Design and Assessment of Strategic Airlifters for Rapid Deployment

A System of Systems Approach

Hotters Dani

TU Delft

Design and Assessment of Strategic Airlifters for Rapid Deployment

A System of Systems Approach

Thesis report

by

Hotters Dani

to obtain the degree of Master of Science
at the Delft University of Technology
to be defended publicly on 10 Januari 2025

Thesis committee:		
Chair:	Dr. Ir. G. la Rocca	(TUDelft)
Supervisors:	Dr. Ir. F. Oliviero	(TUDelft)
	P. S. Prakasha	(DLR)
	T. Dietl	(DLR)
	Ir. N. Kalliatakis	(DLR)
External examiner:	Dr. A. Bombelli	(TUDelft)
Place:	Faculty of Aerospace Engineering, Delft	
Project Duration:	March, 2024 - Januari, 2025	
Student number:	4769732	

An electronic version of this thesis is available at `http://repository.tudelft.nl/`.
The cover image was taken by Santos Caceres (modified): www.instagram.com

Faculty of Aerospace Engineering · Delft University of Technology

Delft University of Technology

Acknowledgments

I want to express my gratitude to the German Aerospace Center (DLR), particularly to my supervisors, Prajwal Shiva Prakasha, Tobias Dietl, and Nikolaos Kalliatakis, but also to my supervisor from TUDelft, Fabrizio Oliviero. Their guidance and mentorship throughout both the thesis and internship have been invaluable, and I am grateful for the opportunity that I have been given to work alongside these awesome people. My appreciation extends to all colleagues at DLR who contributed to making the experience not only fun but also educational. The after works, coffee breaks and occasional cakes played a significant role in retaining the motivation during the stressful moments.

Secondly, I would like to thank my friends Felix Kuhnert, Niels Engelen, and Romain Coumans. Their interest in my work has been motivating and encouraging. I'm grateful for the guidance, insights, and motivation they gave me along the way.

Finally, I would like to thank my family for their financial and emotional support during the past years to make my education possible. This encouragement and belief in my potential have motivated me throughout my journey. The surprise visit to Hamburg, in particular, created a lasting memory that I will treasure for years to come. I would also like to make a special mention to my grandfather, Alfons Vanaubel†, who recently passed away. His influence and support meant the world to me, and I deeply appreciative all that he and the rest of my family have done for me throughout the past years.

Dani Hotters
Hamburg, December 2024

Contents

Nomenclature

List of Abbreviations

ABCT Armored Brigade Combat Team

ABMS Agent-Based Modeling and Simulation

AFIT Air Force Institute of Technology

AHP Analytical Hierarchical Process

AMC Air Mobility Command

APU Auxiliary Power Unit

CERs Cost Estimation Relationships

CPACS Common Parametric Aircraft Configuration Schema

CSJOR Combined Joint Statement of Requirements

DLR German Aerospace Center

DoE Design of Experiments

EADS European Aeronautic Defense and Space Company

EU European Union

FLOPS Flight Optimization System

HADR Humanitarian Aid and Disaster Relief

JAPCC Joint Air Power Competence Centre

MoE Measure of Effectiveness

MTOM Maximum Take-Off Mass

NATO North Atlantic Treaty Organization

NRF NATO's Response Force

OEM Operative Empty Mass

SAC Strategic Airlift Capability

SALIS Strategic Airlift Interim Solution

SATOC Strategic Air Transport for Outsized Cargo

SBCT Stryker Brigade Combat Team

SME Subject Matter Expert

SoS System of Systems

SoSE System of Systems Engineering

SoSiD System of Systems Inverse Design

STOL Short Take-Off and Landing

TLARs Top-Level Aircraft Requirements

U.S. United States

VJTF Very High Readiness Joint Task Force

C_M	Mission Cost	[usd]
$C_{a,f}$	Fleet Acquisition Cost	[usd]
C_{PROG}	Program costs	[usd]
$CPFH$	Cost Per Flight Hour	[usd/h]
EW	Operative Empty Weight	[lbs]
L	Length	[m]
N_z	Ultimate load factor	[-]
N_{NPC}	Amount of non-palletized cargo	[-]
N_{PC}	Amount of palletized cargo	[-]
PPE	Pallet Position Equivalent	[-]
S_M	Mission Success	[%]
SPC	Cruise speed	[kts]
W	Width	[m]
W_{dg}	Gross Design Weight	[lbs]

List of Figures

List of Tables

1 Introduction

Strategic airlift plays a vital role in transporting large volumes of cargo across the world to address urgent needs. Unlike other means of transportation, strategic airlift offers unmatched speed, enabling the rapid delivery of critical supplies such as food, water, medical equipment, and vehicles to distant locations. While alternative options like sealift are invaluable for large-scale logistical operations, their slower pace makes them unsuitable for time-sensitive missions most of the time.

The demand for strategic airlift capability has grown significantly in Europe over recent decades. A rise in natural disasters requiring humanitarian intervention and the European Union's (EU) expanding defense commitments have intensified the need for airlift capacity. However, Europe faces a shortfall in its ability to meet airlift requirements, particularly for the transport of outsized and heavy cargo. This gap in capabilities is often dubbed *the strategic airlift gap*.

