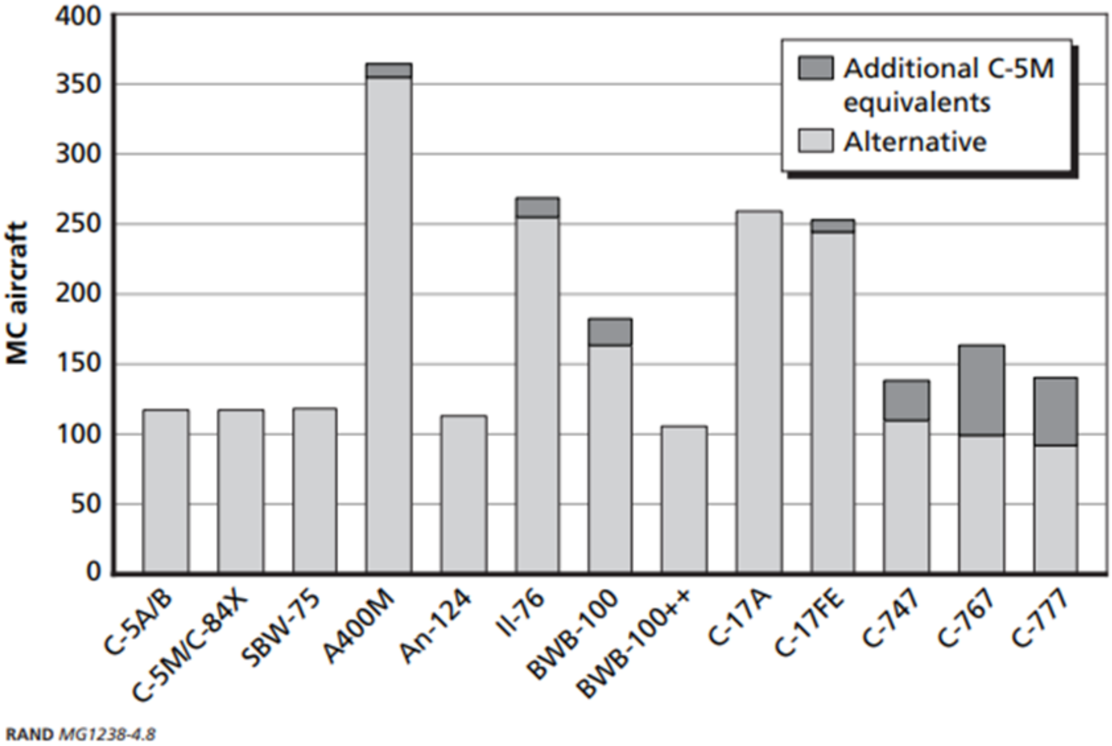


Figure 2.7: Required number of each alternative to meet airlift demand (from [10])

A trade-off was then performed using procurement costs per year and total aircraft life cycle costs, based on the calculated retirement profile and training costs [10]. The study concluded that blended wing bodies offer the best capabilities for future airlift, however due to the technological risk of a future design and the similar fleet capabilities and cost, RAND corporation instead opted for a heterogenous fleet of C-747 (adapted commercial Boeing 747) and C-5 variants, for outsized cargo [10].

The study is useful for motivating a further analysis on how a future fleet should be constructed and the subsequent performance capabilities of different fleet compositions in a modelled airlift. For example, a takeaway of this study is that aircraft such as the C-747 or similar should be tested for its potential alongside the C-5. Additionally, the procurement cost modelling can be used when quantifying fleet trade-offs for similar performance.

There is some literature which focuses on the presentation of a new tool that is purposed as a decision support system to aid governmental bodies and air forces in determining the best future fleet based on the capabilities and performance of said fleet in the tool. Such an example is seen through the cooperation of the Lockheed Martin Aeronautics Company and Georgia Institute of Technology, where J. Salmon et al. [11] created a strategic airlift comparison (SAC) tool to justify further spending on the campaign of upgrading the

USAF's fleet of old C-5A's to an improved set of C-5M's. C-5M's are C-5A's which have undergone avionics modernization and reliability enhancement and re-engining, providing greater fleet longevity, reliability and payload-range characteristics [11]. At the time of the article, only half of the C-5A fleet (111 units) was capable of upgrade due to budget constraints. Since the Lockheed Martin Company was the holder of the contract, it sought to expand the upgrade programs to the entirety of the fleet. As such the purpose of the literature was to offer a meaningful and valid comparison between the the capabilities of a C-5A fleet to a C-5M fleet

The authors employed a modelling and simulation approach, opting for a discrete event simulation (DES). The benefit of a DES is that it allows for reactive events and decision making based on each system of the simulation- such as the modelling of tasks being carried out upon the landing of each aircraft [11]. The DES created had a simplified logic where upon initialization, all cargo missions were defined for an aircraft, and then per mission, the optimal routing sequence for the aircraft would be generated. After flying the mission, a check would be performed for servicing and then utilization rate, to ensure that aircraft do not exceed a 16 hrs use time per day. The flow diagram is shown in Figure 2.8.

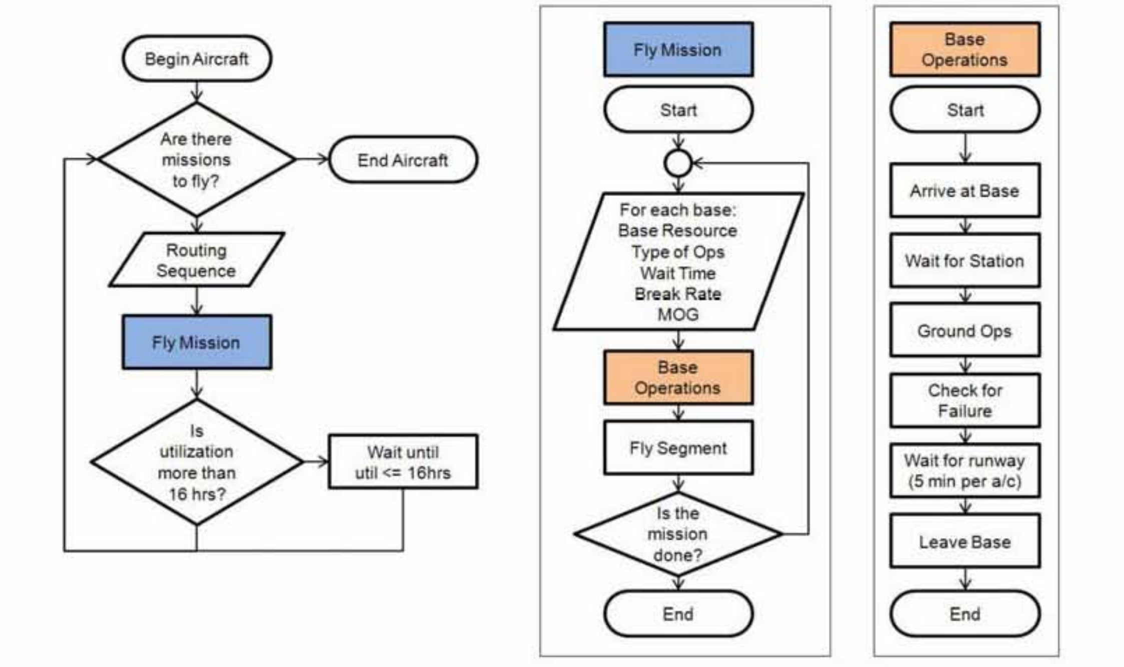


Figure 2.8: SAC tool simulation logic flow block diagram (from [11])

Aircraft routing in the SAC tool was also kept straightforward. A user would constrain the routing to one of 4 possibilities. The routing would be based on the cargo's origin, or aerial port of embarkation (APOE), and the cargo's destination, or aerial port of debarkation (APOD), and the opportunity to create 1 or 2 en-route bases. The en-route bases are optional inputs which are used for refuelling purposes to extend the aircraft's range or payload capabilities [11]. The routing options are:

1. Forward flight: $APOE \implies APOD$
   Return flight: $APOD \implies APOE$
2. Forward flight: $APOE \implies$ En-route base A $\implies APOD$
   Return flight: $APOD \implies APOE$
3. Forward flight: $APOE \implies$ En-route base A $\implies APOD$
   Return flight: $APOD \implies$ En-route base A $\implies APOE$
4. Forward flight: $APOE \implies$ En-route base A $\implies APOD$
   Return flight: $APOD \implies$ En-route base B $\implies APOE$

Such a denomination of routing was decided since the tool only has 2 aircraft types built-in, the C-5 (C-5A and C-5M) and the C-17 [11]. The user would specify the type of aircraft and then the routing scheme. Other aspects such as fleet size, repair rates and probabilities and maximum on-ground values for the APOE and APOD were also taken as inputs. Even the different flight times for each leg were based on user input, which the authors used as basis for their block speed calculation [11]. The overview of simulation inputs is shown in Table 2.2. Hybrid fleet architectures were not supported.

Table 2.2: SAC tool user inputs (from [11])

SimPy Inputs	Min	Max
Type of Aircraft	0	1
Fleet Size	1	70
Number of Flights	1	1000
Routing	1	4
Flight Time: Leg 1	30	1200
Flight Time: Leg 2	30	1200
Flight Time: Leg 3	30	1200
Flight Time: Leg 4	30	1200
Repair Prob: 0 to 4 hrs	0	1
Repair Prob: 4 to 12 hrs	0	1
Repair Prob: 12 to 24 hrs	0	1
Break Rate	0.01	0.6
MOG: APOE	1	15
MOG: APOD	1	15
MOG: En Route 1	1	15
MOG: En Route 2	1	15

After the initial model inputs, the user inputs airbase information and aircraft information. Airbase inputs are based on a pre-defined list of airfields that the user filters through based on specifications such as airfield length and width and the airfield elevation. This is possible due to the tool being presented with the JMP statistical software which offers converts sheets of data into manipulable sliders and presentation schema [11]. The airfield length and width along with the elevation is used to determine the payload-range capabilities of the aircraft at each airbase, which is then shown to the user on a world map (see Figure 2.9). The ambient temperature at the APOE can also be set from 5 to 40 °C [11].

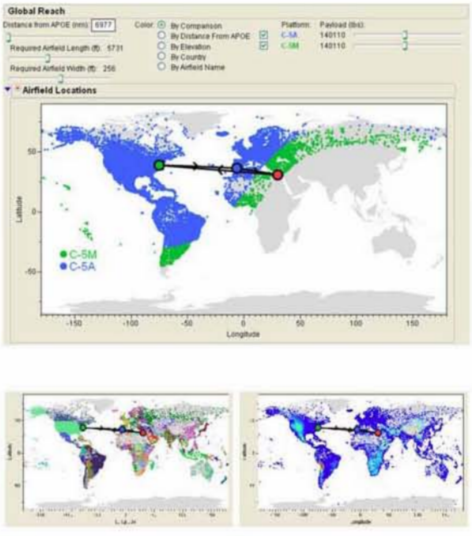

Global Reach
Distance from APOE (nm): 6977
Required Airfield Length (ft): 5731
Required Airfield Width (ft): 256
Color: ● By Comparison ○ By Distance From APOE ○ By Elevation ○ By Country ○ By Airfield Name
Platform: ☑ C-5A Payload (lbs): 140110
☑ C-5M 140110

Figure 2.9: Example of airfield filtering and coloring schemes (from [11])

Given the different inputs available and the need for the tool to be widely accessible, the authors created a surrogate model of the simulation. This was based on a design space of over 50’000 cases to match the different input combinations, and each case was run 1000 times to eliminate random variability based on failure chances and repair times. Each set of 1000 runs would be completed in the order of a few minutes, with the total data aggregation taking several days across multiple machines [11]. The culmination of the tool is a single JMP layout, shown in Figure 2.10.

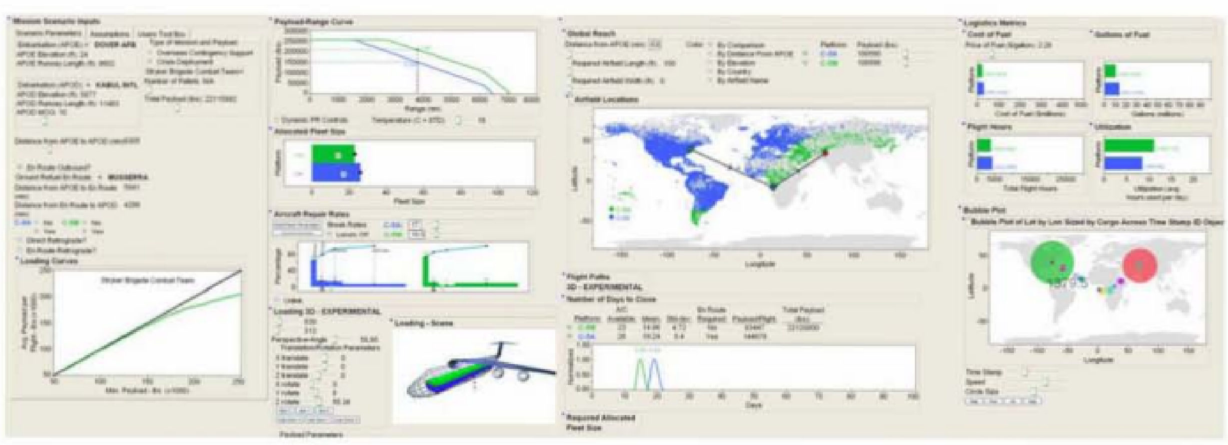
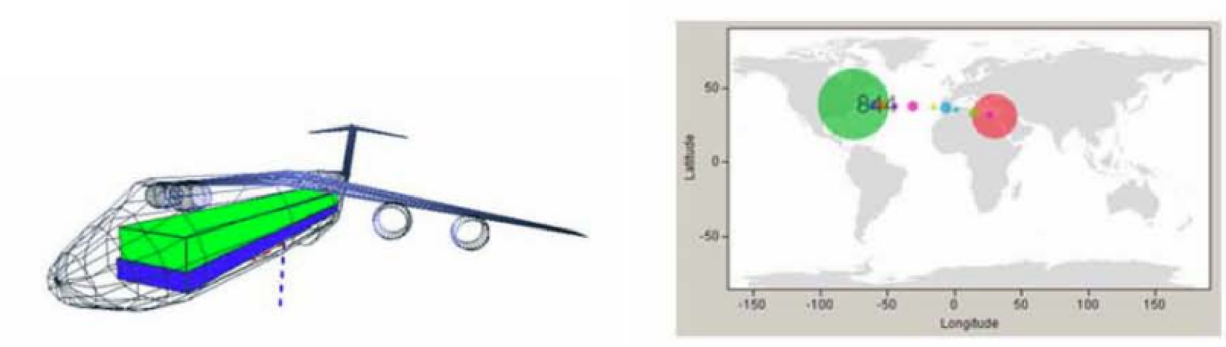


Figure 2.10: SAC tool layout (from [11])

To aid the user, additional visualizations were created. When a C-5 is selected as the aircraft, a 3-D model of the aircraft is shown (Figure 2.11a) containing 2 volumes, associated with the C-5A and C-5M. It illustrates the benefits of the improved engine and propulsion capabilities of the C-5M offering a greater payload. These values are based purely on the maximum payload translated to a rectangular box, not an accurate analysis of the internals [11]. There is also a probability distribution plot, which plots the time to close (total mission time to transport all cargo). It shows the mean and variance of the time to close distribution so that users can tailor inputs and see the effects on the mission effectiveness [11], which is generated per-basis using a surrogate model. For example, the user can identify the required reliability (through break rate and repair times) so that time to close attains a certain, more acceptable value. Mission output metrics such as cost, fuel use, flight hours and required fleet size to complete the mission are also presented [11]. Lastly there is a bubble plot (Figure 2.11b) which displays the cargo distribution across the map at a specific timestamp- useful for comparing the differences in missions at a given time step [11].



(a) 3D loading volume representation: blue=C-5A, green=C-5M (from [11]

(b) Bubble plot displaying movement of payload (from [11])

Figure 2.11: Additional visualizations from SAC tool (from [11])

The authors highlighted some results regarding the comparison of the C-5A and C-5M based on a sample mission. For example, they specified the routing such that the C-5A would require an en-route stopover whilst the C-5M would be able to perform a direct forward flight. In such a case, the C-5A fleet would complete the mission faster, but due to the additional refuelling, the total operation costs are greater than the fleet of C-5M's. Increasing the fleet size can aid in reducing the time to close, but at the expense of a higher maintenance cost for multiple aircraft [11]. Sometimes, alternative en-route bases which required greater travel distance but with greater maximum on ground capacity resulted in a reduced time to close since the bottleneck of airfield capacity during repair times is reduced [11]. Lastly, engine comparison between the two aircraft was outlined based on the effect of the ambient temperature at the APOE. Notably, at higher temperatures, the benefits of the upgraded engine are reflected in a faster time to close, however as temperatures decrease the capability gap is insignificant [11].

Summary

In conclusion, aircraft design with relevance to rapid airlift is quite unexplored. Opportunities for expanding analysis as C. Weit et al. [5] have done on tactical airlift but with strategic aircraft are promising. Questions dealing with determining the most influential strategic aircraft parameters for future cargo fleet design becoming prominent to combat the aging fleet and unpredictability of missions. Using the methods of the aforementioned papers aids in answering these questions. J. Maywald et al.'s [6] [7] contributions are evidence for how a redesigned air fleet using smaller can improve airlift time and costs, which combined with the implications of RAND corporation's analysis [10], offer great motive for a more in-depth analysis on different airlift fleet combinations with non-conventional strategic aircraft. C. Weit et al.'s [5] analysis of aircraft design parameters offers a framework for linking aircraft design to a fleet's operational success. Awareness of the payload capabilities for new aircraft/ fleets is essential given the prospective storage of multiple UAVs for tactical airlift [9]. The work by J. Salmon et al. [11] offers an alternative result of C. Weit et al.'s [5] decision support tool but for strategic airlift comparison. The papers analyzed in this review restricted themselves by analyzing only military or HA/DR operations, meaning no holistic analysis on the conclusions found was given. As such, the question of to how to incorporate both HA/DR or military operations in the design of aircraft has yet been answered.

A set of models from the presented aircraft and fleet design literature can be used for the thesis methodologies. Namely:

- Break rates and repair time denomination from [11] - representing service times in a probabilistic manner, utilizing a variable service time.
- Dashboard and toolkit presentation models from [5] - methods on how to present results effectively and allow for user input.
- Flight speed modelling from [5] - simplifying the aircraft speed for all in-air movement to be a denomination of the cruise speed specification.
- Cargo allocation algorithm based on available missions from [7] - assigning cargo based on pallet utilization to ensure that missions are not conducted with little cargo if possible.

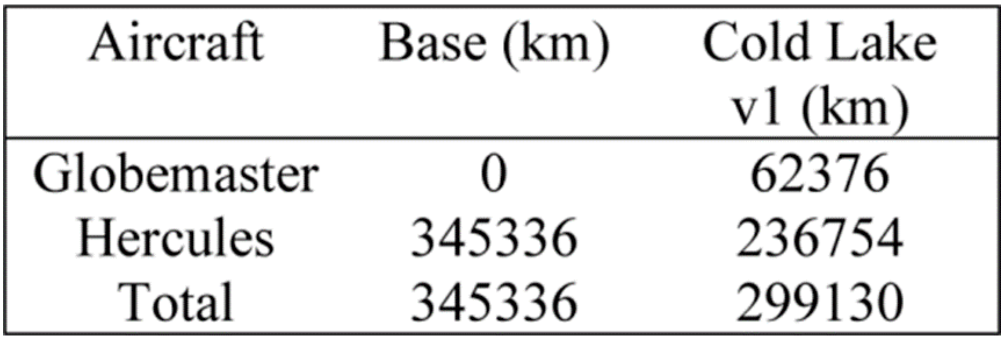
4 Route Planning

The bulk of literature concerning rapid airlift logistics deals with the creation and optimization of route planning schemes. This is mainly due to most of the modern methods being archaic and inefficient, wasting valuable time and money for airlift operations. As such most researchers sought to either simplify the process for operators, by creating a framework or tool that could be adapted with different inputs and would output optimal fleet structures and flight / load plans, or examine the benefits of novel operation techniques such as aerial refueling to enable a more optimal route and load planner.

R. Barwell [12] constructed a simulation environment which aimed to verify the ability of a sample Canadian air fleet in conducting a strategic airlift within the Canadian Arctic. For this, the author analyzed the impact of including a temporary support base that would allow for cargo swapping between larger aircraft (like the C-17 Globemaster) and smaller aircraft conducting tactical missions (AC-130J-30 Super Hercules) [12]. The modelling of the operation was done using a discrete event systems specification (DEVS). 2 DEVS models were created, one for the airbases and another for the aircraft [12]. The airbase system would interact with the aircraft system for aircraft loading when an aircraft is available and enough cargo to fill half of the aircraft's capacity was generated. Upon loading, the aircraft would travel to its destination (either the final destination or the support base) and then unload all its cargo at its destination and re-enter the available aircraft pool. Each aircraft was designated a specific leg, meaning an aircraft flying to the support base could not fly from the support base to the final destinations [12]. In addition, the cargo was simplified such that only 1 pallet position equivalent (PPE) cargo was considered, excluding any potentially large or outsized cargo which could occupy multiple pallet positions [12]. Because of the simulation framework, users only needed to specify the airbase information (GPS location and cargo requirements) and aircraft information (payload capacity and speed) [12], meaning aspects such as available airbase capacity, or fuel consumption of the aircraft are disregarded.

Despite this simplification, noteworthy results were found. The creation of a support base (Cold Lake) and the implementation of larger aircraft were evaluated for effect on airlift time and distance flown. An original movement consisting of only 3 Super Hercules was compared to the same movement with inclusion of 2 C-17A Globemaster's which transported the cargo from the origin to Cold Lake, upon which the Super Hercules would transport the final leg. The airlift time reduced from 23 days, 14 hours and 11 minutes to 14 days, 20 hours and 38 minutes [12]. The distance flown, despite the addition of a support base and more assets also reduced, as shown in Table 2.3.

Table 2.3: Distance comparison with support base inclusion (Cold Lake) (from [12])



Aircraft	Base (km)	Cold Lake v1 (km)
Globemaster	0	62376
Hercules	345336	236754
Total	345336	299130

Having the support base closer to the final destinations aided in reducing airlift time, by up to 3 days, and total distance flown, but as the support base are positioned closer to the destinations, the benefits plateau [12]. This was due to another rate limiting step which was the time required for initial transport of the cargo to the support base. It was determined that this factor could be diminished by procuring a greater fleet for the initial leg based on the higher wait times of the aircraft conducting the final leg as the support base neared the destinations [12]. In effect, this research proves that despite model simplifications, meaningful results can be extrapolated and the methods applied can be used in a real-life scenario to aid in route determination and operations planning. Their research can be furthered by considering aircraft that are capable of multi-leg flight, meaning the support base could be used as a refueling/ servicing point, which could reduce waiting times and airlift time and costs due to fewer aircraft being required. The determination of when an aircraft is suitable to depart (50% loaded) can be taken from this paper and further explored as a sensitivity to analyze which departure condition leads to more effective mission.

Aerial refueling benefits were also examined and their impact on optimal flight path routing, as done by M. Toydas [13]. To do so, two mathematical models were created; the first is a nonlinear mixed integer model for the aerial refueling option and the second is a nonlinear model of a traditional strategic airlift where aircraft fly from embarkation hubs directly to debarkation hubs [13]. In the aerial refueling model, the aircraft have the opportunity to fly slightly off-course to an optimally computed rendezvous zone where a tanker aircraft, originating from a nearby base, refuels the aircraft. The aircraft pair stays within a circular zone around the rendezvous point so to minimize time loss on account of both the cargo aircraft and tanker aircraft. The flight trajectory in such an instance for the tanker and cargo aircraft is shown in Figure 2.12.

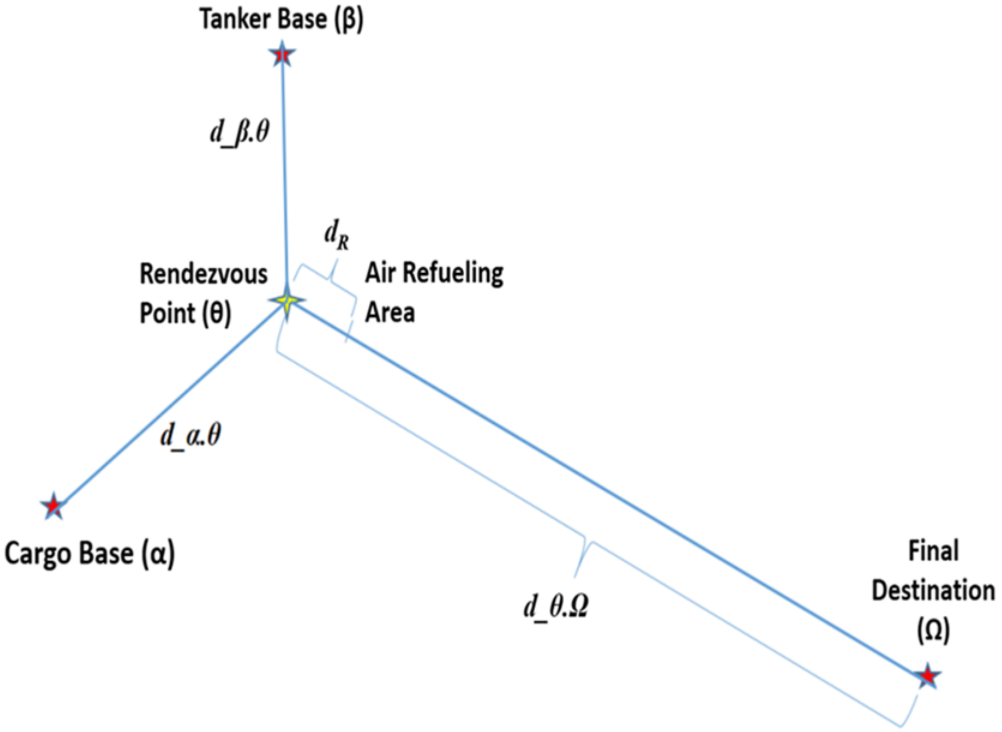


Figure 2.12: Aerial refueling flight legs (from [13])

Both models have the objective to minimize total airlift time. Fuel consumption was modelled with a nonlinear function of airspeed, altitude and gross weight, as well as two coefficients for the distance travelled in miles per 1’000 pounds of fuel burned [13] (based on a linear relationship from previous author’s works [14]). Distance was computed using the haversine distance formula to output the great-circle distance between two bases/ locations [13]. Since optimization is required to find the best rendezvous location, Taylor series approximations are applied to model 1’s haversine formula to remove the trigonometric functions [13].

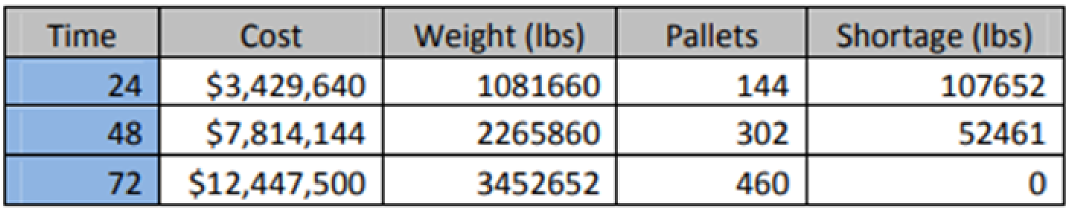
Using these two models, and a sample cargo airlift using C-5 for cargo sortie and the KC-10 as the tanker aircraft from Rammstein Air Base, Germany to Al Udeid Air Base, Qatar was conducted to compare airlift time, number of sorties and fuel consumption. Assumptions on having adequate ramp space, equipment and personnel at all times were applied to focus results on aerial refueling effects [13]. With limiting aircraft loading to only one at a time, result comparison indicated a reduced number of required sorties (109 versus 159), airlift time (478.42 hours versus 690.89 hours), and total fuel consumption (6.8 million pounds in saving even with tanker fueling) due to the increased payload capabilities of the cargo aircraft when using aerial refueling [13]. Increasing the number of aircraft being loaded simultaneously to 4 results in a reduced airlift time of 119.61 hours, and an additional 53.11 hours without aerial refueling [13].

Therefore, aerial refueling options should be considered for optimal airlift design and the likelihood of future missions incorporating such a technique is high given the reduction time and fuel costs. Future research analyzing the aerial refueling effect on a heterogenous fleet are recommended [13] as well as using more bases/ destinations for the aircraft to fly to, which could allow for a comparison between traditional intermediate stops and aerial refueling techniques. The techniques of using the haversine formula to determine distances accurately and implementing a rendezvous point and an accompanying refueling area based on a specified radius can be used in this thesis.

In terms of HA/DR, P. Mogilevsky [15] created a Disaster Relief Airlift Planner (DRAP) which uses an integer linear program to optimize heterogenous fleet flight routing based on the inputted disaster location(s), available airport(s), aircraft and supply stockpiles. By considering the cost of flight and cost of resource delay for different routes, DRAP minimizes the disaster material shortages during foreign humanitarian aid (FHA) missions [15]. The nodes (or airbases/ disaster locations) could be inputted using a name, a set of coordinates and a list of aircraft available to land there [15]. Great-circle distances (haversine formula) would be used to compute the route length for the aircraft. Based on a set of nodes, aircraft would create routes along the nodes to get to a final destination, upon which the aircraft's maximum allowable payload would be determined by the longest flight leg [15]. The aircraft loading capacity was simplified into a linear payload-range relation, which was proven sufficiently accurate based on a comparison with a datasheet [15].

The optimal route is chosen based on the route which offers the lowest combination of cost and resource delay. Cost per route was calculated based on the summation of fuel costs and operating costs. Fuel costs were modelled as a multiplication of the route distance by the gallons of fuel per mile rate for the aircraft and the cost of a gallon of fuel at the time (2013). Operating costs were taken as a static value of cost per hour basis per user, based on data from J4 (logistics) branch of USAPCOM [15]. The cost per hour was then multiplied by the route time, which was simplified to be based on the route distance and the cruise velocity [15]. The planner was then used in a time constrained scenario, where a cyclone has hit Malaysia resulting in a set amount of required, deliverable aid material, and as much cargo as possible has to be transported within a specific horizon. The planner used a set of C-5's and C-17's to conduct the strategic airlift from US airbases to Guam, South Korea and Japan. C-130's would then be responsible for the tactical airlift delivery of resources from the aforementioned bases to the affected regions in Malaysia. Results show a reduced time horizon intuitively reduce the cost of airlift but consequently result in greater resource shortage at final destinations [15]. The time horizons and associated shortage and costs is shown in Table 3.

Table 2.4: Time horizon resource shortage and cost overview (from [15])



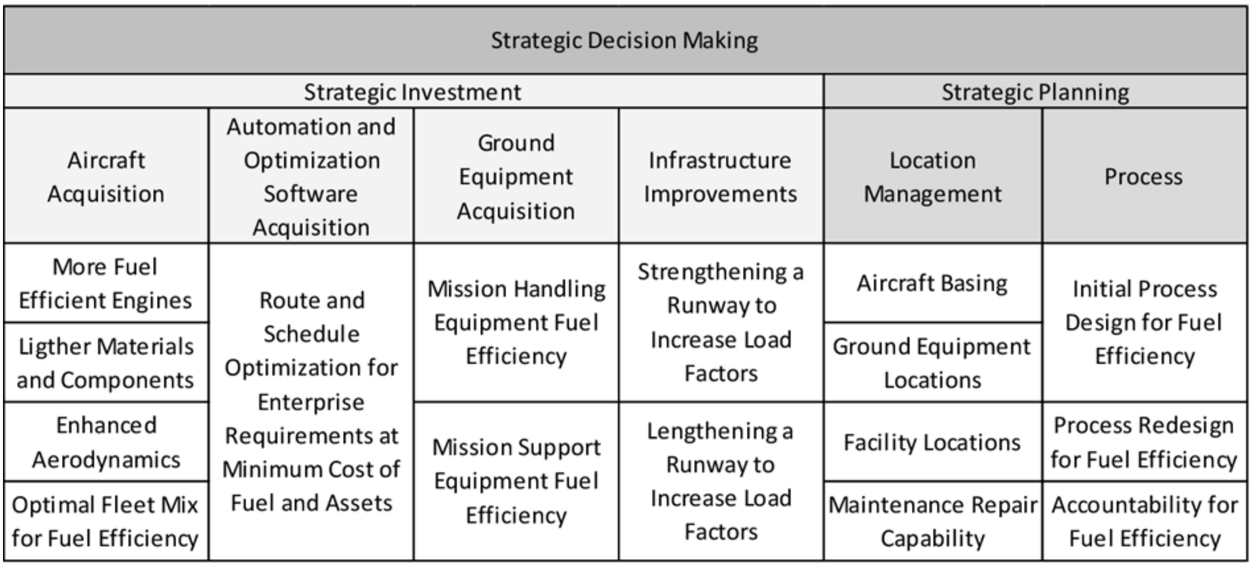
Time	Cost	Weight (lbs)	Pallets	Shortage (lbs)
24	$3,429,640	1081660	144	107652
48	$7,814,144	2265860	302	52461
72	$12,447,500	3452652	460	0

DRAP also logs the different route details (times flown, aircraft flying, pallets and weight transported and cost) as well as the overview of commodities/ cargo that was loaded and unloaded at each airbase [15]. By increasing the input fleet, the planner's methods were verified by showing a faster airlift time and reduced costs to deliver the same cargo as a smaller fleet [15].

P. Mogilevsky's [15] DRAP formalization can be used as a basis for the method of implementing a planner into a simulation environment; it has the ability to allow users to input essential parameters whilst simplifying certain complexities such as the fuel consumption and costs to make a manageable model and focus on the systems of systems nature of the airlift. The ability to model fuel cost based on an average fuel consumption per mile based on cruise is a utility that can be adopted in the thesis to simplify fuel modelling. Within the research, the assumption was made about the serviceability of the aircrafts and common availability of ramp space despite regions potentially having underdeveloped or restrictive infrastructure, as is expected in a natural disaster situation. Analyzing how such effects, and the dynamic / spontaneous environment that is to be expected of a natural disaster, change the routing and airlift effectiveness are not dealt with and can be an exploration of the thesis.

A. D. Reiman [8] wrote a dissertation in which he reviewed airlift operations and the metrics upon which other researchers have evaluated airlift success. They then proposed their own strategic route planner based on the reviewed metrics. Although the goal of an airlift is the maximization of cargo throughput, enterprise operators seek to minimize the costs and fuel consumption, meaning that an effective metric incorporating these aspects should be defined [8]. The author presents common techniques that are used to improve fuel efficiency, ranging from aircraft acquisition (fuel efficient engines, lighter aircraft with enhanced aerodynamics) to infrastructure improvements (runway load factor capability) and routing. These are summarized in Table 2.5. The focus of the research was to improve the routing and scheduling as well as the strategic planning, via location management and processing.

Table 2.5: Decision making processes and methods to improve fuel efficiency (from [8])



Strategic Decision Making					
Strategic Investment				Strategic Planning	
Aircraft Acquisition	Automation and Optimization Software Acquisition	Ground Equipment Acquisition	Infrastructure Improvements	Location Management	Process
More Fuel Efficient Engines	Route and Schedule Optimization for Enterprise Requirements at Minimum Cost of Fuel and Assets	Mission Handling Equipment Fuel Efficiency	Strengthening a Runway to Increase Load Factors	Aircraft Basing	Initial Process Design for Fuel Efficiency
Ligther Materials and Components				Ground Equipment Locations	
Enhanced Aerodynamics		Mission Support Equipment Fuel Efficiency	Lengthening a Runway to Increase Load Factors	Facility Locations	Process Redesign for Fuel Efficiency
Optimal Fleet Mix for Fuel Efficiency				Maintenance Repair Capability	Accountability for Fuel Efficiency

The industry standard fuel efficiency metric is the Fuel Efficiency Index (FEI), which incorporates the cargo throughput, distance flown and the fuel burned [8]. This is to fulfill the objective of fuel efficiency; "to move the greatest quantity of cargo and passengers at the least cost of fuel for a given distance, set of assets and unit of time" [8]. A simplified version of the FEI is presented in Equation 2.1, which can be adapted for passengers by replacing the cargo mass.

$$CargoFEI = \frac{\sum_{i=1}^{n} \frac{CargoMass_i * Distance_i}{FuelBurn_i}}{n}, \quad \text{where n = \# of sorties} \tag{2.1}$$

An evaluation of the FEI for a set of sorties conducted in November 2010 was done for varying aircraft used in the movement. The result of this showed an average FEI of 267, where larger aircraft such as the C-17A and C-5B/M had some of the highest values (up to 571), whereas smaller aircraft like the KC-135T had a FEI of 33 [8].

The impact of certain factors on the FEI was also analyzed. The sortie distance and the corresponding sortie FEI for the C-17A was plotted, as shown in Figure 2.13. Although the maximum FEI decreases, the results indicate a higher mean FEI is obtained for longer sortie distances. The conclusion is that sorties operating at maximum payload should seek to maintain shorter routes instead of extending distances, even if possible. Sorties with sub-optimal payload should conversely seek to fly longer ranges with the same payload [8]. Load factor (proportion of actual load to total/ optimal load) correlations with the FEI were then also compared. Based on the movement in 2010, a table of each aircraft's weight value(s) and average load factors was generated, shown in Figure 2.14. The low mean load factors highlight inefficiencies in cargo airlift and the potential for improvement. Similar to the sortie distance, the C-17A FEI is plotted against the load factor in Figure 2.14.

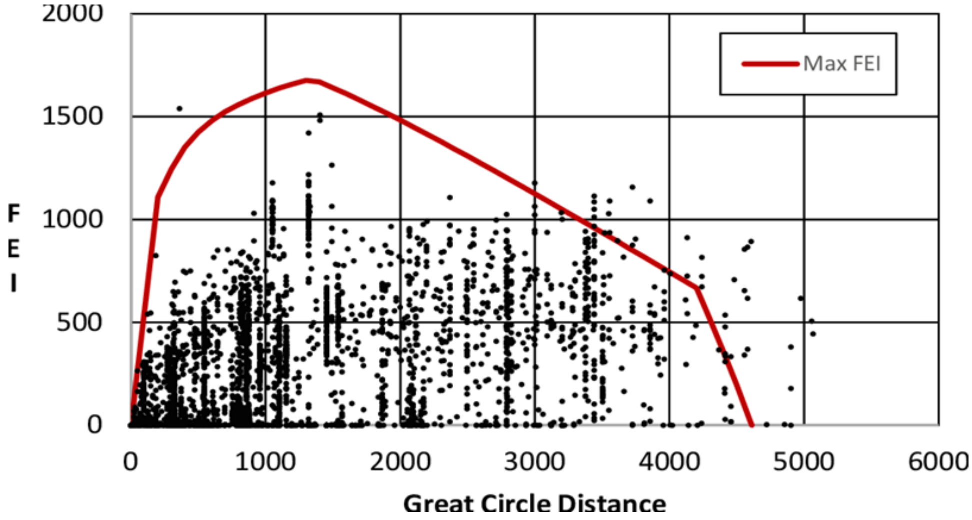


Figure 2.13: FEI and sortie distance trend for C-17A (from [8])

Table 2.6: Weight characteristics and mean sortie load factor for aircraft (from [8])

	Maximum Gross Takeoff Weight	Empty Weight	Load Factors
C-17A	585	282.5	23%
C-5A	769	380	23%
C-5B	769	380	31%
C-5M	769	380	28%
C-130E	155	90	15%
C-130H	155	90	21%
C-130J	155	90	27%
KC-10A	590	241	3%
KC-135R	322.5	119.23	3%
KC-135T	322.5	119.23	2%
Total			22%

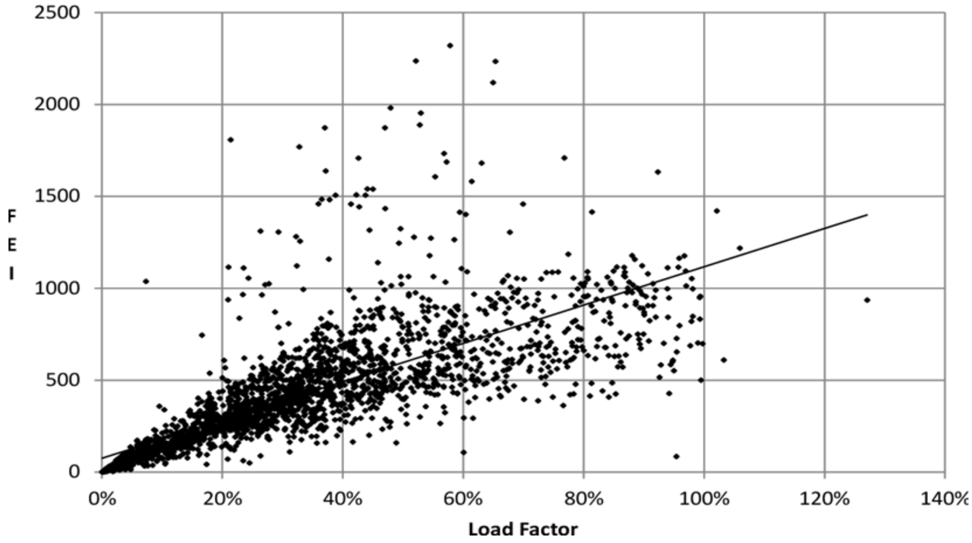


Figure 2.14: FEI and load factor trend for C-17A (from [8])

The load factors above 100% are likely due to waivers permitting the loading above the maximum takeoff weight [8]. The effect of load factor is much greater than the sortie distance, with a 74% correlation compared to 44%, which motivates the need to improve cargo load utilization in airlifts to maximize fuel efficiency. Inactive sorties, equivalent to cargo deadheads, are flights where the aircraft are absent of payload and are en-route to a cargo pickup or repositioning. Such sorties reduce the mean load factor and overall airlift efficiency [8]. The goal is therefore to reduce the inactive miles or distance flown during an inactive sortie by ensuring aircraft closest to the cargo are chosen for the mission. Thus, using inactive miles as an operational effectiveness metric can be useful in understanding which hubs and aircraft origin locations are sub-optimal or redundant and can be optimized.

The last component of the FEI is the fuel consumed during the sortie. Once again, the author plotted the FEI and fuel consumption for each C-17A sortie, shown in Figure 2.15. The trend displayed is unexpected. As the fuel consumption increases, the FEI was predicted to decrease, however the results present a positive correlation. The 2 suspected reasons for this are due to the sortie distance having a greater (positive) effect on FEI, outweighing the resulting increased fuel consumption, and that higher loaded sorties burn more fuel but still maintain a high FEI due to the cargo throughput [8].

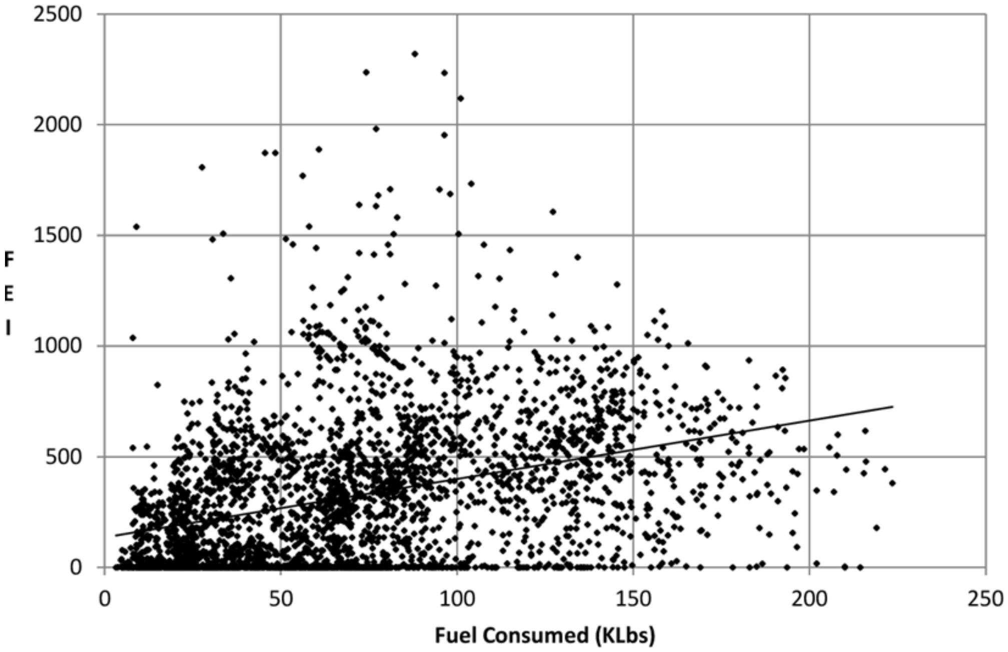


Figure 2.15: FEI and sortie fuel consumed for C-17A (from [8])

A. D. Reiman [8] then implemented a routing algorithm which uses nodal reduction heuristics to determine optimal aircraft routes depending on the aircraft type and its capabilities so that low value routes are not used in route comparison. Route comparison is then based on a measure of route effectiveness, determined through cargo throughput and route efficiency, based on the prescribed FEI. Such a formulation was then tested to see the impact of distance, aircraft type (C-5, C-17 and C-130), staging and trans-load operations (where the aircraft would perform a stop, unload and load cargo, and then continue to its final destination) on cargo throughput and fuel efficiency. Increasing the distance flown reduced the cargo throughput but the planner was able to determine upper and lower boundaries for each aircraft type ensuring the optimal aircraft is chosen based on cargo throughput and time objectives [8]. The aircraft type analysis confirmed that the C-17A's high utilization is due to the maximized cargo throughput obtained per sortie [8]. Trans-load sorties were found to be unfavorable due to the fuel costs and increased ground times, making them inferior to simple one-leg travels or refueling stops [8].

A. D. Reiman's [8] research on fuel efficiency and cargo throughput can be used as a basis for a routing algorithm where the metrics of fuel and cargo throughput are considered. For example, determining future aircraft/ airlift improvements based on the resultant reduced fuel consumption whilst maintaining or improving throughput. Additionally, Table 2.5's conceptual improvements can be used for motivating design improvements when exploring potential aircraft design effects on the operational effectiveness.

Summary

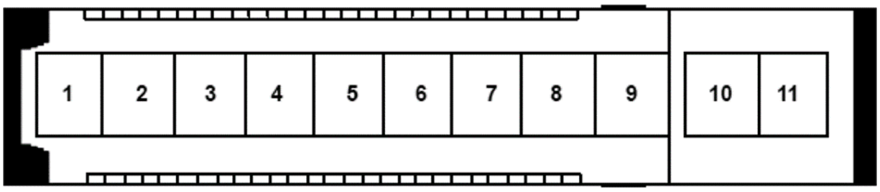
In summary, airlift route planning literature is fairly well developed, with planners being able to incorporate aspects such as aerial refueling [13], operations and fuel costs [15] and the creation of temporary support bases [12] whilst developments are made to make the interface with potential operators more simplistic and easy-to-use. Route planning literature also gives insights into the different metrics such as FEI and cargo throughput, load factor and inactive miles, which can be used to compare routing schemes and airlift effectiveness and efficiency [8]. The takeaways from this section are the different methods by which a simulation framework can be composed of, with varying degrees of complexity for parameters such as fuel consumption and cargo load prioritization, and how each method can produce meaningful results. Regarding future research, the idea that certain bases may be periodically unavailable throughout an airlift, due to a dynamic operations environment can offer insights to the robustness of both a planner model and the airlift fleet with respect to the mission success parameters (airlift time, cost and resource shortages). Other topics that can be further explored are those relating to the creation of new support bases mid-operation. Most airlifts are time sensitive and unpredictable, though the idea of focusing efforts and resources to creating a new, albeit rudimentary, support base could prove fruitful due to the subsequent reduced fuel demands and the ability to create a new airbase optimally placed.

A set of models from the presented route planning literature can be used for the thesis methodologies. Namely:

- Mission evaluation metric of FEI from [8] - the use of the FEI (and its constituents) for comparing routes and mission effectiveness.
- Use of nodal reduction techniques from [8] - simplifying routing schemes where each airbase is presented as a node and routes are generated based on the linking of nodes. Routes are then compared against each other based on their value according to a metric (potentially FEI [8]) to determine optimal routing.
- Cost estimation techniques from [15] - modelling route costs based on summation of fuel costs and a standard, static cost for operation from available data.
- Aircraft loading capacity and range from [15] - using Breguet range equation to determine the payload range characteristics for the aircraft and then determining the maximum payload (or fuel) based on the route length. In the paper this was based on a linear relation but for the thesis, the Breguet equation will be used.
- Aircraft distance and position modelling from [13] - use of great-circle distance to determine aircraft flight distance. Potential use of Taylor series approximations to allow for optimizations of the great circle distance- for optimal support base determination and aerial refueling capabilities.
- Intermediate base creation modelling from [12] - creation of an intermediate base based on the factor of reducing reducing time to transport the cargo from the APOE or reducing time from the intermediate base.

5 Airlift Operational Design

In terms of airlift operations, literature concerns the study of inefficiencies with cargo loading processes, the utilization of commercial/ reserve fleets and the optimization of infrastructure servicing and capacity. Cargo loading for airlift is based on available pallet positions on the aircraft. The loading of pallets into these positions is very inefficient however, where improper loading leads to pallet positions being misused or space being wasted [16]. N. Carlson et al [16] proposed to eliminate some of these inefficiencies by using a set of novel techniques with different degrees of complexity. The techniques evaluated were: the layering of pallets on top of one another when under a pallet weight threshold (6000 lbs.), the aggregation of smaller, broken down pallets (i.e.: food/ water pallets) into available pallet positions, placing tonneau covers onto rolling stock such as trucks so that other (smaller) rolling stock could be placed on top, the swapping of the rail system (traditionally mono-rail) to dual rail when no large rolling stock placements are required (such as tanks), passenger re-placement to minimize pallet positions from being occupied, and the changing of the C-17A cargo compartment to be focused more on cargo delivery instead of aerial delivery [16]. The distinction between aerial delivery and cargo delivery configurations are presented in Figure 2.16 respectively.



(a) C-17 Aerial delivery configuration pallet positions

(b) C-17 Cargo delivery configuration pallet positions

Figure 2.16: Different C-17 pallet configurations (from [16])

These techniques were applied together on a sample airlift spanning April through October of 2016, which was composed of 30 movements and a total 159 sorties. To evaluate the success of the techniques, results were generated for the instance where the above techniques were applied and one where conventional loading practices were performed. In both scenarios, the authors applied a cargo throughput optimized routing, which conducted the route planning with the consideration of adding a refueling stop in between the journey for the sake of increasing payload utilization and cargo throughput [16]. The results showed that through the application of the techniques, 38 sorties were able to be removed due to load redistribution, and 16.4% of the original sorties could be flown with smaller aircraft (C-5B/M□C-17A, C-17A□ C-13J-30), reducing overall costs and aircraft utilization [16]. Yet, even though cargo compartment utilization, based on the maximum allowable payload for the leg, increased with respect to the original movement by 18.47%, the mean utilization was still less than 50%, indicating the need for further loading improvements despite maximum floor space occupancy [16]. The authors did not highlight the potential time requirements for cargo loading with the new techniques, which may have adverse effects on total airlift efficiency.

N. Carlson et al.'s [16] research on load utilization may be too specific for a more holistic modelling of airlift processes, but the projected utilization rates with improved loading techniques and the different configurations that aircraft can be loaded based on the pallet system can be extracted and applied into this thesis to emulate future airlift operations.

During large cargo movements, it is within the US government's jurisdiction to inquire the aid of commercial air carriers to aid in cargo transport, under the call-sign of the 'reserve fleet.' The assignment of reserve fleet aircraft to sorties is based on a bidding process where the military offers a price for the sortie to compensate the reserve fleet for prioritizing cargo delivery instead of their commercial enterprise. This price, or reserve price, is often initiated to each carrier as a multiple of the of a nominal price the military would pay considering the mission was assigned conventionally [17]. Each carrier can then accept the reserve price, but as competition occurs, the reserve price decreases as the carriers try to outbid one another. The goal of the military is to have the reserve price become as close to or equal to the assignment price (the fixed rate based on the round-trip mile distance between the embarkation and debarkation points) [17]. If the cargo delivery time requirement becomes critical, and no carriers have offered a bid, then the mission is assigned to the carrier that has conducted the fewest missions at the time [17]. G.A. Godfrey et al. [17] expanded this process by allowing for a collaboration between the carriers through an auctioning system which allowed for mission/ sortie swapping when mutually beneficial.

G.A. Godfrey et al.'s [17] auction framework and agent-based simulation made to be multi-threaded, meaning each buyer agent (carriers) and seller agent (military) would function on an independent processing thread, allowing for parallel processing. To incentivize early volunteering, the carriers were created such that after finishing their fractional share of total missions, they would not have to be considered for bidding again [17]. The swapping of missions begins when a carrier has already "won" a mission and following this a more suitable mission appears before the carrier conducts the mission. In such a case, the carrier can then propose its mission to another carrier for the same price, and upon acceptance, swapping occurs. The operational logic of the simulation is presented in Figure 2.17.

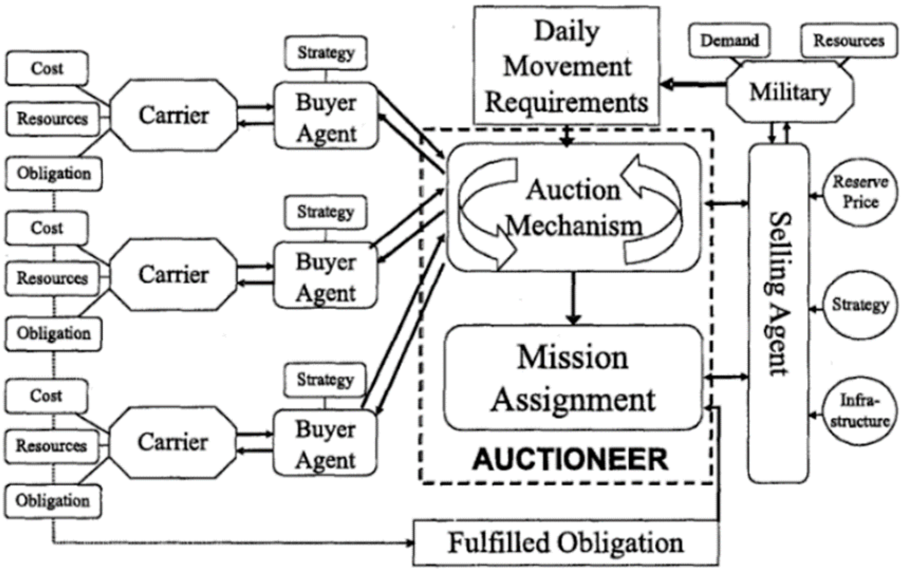


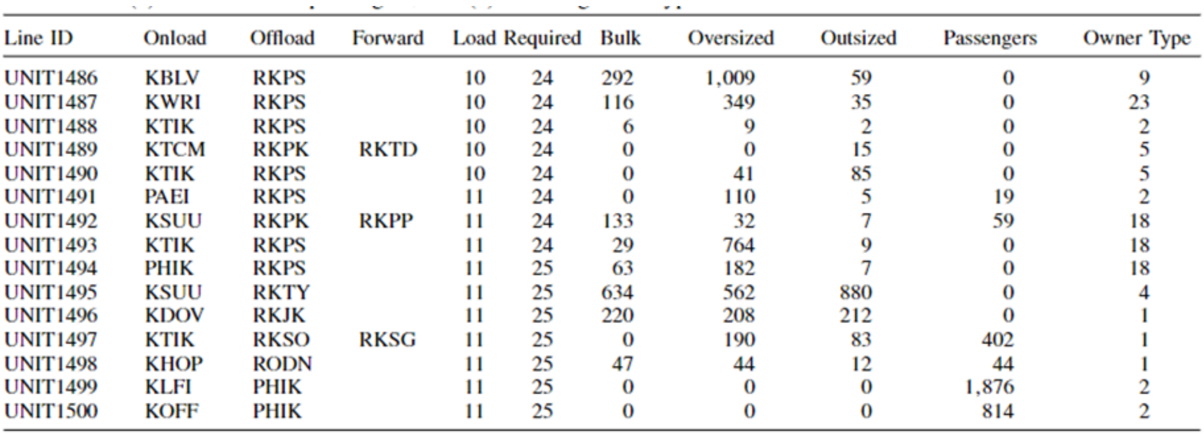
Figure 2.17: Reserve fleet auction and bidding model (from [17])

To test the model, the authors used TPFDD based on a sample Desert Shield Operation scenario provided by the US Transportation Command for the Defense Advanced Research Projects Agency (DARPA). The reserve price was then set to be a multiple of the actual cost of each mission based on the data [17]. Through auction swapping, total costs were reduced by 50% compared with a base fleet assignment model where each carrier is simply assigned the missions, wherein the carriers then decide the optimal hub and departure time that minimizes the cost to satisfy the mission [17]. Such a prospect of including the commercial fleet is something the authors predict to be a significant factor in future operations [17].

The work done by the authors can be used to motivate the inclusion of commercial aircraft in airlift operations, an aspect that is absent in current literature. This research did not discuss the effectiveness of using the reserve fleet in completing operations in a timely manner; auctioning and bidding the missions may lead to fewer costs but when time requirements are stringent or priority, the auction model and reliance on a reserve fleet may add further complications and delays to the airlift. One way of simplifying the incorporation of a commercial/ reserve fleet in a rapid cargo airlift simulation is by having a hybrid fleet architecture. By modelling commercial aircraft separately (potentially with a different loading, routing and operation logic) from the conventional strategic aircraft, the implications of having different fleet carriers is preserved whilst enabling for a collaborative effort in conducting the airlift.

S.F. Baker et al. [18] created a large-scale linear programming model to evaluate strategic airlift using a route planner subject to physical and policy constraints. The authors stressed that the purpose of the model was to evaluate tactical and strategic airlift concerns within an airlift operation, as opposed to recommending scheduling operations [18]. Due to this distinction, TPFDD of a Korean airlift movement was opted for the model's basis since it provides high quality lists of the cargo and troop scheduling requirements of an airlift movement (base of origin and destination, available loading and required arrival dates and the cargo distribution) [18]. A sample of the TPFDD used in the work is presented in Table 2.7, where the aforementioned data including the line ID (for tracking purposes) and abbreviated air hubs are detailed.

Table 2.7: Sample TPFDD for Korean airlift movement (from [18])

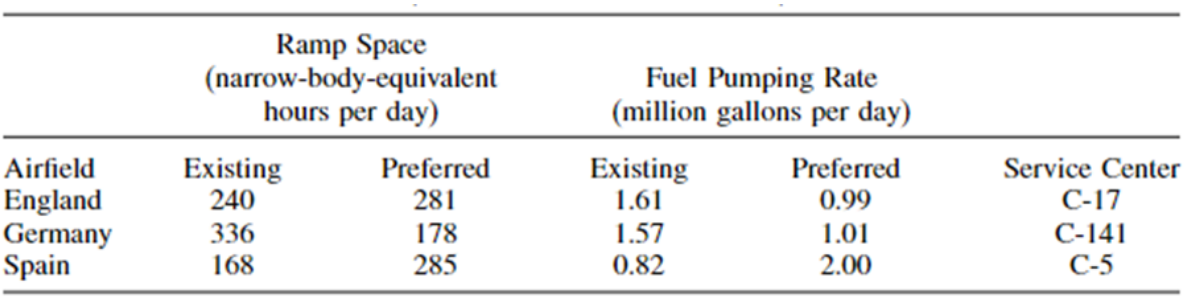


Line ID	Onload	Offload	Forward	Load	Required	Bulk	Oversized	Outsized	Passengers	Owner Type
UNIT1486	KBLV	RKPS		10	24	292	1,009	59	0	9
UNIT1487	KWRI	RKPS		10	24	116	349	35	0	23
UNIT1488	KTIK	RKPS		10	24	6	9	2	0	2
UNIT1489	KTCM	RKPK	RKTD	10	24	0	0	15	0	5
UNIT1490	KTIK	RKPS		10	24	0	41	85	0	5
UNIT1491	PAEI	RKPS		11	24	0	110	5	19	2
UNIT1492	KSUU	RKPK	RKPP	11	24	133	32	7	59	18
UNIT1493	KTIK	RKPS		11	24	29	764	9	0	18
UNIT1494	PHIK	RKPS		11	25	63	182	7	0	18
UNIT1495	KSUU	RKTY		11	25	634	562	880	0	4
UNIT1496	KDOV	RKJK		11	25	220	208	212	0	1
UNIT1497	KTIK	RKSO	RKSG	11	25	0	190	83	402	1
UNIT1498	KHOP	RODN		11	25	47	44	12	44	1
UNIT1499	KLFI	PHIK		11	25	0	0	0	1,876	2
UNIT1500	KOFF	PHIK		11	25	0	0	0	814	2

A fleet of C-5A's, C-17A's, C-141B's, B-747F's, KC-10's and KC-135's was used for the strategic and tactical airlift, with the KC-10 being used for aerial refueling predominantly. The aircraft data used in the model were the aircraft speed, average (maximum) flight hours per day, cargo/ passenger carrying capacity, payload- range diagram, required service times and airfield capacity, and aerial refueling capabilities [18]. For aerial refueling, delays are emplaced by means of a fractional probability of delay which results in a time delay and airfield capacity at a 'divert base' [18]. The authors highlight that even though in reality airfields for strategic and tactical purposes may be distanced from one another, aggregation of the bases under one node is an acceptable approximation given the general proximity of the bases relative to the airlift flight distances [18].

The model developed in this research, the NRMO, has the key objective function to prioritize late delivery (compared to non-delivery), but timely delivery is preferred if possible [18]. Additionally, the objective function has a positive weight/ reward for the aircraft to stay at embarkation hubs, enabling faster treatment of unforeseen contingencies and repair [18]. The authors simplify airbase infrastructure to two main parameters, the available ramp space (measured in narrow-body equivalent- equal to C-141 - parking space hours per day) and the service consumption rates, which is mainly composed of fuel pump rates [18]. This simplification allowed for, given the airlift case analyzed, the computation of optimal infrastructure conditions for different airbases located in Spain, Germany and England, to minimize redundancy, such as excessive capacity and fuel pump rates, whilst minimizing airlift time [18] by ensuring optimal fuel pump and capacity is met when required. The results are presented in Table 2.8.

Table 2.8: Ramp space and fuel pumping rate optimization for sampled airlift (from [18])



	Ramp Space (narrow-body-equivalent hours per day)		Fuel Pumping Rate (million gallons per day)		
Airfield	Existing	Preferred	Existing	Preferred	Service Center
England	240	281	1.61	0.99	C-17
Germany	336	178	1.57	1.01	C-141
Spain	168	285	0.82	2.00	C-5

Upon optimizing the airbase infrastructure, an increase of 12% daily cargo delivery was be obtained, highlighting the benefits of optimized infrastructure on airlift success. S.F. Baker at al. [18] also categorized the airbases such that different aircraft had different servicing bases, under the notion that 'birds of a feather flock together', which aids in simplifying the operational complexity of ground servicing and repairs. The authors also conducted an analysis of future, improved aircraft through an assumed increased reliability, which was itself simplified into reduced ground service times [18]. Although the actual implications of a higher reliability or upgraded technology (improved payload capacity, speed etc.) were not directly analyzed, the reduced servicing times resulted in an increase of up to 10% in troops delivered and 8% in cargo delivered [18].

S.F. Baker et al.'s [18] work can be adopted into future research in several ways. The format for cargo data shown in Table 2.7 is useful for defining the data categories a sample user should input into a model to allow for accurate airlift operations. The ability to have separate aircraft servicing times and bases is an aspect that can be incorporated as well to emulate the philosophy used in real-life. The alternative method of route prioritization and cargo allocation- the minimization of delays by prioritizing a late delivery as opposed to a non-delivery- can be explored compared to other objectives in airlift modelling, such as fiscal cost reduction and cargo throughput or the FEI [8]. Lastly the modelling of airbase infrastructure capabilities through ramp space and fuel pump rates can be used and expanded in this thesis to include the complexities of airbase design alongside routing, aircraft and other operation's design.

Summary

Airlift operations literature, unlike aircraft design or route planning literature, deals with the different activities that an airlift is composed of yet not succinctly associated with. For this reason, the reviewing of such literature can prove beneficial for the sake of understanding which aspects of an airlift operation can be realistically altered and optimized in a design of experiments. The focus of this thesis is more about aircraft design and the systems of systems modelling, but developing a robust fleet and model is reliant on the multi-faceted testing. This operations literature revealed which aspects of airlift operations such as changes in service/ loading times [16], infrastructure quality [18] or even the utility of a commercially adapted aircraft [17] are worth considering and manipulating for understanding the interplay between aircraft design/ fleet architecture and the airlift's success.

A set of models from the presented airlift operational design and airbase considerations literature can be used for the thesis methodologies. Namely:

- Cargo dataset formulation modelling from [18] - a method on how to present the cargo requirements using TPFDD.
- Preliminary airbase modelling from [18] - modelling airbases based on ramp-space, fuel pump rate and locations (gps data). The incorporation of having airbase specific servicing data may be employed as well.
- Objective function formulation from [18] - incorporating the prioritization of having aircraft stay close to APOE's to benefit from faster versatility with new demands or servicing requirements.
- Mission swapping and bidding model from [17] - having different agents submit bids for missions and having an auction manager which assigns the mission to the best agent. If required, an agent can replace its mission with another agent's.
- Pallet configuration system modelling from [16] - model each aircraft's payload capabilities based on the PPE and the available pallet positions for the aircraft. This is a simplified approach to the volume utilization of the internals.

6 Research Outline

This chapter acts as a conclusion to the literature review where a main research question for the thesis and the associated sub-questions are derived. The main research objective will be formalized and planning will be outlined

6.1 Research Questions

The purpose of this literature study is to establish the public levels of knowledge on rapid cargo airlift so that knowledge gaps can be identified and phrased under a research question. Given the literature reviewed in the previous chapters, it is clear that there is little exploration in the realm of aircraft design on rapid cargo airlift, especially regarding strategic airlift aircraft. Additionally, the majority of studies outlined used cargo demand models where the cargo requirements were constant and known from initialization, meaning dynamic cargo demand generation is unexplored. These gaps in knowledge can be framed into a research question for this thesis project:

"How can agent-based modelling and a dynamic operations environment facilitate the formulation of future aircraft, fleet and mission requirements for rapid cargo airlift?"

The dynamic operations environment refers to the ability to create new cargo requirements throughout the operation, as well as the prospect of changing the environment conditions, such as airbase availability. To accommodate the dynamics, an agent-based modelling approach will be used in a simulation environment, so that the different aircraft and dispatchers can be modelled as agents which can react to the new demand and environment based on a logic set. In doing so, aircraft parameters, such as lift-to-drag ratio, payload-range capabilities and fuel consumptions, can be incrementally varied so that a direct link is made between top level aircraft design and the functional effectiveness of the aircraft in the designed mission. The same can be done for fleet design, with different architectures, and mission operational designs, such as aircraft positions upon initialization, or the mission objective (time versus cost).

To help answer the main research question, sub-questions can be derived:

1. What methods of implementation can be used to emulate a dynamic or unpredictable operations environment?
2. How important is aircraft design and fleet architecture in the rapid cargo airlift mission's success?
3. How does the distinction between military and HA/DR cargo affect the planning of operations and effective aircraft design?

Question 1) deals with the simulation and agent logic; the way in which cargo will be generated, modelled and distributed to aircraft throughout the simulation, whilst dealing with effects such as aircraft servicing times or the changing of an airbase's infrastructure (ramp space, fuel pump rates, consumption of resources, accessibility). Since the aim is to emulate unpredictability, these aspects will all incorporate a probability chance of occurrence.

Question 2) considers the level of aircraft and fleet design for the thesis, specifically if a simple parametric change in the aircraft's performance data can result in noteworthy benefits for the airlift's effectiveness (speed, cost, etc.). This question may also lead into the question of the required depth of aircraft design (top level, conceptual, detailed) in order to appropriately gauge the impact on the mission's success.

Question 3) is a result of including both military and HA/DR mission types in the thesis and is important due to its presence enabling holistic analysis of each aircraft, fleet or operation's design choice. This inclusion of both mission types is novel, and therefore the implications of this choice on determining future top-level requirements must be considered.

6.2 Research Objective

The objective of this thesis is to extrapolate design requirements for the necessary disciplines of a rapid cargo airlift based on the direct evaluation of mission success, thereby linking design and operational effectiveness. In doing so, future top-level requirements for the cargo aircraft can be formulated whilst giving opportunity for concept of operations (CONOPS) and fleet design effects to be evaluated. The purpose of such research is to improve the efficiency of rapid cargo airlift, which has been shown to be a costly endeavor [4], and to offer design approaches for the development and acquisition of future air fleets [10]. The notable novelties of this thesis are: the inclusion of spontaneous cargo generation for both military and HA/DR missions- as opposed to relying only on known or forecasted data for one mission type upon initialization, and the ability to analyze the interaction of multiple, previously established models (such as airbase modelling and aircraft modelling) whilst improving the extensibility of these models with more parameters. In doing so, the goal of obtaining a holistic, unbiased and robust analysis of design choices on the operation's effectiveness is easier attained.

6.3 Research Planning

This research project is deconstructed into 6 phases so that planning can be outlined easier. The phases are shown in Figure 2.18, where the key milestones relevant to the thesis are shown below the phases.

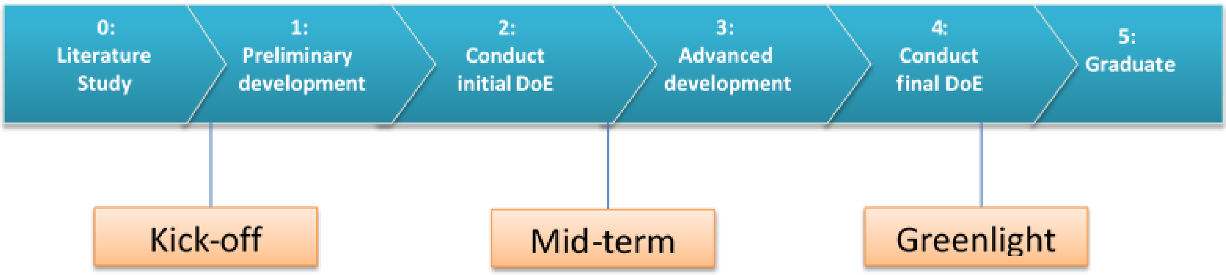


Figure 2.18: Research planning phases and milestones

The kick-off milestone represents the beginning of the official technical development phase of the research project and as such occurs at the end of the literature study. The mid-term milestone includes a review where the current results and developments are evaluated and future plans for improvement and remaining steps are outlined. The greenlight milestone is similar to the mid-term; a review of the project is made once again but with the end goal of determining if the thesis is sufficient for graduation based on a draft paper and final results. Since this thesis is a collaboration between the German Aerospace Center (DLR) and TU Delft, the tools available from DLR will be employed as foundations for the work of the project. Namely, the SoSID simulation toolkit [19] which is used to model system of systems behavior by using agent-based modelling for intra-city urban air mobility will be repurposed for inter-continental cargo operations.

The phases are as follows:

1. Literature Study
    - Period: 2 months
    - Objective: accrue literature on rapid cargo airlift to identify current capabilities and gaps for future research
    - Output: a literature study paper and a consolidated research question
2. Preliminary development
    - Period: 1.5 months
    - Objective: develop simulation environment; create cargo generation and fuel consumption models; establish agent logic
    - Output: a functional simulation that captures the basics of rapid cargo airlift
3. Conduct initial DoE
    - Period: 1-2 weeks
    - Objective: obtain understanding of simulation limitations and reflect development state
    - Output: a roadmap for future model developments and improvements

4. Advanced development
    - Period: 1.5 months
    - Objective: implement feedback on initial DoE and explore avenues for additional features and design variables
    - Output: a complex simulation that incorporates several design variables and can be used to compare multiple designs for different mission types
5. Conduct final DoE
    - Period: 2 weeks
    - Objective: encapsulate all input design effects on mission success and enables determination of most successful aircraft, fleet and CONOPS designs
    - Output: draft thesis paper including robust results
6. Graduate
    - Period: 1 month
    - Objective: present research project (includes methodology, results, analysis and conclusions)
    - Output: a finalized thesis paper and graduation presentation

7 Conclusion

The purpose of this literature study was to explore the current capabilities of rapid cargo airlift and the modern developments being researched so that a research question on further exploration avenues to increase the airlift efficiency could be constructed. This was done by conducting a review of literature available for rapid cargo airlift, which mainly dealt with route planning optimization and partially operational planning benefits like aerial refueling effects and the use of intermediate / support hubs. In terms of aircraft design, there is a noticeable absence of studies which evaluate the effect of aircraft design parameters on the operation effectiveness; where only recently studies on vehicle design for tactical airlift have begun with VTOL analysis. As well as this, most studies evaluating specific techniques, like cargo loading techniques, aerial refueling and the effect of infrastructure quality are done with numerical models instead of simulation, which means greater systems of systems complexities are not considered appropriately. Lastly, the literature studied commonly uses detailed cargo data upon initialization which is not always publicly available and does not reflect the unpredictability of rapid cargo airlift missions. This helps with obtaining results with high accuracy but has adverse effects with performance bias as only one airlift situation is considered.

Therefore, there is a gap for a simulation which analyzes CONOPS techniques along with conceptual aircraft design, in an environment that integrates spontaneous cargo generation and considers both HA/DR and military mission domains. Such a research gap leads to the question: **How can agent-based modelling and a dynamic operations environment facilitate the formulation of future aircraft, fleet and mission requirements for rapid cargo airlift?** The dynamic operation environment is relating to the prospects of having a variable cargo demand model (probabilistic creation of cargo requirements given constraints such as maximum size) and unpredictable airbase availability. Agent-based modelling enables the aircraft and airbases to accommodate the unpredictable operation environment. With such a simulation, design parameters such as the aircraft design, fleet architecture and mission design, can be evaluated in terms of direct operational success outputs (airlift time, cost, aircraft utilization rate, resource shortage, etc.) and effectively compared. Such a method also reduces the risk of bias since airlifts will not be tailored to specific cargo requirements. With the literature study finalized, the next step is to develop the methodology and create the simulation environment and associated models (outlined in Figure 2.18) which is done using the DLR in-house toolkit SoSID.

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Chapter 3

Supporting Work

1 Time step and runs per case analysis

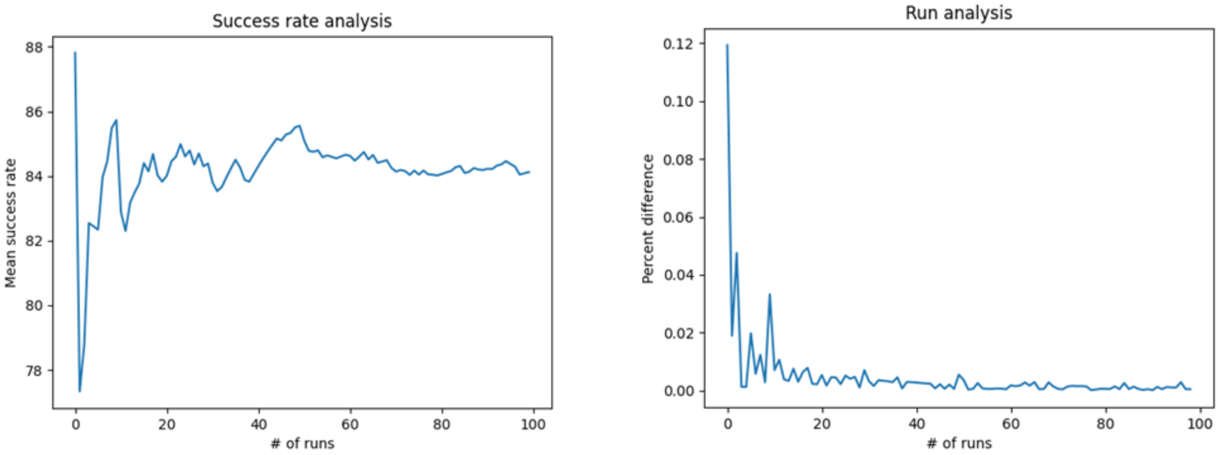
Since the simulation uses stochastic events such as aircraft servicing chances and spontaneous cargo generation chances, the impact of the time step on these events and the greater simulation success must be evaluated. From a time perspective, a larger time step means a lower simulation run-time as fewer computational steps are checked, which is beneficial when reducing computation time. The fear is that increasing the time step could result in imprecision, with events being missed or incorrectly scheduled, making the results less reliable. Using the mission setup showcased in chapter 1, Mission 4 which was used as a baseline for the trade-space will be evaluated since it contains the most variability amongst the missions.

Time steps starting from 15 s to 60 s in increments of 15 s were evaluated and the key MoE's of mission time [hrs] and delivery success were measured across a set of 100 runs, each instances with their own RNG seed to ensure each parallel mission was treated similarly. By increasing the time step, more simulation events are scheduled at a single point in time. For instance, if two aircraft were to arrive at different airbases, one at 1 day 16 hours 3 minutes and 5 seconds and another at 1 day 16 hours 3 minutes and 55 seconds, a time step of 60 s would cause the simulation to check both of these aircraft for servicing at the same time. In the instance both aircraft are serviced, their flights would be rescheduled together and both would be unable to bid for the set time. However, if a smaller time step were chosen, these aircraft would be checked for servicing separately. If both aircraft receive servicing, this time the aircraft which arrived earlier would reschedule its flights, reinstating cargo, whilst the other aircraft would be able to bid for this cargo as it is not being serviced. Once the second aircraft receives servicing, the cargo would once again be reinstated, but due to the different flight schedules of other aircraft (due to the initial aircraft's cargo bidding), it is possible that some of this cargo receives a completely different flight path compared to a larger time step. It is for this reason the time step analysis is important to determine how much of an impact these time steps have and the number of required simulation runs to ensure an accurate representation of the mission's performance is obtained.

The mean values for the different MoE's and time steps are shown in Figure 3.1, where the error bars represent one standard deviation from the mean. As time step is varied, there are indeed changes among the mission time and delivery success, however these variations are within the order of 1 hour for mission time and 2% for delivery success. While these are differences, they are not significant and due to the greatly reduced computation time of a higher time step, it is seemingly likely that the time step of 60 s is sufficiently accurate, obtaining similar values to a time step of 15 s.

Figure 3.1: Time step sensitivity on mission time and delivery success

To determine the required number of simulation runs to obtain a feasible mean value, the successful delivery percentage was checked for convergence. This output relates to the success of the airlift itself, so it is the ideal metric to ensure the data obtained is representative of the mission's performance. Figure 3.2 presents the development of mean delivery success and the corresponding percentage difference in the mean value across the runs for a time step of 60 s. To obtain a less than 0.5% difference in the mean value, 12 runs are required. From this point, the delivery success stays within the boundary of 84-86%, converging to 84%. As a safety and to ensure a similar convergence across a different set of RNG, 15 runs per case will be used. Increasing the runs per case naturally increasing the time required to get a reliable data set, but the time step of 60 s offsets this.



(a) Delivery success convergence

(b) Percentage difference in mean

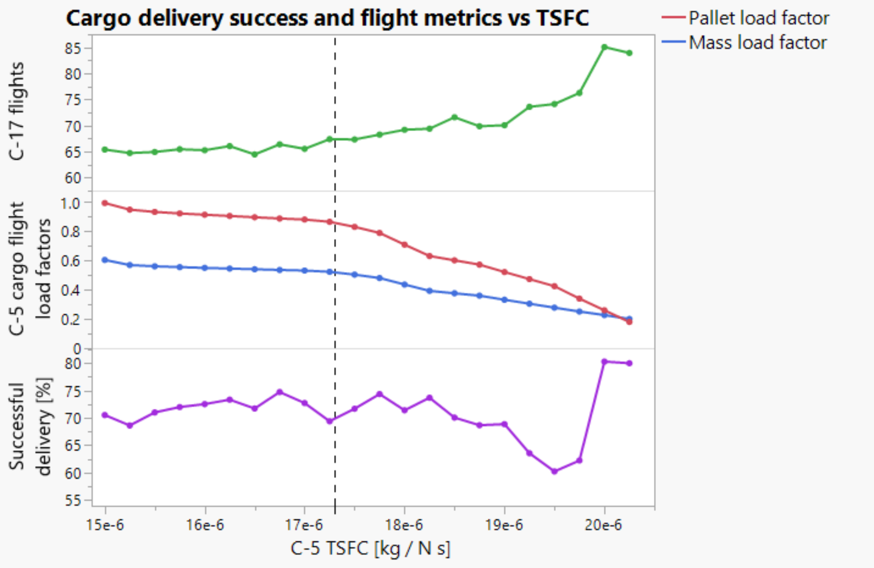
Figure 3.2: Required runs and convergence analysis (time step = 60 s)

2 Sensitivity analysis

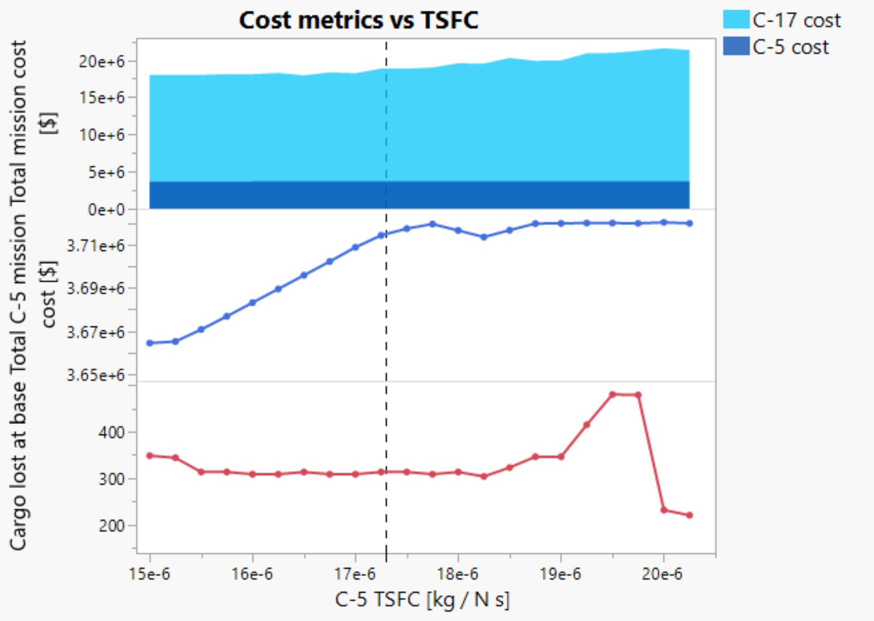
To verify the model's behavior and to explore future avenues for aircraft design, a sensitivity analysis on the aircraft model is done. This also verifies the airlift model as the outputs used are based on the total movement's data and aircraft fleet performance. The parameters varied in this analysis are the design TSFC, design L/D, payload, pallet and fuel capacity, CPFH and break rate. Each of these sensitivities will be varied in positive and negative increments, which can also be useful for aircraft designers to extrapolate how a simple subsystem change can impact the aircraft's operational performance. The C-5M will be used for this analysis. This is because it can offer a continuation or prelude to the trade-space described in chapter 1, providing additional insights into key performance parameters. Also, since by the standard use of cost as an objective, the C-17 is utilized and prioritized more frequently than the C-5M, so the hope is that by modulating the C-5M's design, the variations which change this are better highlighted.

TSFC

The aircraft's design TSFC is varied with about a ±20% difference with respect to the baseline C-5M. Figure 3.3 presents the cargo delivery success, flight and cost metrics for this variation. When the TSFC is increased, naturally the amount of fuel used to perform the same flight is increased. If all other parameters stay the same, the aircraft will gradually have to reduce its cargo load as shown in Figure 3.3a. This then results in more flights being scheduled, where most of the flights are carried out by the C-17 due to its reduced cost. The usage of the C-5 maintains itself as it still offers a fast departure time for the cargo it does carry, which can outweigh the fuel cost increase. Interestingly, the delivery success does not change much initially. Only when the TSFC is increased to margins that greatly reduce the load factor to <0.3 are the impacts of C-17 over-utilization reflected in the delivery success. This is because as the TSFC increases and the C-5 carries less cargo, the C-17's start to gradually lose their ability to transport cargo from Kadena to Subang and instead have to focus more time on the first flight leg from Travis to Kadena. The large increase in cargo lost at base reflects this as eventually only one C-17 (originally two) is available to conduct the travel from Kadena to Subang in the first few days, which means more cargo is present upon the airbase's access restriction. The cargo present then has to be recreated, essentially restarting the cargo from the origin, making many of the initial flights redundant.



(a) Delivery success and flight analysis



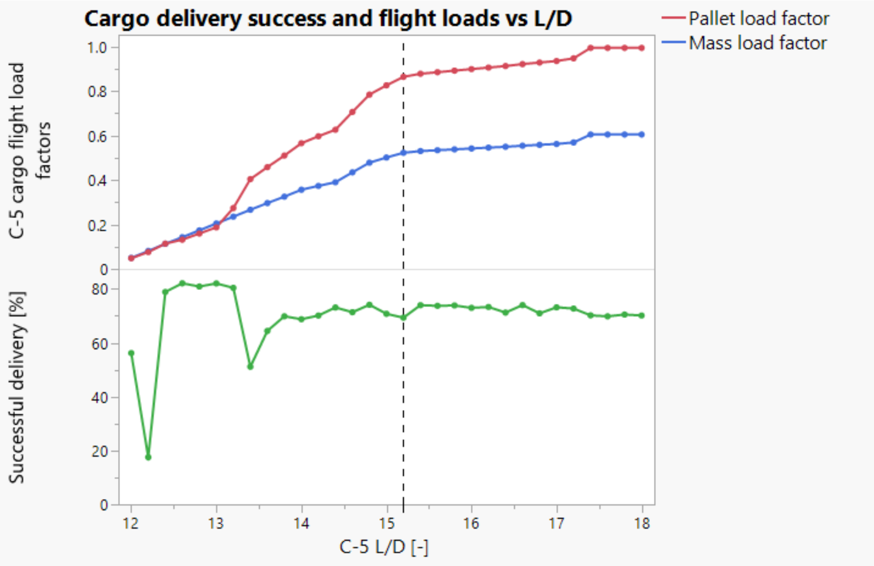
(b) Lost cargo and cost analysis

Figure 3.3: TSFC sensitivity analysis [black line represents baseline C-5M]

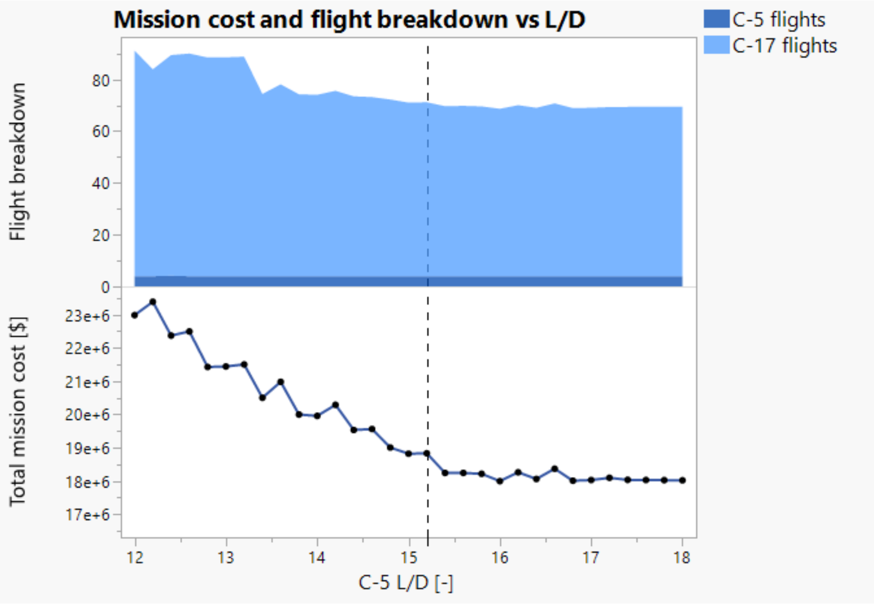
However, when the TSFC reaches above 2 E-6 kg/Ns, the delivery success drastically increases. This occurs because of however the dispatcher processes the cargo bids. When the TSFC is increased, the bidding value of the C-5M's becomes worse. However, when the C-5M are still present at the origin base, they offer a greatly reduced time saving to the C-17, meaning that they are still chosen for bids initially. Only after the C-5 fly their first flight and are no longer near the cargo origin, does the dispatcher ignore C-5 bids. Since the dispatcher prioritizes cargo based on departure time, water cases were processed first and then VTOLs. Due to the magnitude of water to be transported, the dispatcher would end up assigning the last chunk of water cases to C-5 before assigning them VTOLs. The VTOLs have the lowest density, making flights with them quite inefficient due to a low cargo unit throughput. Since C-17's are heavily utilized and have a reduced cargo carrying capability, the airlift runs better when the C-5 carry the VTOLs and the C-17 carry all the denser cargo. When the TSFC is increased to high values, the dispatcher ends up using the C-17's each a second time before using a C-5. This then causes all the water cargo to be taken by the C-17 and the VTOL's solely by the C-5. Whilst beneficial for efficiency, the number of flights conducted by 2.5 days in the simulation is the same, just the amount and type of cargo transported is different. When the C-17 do not carry any VTOLs, they bring more cargo units to Kadena within the same number of flights due to better volume utilization (swapping VTOLs for denser cargo). This means that, upon access restriction, more cargo is recreated, impairing delivery success. When the TSFC is further increased, the C-5 are no longer able to carry the VTOLs due to the fuel consumption, resulting in the C-17's carrying them. In this way, the same flights which would have been carrying denser cargo are now carrying VTOLs which constitutes as fewer cargo units. This means that when Kadena's access is changed, VTOLs are now being recreated and not several units of denser cargo. Since the delivery success is based on a unit basis, the delivery success will then increase despite VTOLs being failed deliveries.

L/D

Based on the Breguet range equation, the L/D functions similar to the TSFC, but inversely. Intuitively, this would mean the results from an L/D variation should function similar to the TSFC variation, but opposite. The L/D was varied with a similar ±20% change to the baseline C-5M value, with the results on airlift performance shown in Figure 3.4. When the L/D is high, the aircraft is able to carry more cargo for the same flight due to a reduced drag/ increased lift. At values above 17.5, the constraining factor is no longer the fuel usage but in fact the pallet capacity, indicating further design to be unnecessary. At lower L/D values, the aircraft's ability to carry cargo diminishes and more C-17 flights are scheduled to deal with the required cargo transport. Simlar to TSFC, when the L/D drops to low values, the dispatcher ends up prioritizing a return trip from the C-17 over an initial flight from the C-5, resulting in the C-5 not carrying any of the VTOL's. With the C-17 now carrying the VTOL's they take longer to bring denser cargo to the Kadena airbase, such that by the time it is rendered inaccessible, there is more cargo waiting at the origin than at higher L/D values.



(a) Delivery success and flight load analysis



(b) Cost and flight share analysis

Figure 3.4: L/D sensitivity analysis [black line represents baseline C-5M]

The reduced cargo recreation improves delivery success in these areas. When the C-5 L/D is at extremely low levels, it carries almost no cargo, where the dispatcher almost purely relies on the C-17's. In this instance, the delivery success initially decreases as C-17's just finish delivering the cargo at Kadena by the time it is rendered inaccessible. The success actually increases again for the lowest L/D as the small increment of cargo not carried by C-5M's results in an extra flight by the C-17's before Kadena's access update. And since this flight departs after the access update, it does not bring the extra cargo to Kadena, reducing cargo recreation, and conveniently sets it up to win the recreated cargo bids since it is still present at the origin. This flight change inadvertently makes the airlift better suited for the airbase access change.

Payload capacity

The payload capacity was varied ±20% to the baseline C-5M. Changes in payload capacity are viewed as independent to other aircraft variables in this analysis, meaning the aircraft flies with the same system parameters, but simply has a different MTOM. This can be argued as changes in airframe technologies that keep the shape of the aircraft but allow for a higher load bearing capability. C-5 payload variation effects on the delivery success are found to be almost negligible, as shown in Figure 3.5. This is because the C-5 are not utilized frequently in the simulation, due to their egregious cost, and the few times they are used, they are fuel and pallet capacity limited and not payload limited. This is evidenced by the fact that the pallet load factor is constant and near 1.0 amongst all variations of payload, meaning the same cargo is being loaded, whilst the mass load factor is decreasing, due to the increasing maximum allowable payload for the same payload mass. In effect, for the given airlift setup, the C-5's payload capacity is actually over-designed.

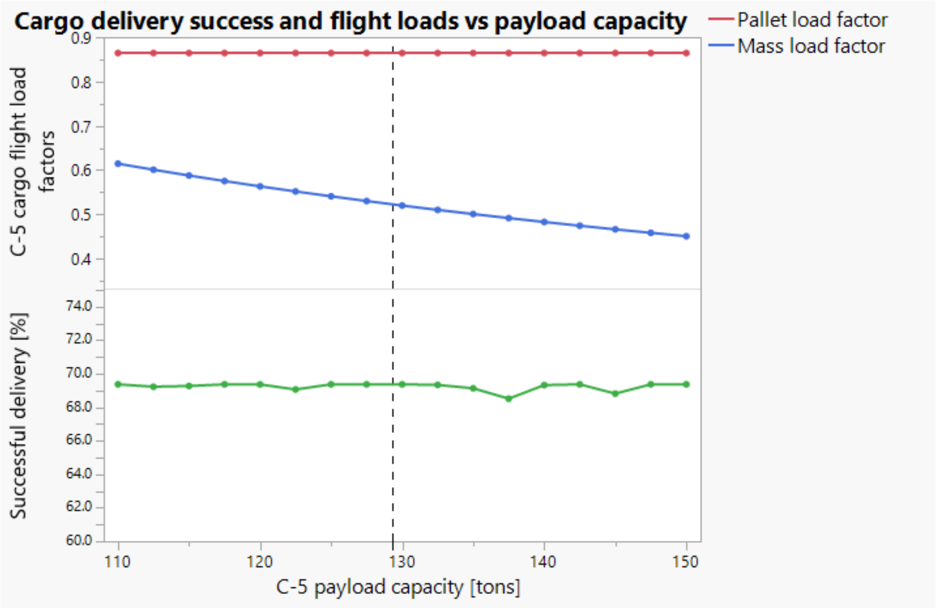
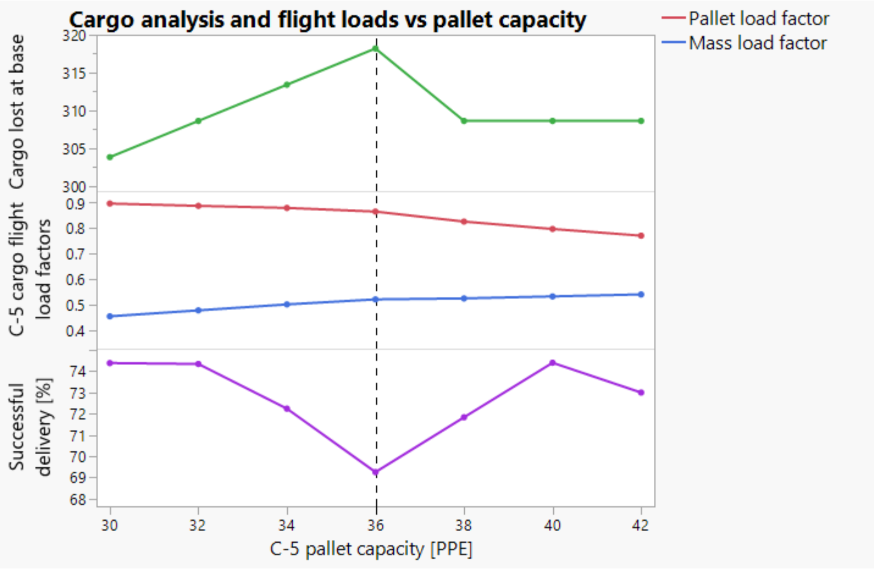


Figure 3.5: Payload capacity sensitivity analysis [black line represents baseline C-5M]

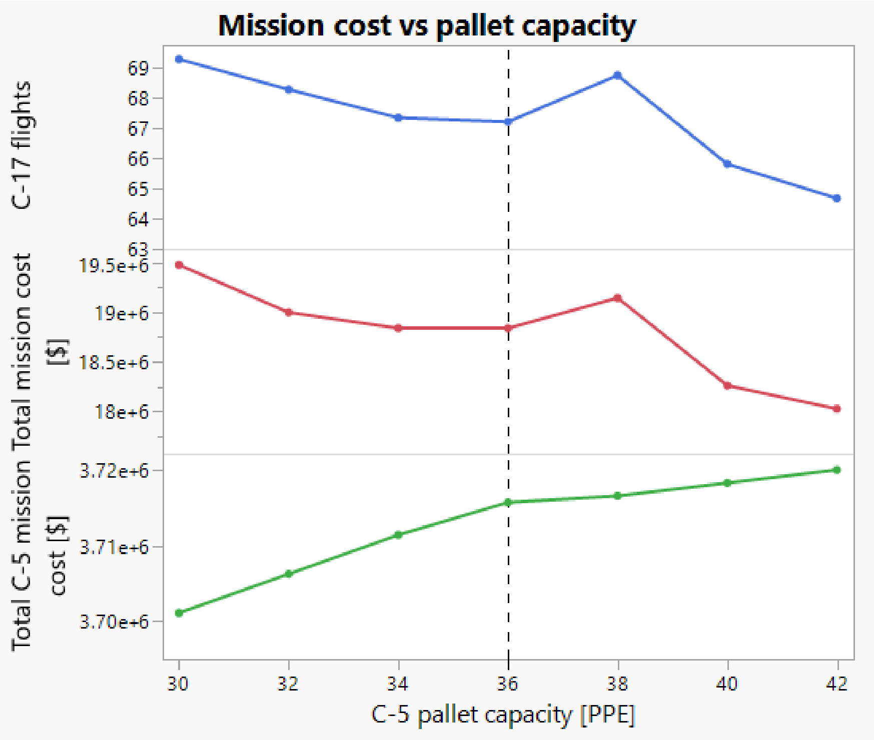
Pallet capacity

Unlike payload variations, the pallet capacity of the aircraft can be changed without actual modifications to the aircraft's design. Through better utilization techniques, such as pallet stacking or changing configuration of the cargo bay, the number of storable pallets can be increased. The pallet capacity of the C-5M was varied in this sensitivity by ±20%, giving a range of 30 to 42 PPE's. The cargo delivery success and load factor analysis is shown in Figure 3.6a. To understand the development of these curves, the type of cargo being loaded into the C-5's must be understood. As previously discussed, the C-5's are used after the first set of C-17 flights are scheduled. This results in the C-5's being used for any remaining water cases, then the VTOL's and then food cases. For the base scenario, the first C-5 is loaded completely with water cases and meets its load limit due to fuel capacity with about 16 pallets being used. The second C-5 carries almost 12 pallets worth of water, completing all water requests, and then carries one HH-60W consuming 9 pallets, and then can manage to carry 2 pallets of food before reaching the load limit due to fuel capacity. The third C-5 carries the last two HH-60W's, and then carries 18 pallets of food, reaching pallet capacity. The remaining C-5 only carries food and reaches load limit due to fuel capacity at almost maximum pallet capacity (36).

When the pallet capacity is decreased, the first C-5 carries the same amount of water as the fuel capacity is what limits the load irrespective of the pallet capacity. The second C-5 gradually removes food cases and eventually only carries the water and the VTOL at 30 pallets. The third and fourth C-5 both remove food as they were at or near pallet capacity originally, where the third C-5 still manages to carry the VTOL's. The reduced amount of food being cargo by C-5's results in more C-17's being required to carry this food from Travis, reducing their availability to take cargo from Kadena. Thus the cargo lost at base increases, increasing recreation demands and reducing successful deliveries. The number of C-17 flights (displayed in Figure 3.6b as the pallet capacity of the C-5 increases as the C-17 have to conduct fewer cargo flights from the US. This occurs despite the increased cargo recreation demands which increases the number of flights.



(a) Cargo and load factor analysis



(b) Cost and C-17 flight analysis

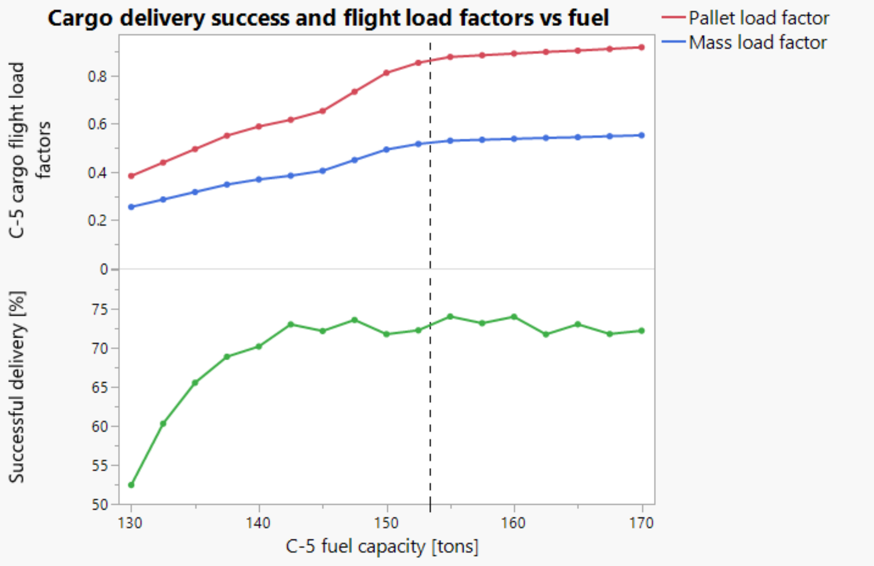
Figure 3.6: Pallet sensitivity analysis [black line represents baseline C-5M]

Conversely, when the pallet capacity is increased, the first C-5 flight remains unchanged, but the last two C-5 flights gradually add more food cases so that they meet fuel limits instead of pallet capacity. The key difference between 36 and 38 pallets is that the second C-5 flight is just able to carry two HH-60W's along with the water cases instead of just one. This replaces the third C-5 flight's HH-60W with food, making it carry the exact same cargo as the last C-5 (just food). The cargo swap allows for more food to be carried, which reduces the amount of food the C-17's have to carry, allowing them to be used more frequently for the final leg of flight. This explains the reduction in cargo lost at base and increased delivery success. This benefit eventually tapers off however as the C-5 with increased pallet capacity meet fuel capacity limits soon after, which is why the mass load factor stabilizes and the pallet load factor decreases. This is reflected by the small changes in C-5 cost as the fuel usage plateaus towards the larger pallet capacity. The C-17 flights increases initially, and then continues the downward trend. Unlike the reducing pallet capacity, the required C-17 flights from the US is decreased twice over, due to the reduced amount of food requests and due to the reduction in cargo recreation due to the VTOL swap. This then allows the C-17 to prioritize the last flight legs, which have a reduced flight distance and thus flight time. This means within the same amount of time, more C-17 flights are conducted, perpetuating the increased delivery success. From that point on, the cargo lost at base is unchanged meaning the resulting changes are purely due to fewer scheduled C-17 flights from the initial movement.

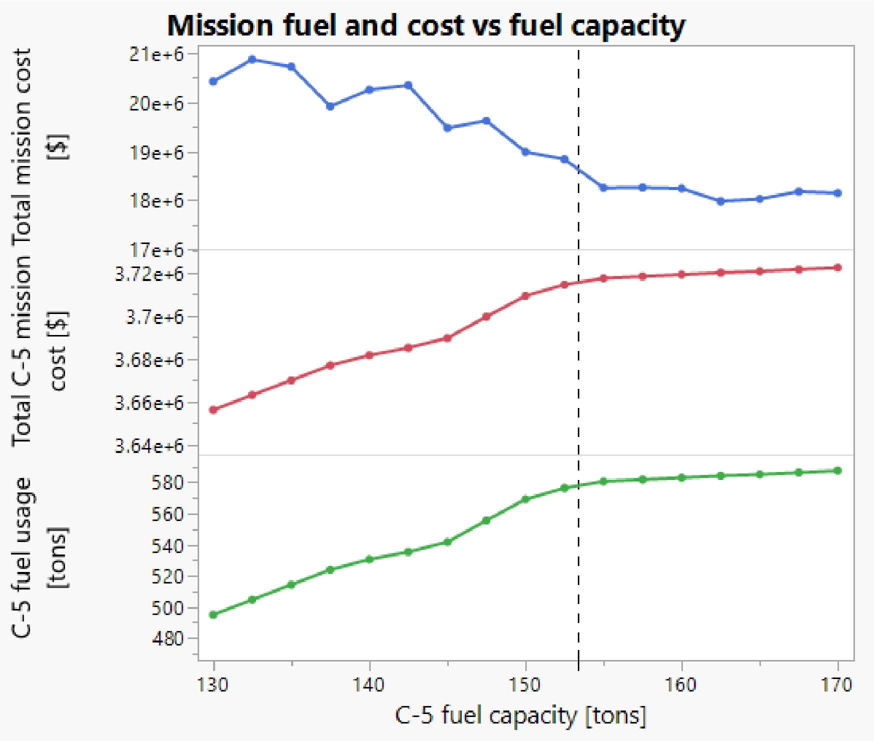
Fuel capacity

Given the fuel capacity to be a limiting factor on the amount of cargo the aircraft carries, an analysis on the aircraft's maximum fuel is beneficial. For this analysis the fuel capacity is varied from 130 tons to 170 tons. These changes can be due to fuel tank sizing changes or the removal/ inclusion of a new fuel tank on the aircraft. The fuel capacity's effect on delivery success, load factors and cost and fuel usage is shown in Figure 3.7. Since the baseline C-5M is already sometimes fuel constrained, reductions in the fuel capacity result in a reduction of loaded cargo mass and consumed pallets. The reduced cargo throughput by the C-5 negatively impacts the delivery success as C-17 are tasked with carrying more cargo from the US instead of conducting the final leg. Naturally, the reduced fuel capacity also decreases the C-5 flight cost as it flies with less cargo, but the increased C-17 utilization increases total mission costs.

When the fuel capacity is increased past the baseline, there is little difference in delivery success and loaded cargo mass since the majority of C-5 flights are already at or near their maximum pallet capacity. Only the first C-5 flight is able to take advantage of the increased fuel by taking up to 10 more pallets worth of water. This reduces the water carried by the second C-5, but it the difference is not significant as it reaches pallet capacity again due to the food cases. Fuel capacity changes therefore only make a difference when the pallet capacity or payload capacity is not constraining, which in effect requires cargo that is dense enough to not consume excess pallets/ volume, but not overly dense to provide excess added weight to where the maximum payload is met.



(a) Delivery success and flight load analysis



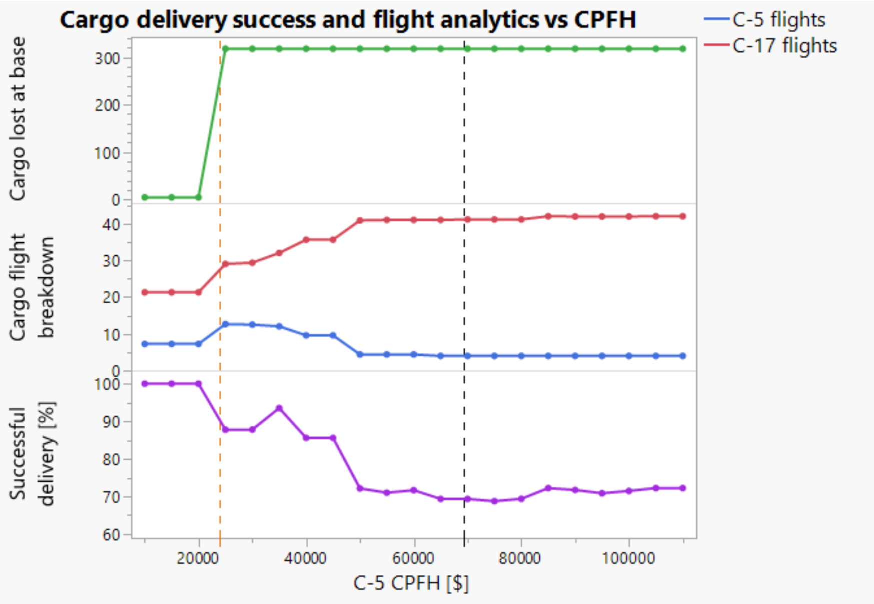
(b) Fuel usage and cost analysis

Figure 3.7: Fuel capacity sensitivity analysis [black line represents baseline C-5M]

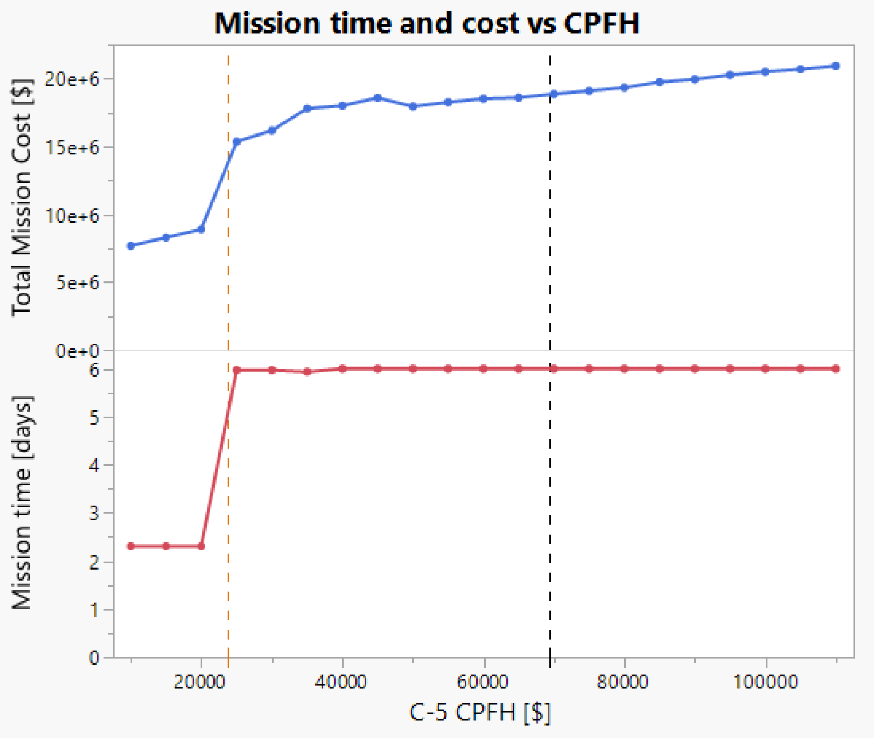
CPFH

Since the cost is used to evaluate each aircraft's bid, the change in CPFH will have a significant impact on how the airlift is conducted, as this is the reason why C-5's are used infrequently. Determining realistic boundaries for the C-5's CPFH, even if with different variations is difficult as CPFH can vary on many factors such time into service life, technology levels, required crew size and expertise, material choices, the intended operation, etc. Hence, this sensitivity study will be used as a more theoretical analysis on the CPFH, where the conditions that must be designed to obtain each CPFH will not be entirely feasible but if they were attained, what would the result be. For this purpose, a large set of CPFH will be evaluated, ranging from $ 10'000 (US) to $ 110'000 (US).

Figure 3.8 displays the impact of CPFH on key MoE's and flight metrics. Both the C-17's and C-5's CPFH are important to this evaluation which is why they are marked on the graphs. When the C-5's CPFH is less than the C-17's (≤$ 20'000 (US)), C-5 bids are prioritized due to their faster or similar flight time and reduced operation cost. In such missions, the cargo throughput benefits from the C-5's cargo carrying capabilities, resulting in successful missions with all cargo being delivered before airbase access restriction. One the other hand, when the C-5's CPFH is significantly higher than the C-17's (≥$ 50'000 (US)), C-5 bids are heavily under-prioritized and only win over C-17 in the very beginning of the simulation when all C-17 have been tasked with their initial flights. C-5's are flown once each in this instance and only due to their initialization at the same location as cargo.



(a) Cargo and flight share analysis



(b) Cost and time analysis

Figure 3.8: CPFH sensitivity analysis [black line represents baseline C-5M, orange is the C-17]

Between these two regions ($ 20’000 (US) < CPFH < $ 50’000 (US)), more interesting effects take place. As soon as the C-5’s CPFH is greater than the C-17’s, the C-5 are only used one time each before the airbase access restriction. Since the C-17 are prioritized, the mission is not completed before this event occurs and thus cargo is lost at the base. This value is constant since the C-5’s priority in the initial movement is unchanged despite the CPFH variations because the C-17 only need one return trip to finish carrying all the initial cargo. The distinction between the CPFH within this range instead is due to the recreated cargo. The differences in CPFH can sometimes result in C-5 being chosen over C-17 since the difference in departure times favors the C-5's and thus the minute increases in C-5 flight cost can result in it losing the bid to the C-17. The number of lost bids increases as the CPFH increases, as shown by the gradual reduction in C-5 flights in Figure 3.8a. Because of the complexity of this relation, it may sometimes be beneficial for the C-5 to lose a bid and instead take another set of cargo, depending on how servicing is conducted and the cargo that the C-17 carries (lower density cargo vs high density cargo).

The significance of CPFH is clear, if a new aircraft with similar payload-range capabilities as the C-5 were to be introduced but with a CPFH that matches or is better than the C-17, significant improvements can be seen in mission cost and time. Even if the mission is a failure (time extending past 6 days), the proportion of delivered cargo and to a lesser extent the mission cost benefits from the reduced CPFH based on how flights and cargo are assigned.

Break rate

The break rate is used to determine servicing likelihood within the simulation per landing basis. Break rates are not easily configurable and usually found from operation history. For this reason, the C-5 break rate was varied from 0 to 30%, indicating a perfect aircraft without servicing problems and one that has a high likelihood of being serviced. The performance and MoE's for the break rate variation is shown in Figure 3.9. Increasing the C-5's break rate up to 30% results in an increased total number of fleet services by one third. One might expect this to impact the delivery success, but due to the C-5's each being used one time each, this makes no impact on a cargo's itinerary. Since the C-5 schedule is cleared upon arrival, no cargo has to be reinstated and no flight swapping occurs. Therefore this analysis does not offer much information regarding the trend between service frequency and mission success. This does hint towards the benefit of increasing the fleet size for the same demand as with more aircraft available, fewer aircraft flights are scheduled, making the impact of break rates negligible.

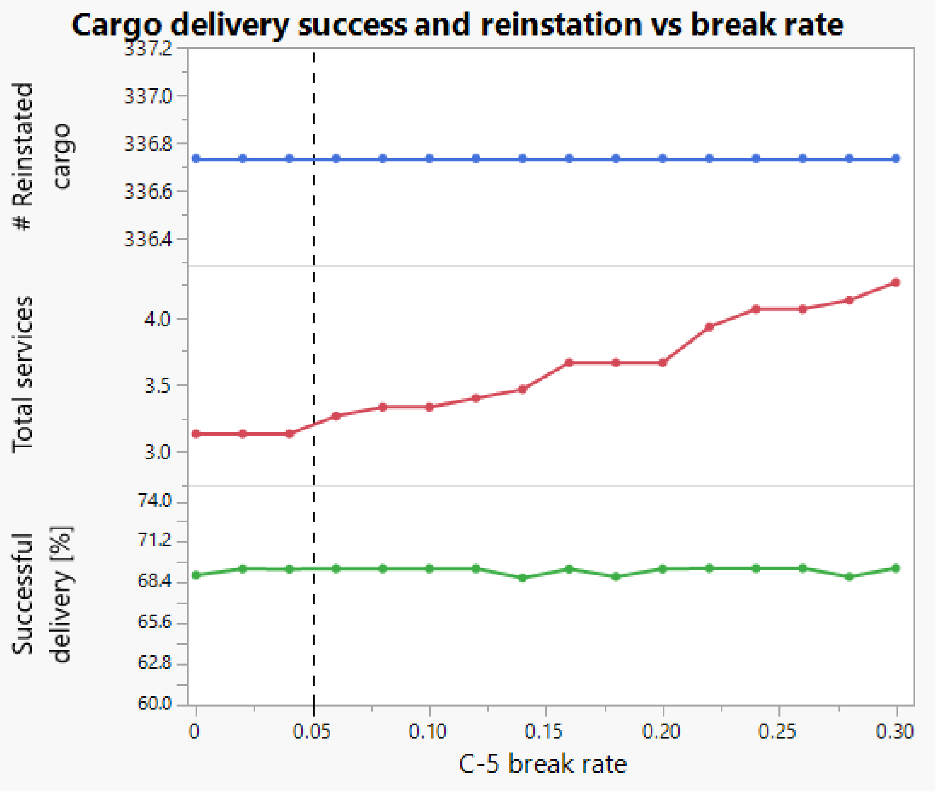


Figure 3.9: Break rate sensitivity analysis [black line represents baseline C-5M]