This thesis focuses on two key aspects of closing this capability gap. First, it seeks to quantify the impact of cargo hold volume constraints on airlift capacity, an often overlooked factor that influences the types and quantities of cargo that can be transported in a single mission. Second, it aims to develop requirements for a new airlifter and compose it into an ideal fleet to enhance the EU's strategic airlift capabilities using a System of Systems (SoS) approach to the problem.

Part I of this thesis presents the work in a scientific paper. This paper describes the problem, details the methodology, and discusses the results. Part II shows a literature review supporting the paper's work. The literature review explores strategic airlift, the existing capability gap, prior research into the airlift gap, and the differences in aircraft design between airlifters and commercial transporters. Finally, Part III shows the supporting work. This work includes a description of the changes made to tools used to answer the research questions: the aircraft design tool *OpenAD* and agent-based simulation tool, the *SoSiD Toolkit*. Furthermore, the generated aircraft models are shown and validated here.

Part I

Scientific Article

Design and Assessment of Strategic Airlifters for Rapid Deployment: A System of Systems Approach

Dani Hotters
Delft University of Technology, Delft, 2628 CD, The Netherlands

Strategic airlift is an essential capability for the rapid global movement of cargo, particularly in crisis operations where timelines are short and cargo demands extreme. Despite the European Union's collective purchase of A400M aircraft, capability gaps remain due to the aircraft's limited ability to airlift heavy and outsized equipment. This study applies Knowledge-Based Engineering aircraft design tools in conjunction with Agent-Based Simulation techniques to evaluate a fleet's ability to move cargo rapidly across strategic distances in high-stakes operational scenarios. One focus of the study is on the often-overlooked constraint of cargo hold volume and its effects on a fleet's ability to transport cargo. The study found that this volume constraint can reduce airlift capacity by roughly 20% in scenarios with medium-density cargo. Further, through design space exploration, this study identifies key top-level aircraft requirements for a new airlifter to work effectively in the European fleet of airlifters. Analysis reveals that a next-generation aircraft requires a wide fuselage capable of double-file loading, an extended fuselage length of 39m, an increased payload capacity of 120 tons, and a cruise speed of Mach 0.8. Such a design could enhance the fleet performance and reduce fleet requirements by roughly 30%.

I. Motivation

High stakes scenarios requiring the rapid movement of significant quantities of cargo over global distances highlight the importance of strategic airlift capabilities. A fleet of A400M aircraft is actively expanding the European strategic airlift fleet. Once these aircraft are all integrated into the fleet, research suggests this feat will significantly bolster airlift capacity. For instance, Hages demonstrated that the future fleet of A400Ms is sufficient to deploy NATO's response force (NRF), which requires the movement of 70,000 tons of cargo over 30 days at a strategic distance of 4,300 nautical miles [1]. However, the study indicates that this new fleet is barely acceptable considering that 15 additional A400Ms are required when a heavier NRF deployment is simulated: 84,500 tons over the same time span and a smaller distance of 3,300 nautical miles [1]. Furthermore, this study does not account for instances where the cargo hold of aircraft "bulk out" - which refers to an aircraft reaching its maximum volume capacity before reaching its maximum payload mass capacity - thereby omitting volume limitations, which significantly reduce fleet capabilities.

Secondly, recent initiatives, such as the European Union's (EU) Strategic Air Transport for Outsized Cargo (SATOC) project, highlight a need to fill the "critical shortfall for strategic air transport for outsized cargo by developing a European solution for the transport of outsized and heavy cargo" [2], indicating that the EU is seeking for a new aircraft to meet the current and future operational demands. Some essential questions that remain unanswered are posed in this study:

Question 1: *How does including a volume constraint impact the airlift capacity during rapid deployment scenarios?*

Question 2: *What are key aircraft requirements for a new strategic outsized cargo airlifter to meet the requirements of rapid deployment scenarios and to work effectively in an existing fleet?*

This paper is structured as follows: Section II describes the methodology used to answer the above-posed questions. Section III presents and discusses the results of the work, while Section IV draws the conclusions.

II. Methodology

A top-level overview of the framework used to answer the research questions is shown in Figure 1. The required steps to answer these questions are:

- Define realistic and constraining scenarios involving the rapid movement of cargo
- Develop models of the A400M and C-17 using the iterative aircraft design tool *OpenAD*, developed by the German Aerospace Center (DLR)
- Simulate a given fleet performing airlift scenarios using the *System of Systems Inverse Design Toolkit* (SoSiD Toolkit), an Agent-Based simulation environment.
- Assess the performance of heterogeneous fleets based on System of Systems (SoS) level Measures of Effectiveness (MoEs) and study the effect of cargo hold volume constraints on this assessment.
- Generate new conceptual aircraft designs by modifying the Top-Level Aircraft Requirements (TLARs) of a baseline aircraft (C-17 model in OpenAD) and evaluating how the MoEs change when the new design is incorporated into the future European fleet of airlifters by creating a design space.

The above steps are further detailed in the following sections. Section II.A describes the scenarios used in the simulations. Section II.B explains how the SoSiD Toolkit works and how it can simulate airlift missions. Section II.C covers the workings of the aircraft design tool OpenAD and how offspring designs are created. Finally, Section II.D describes the Design of Experiments (DoE) that describes the design space, while Section II.E shows the derivation of the MoEs.

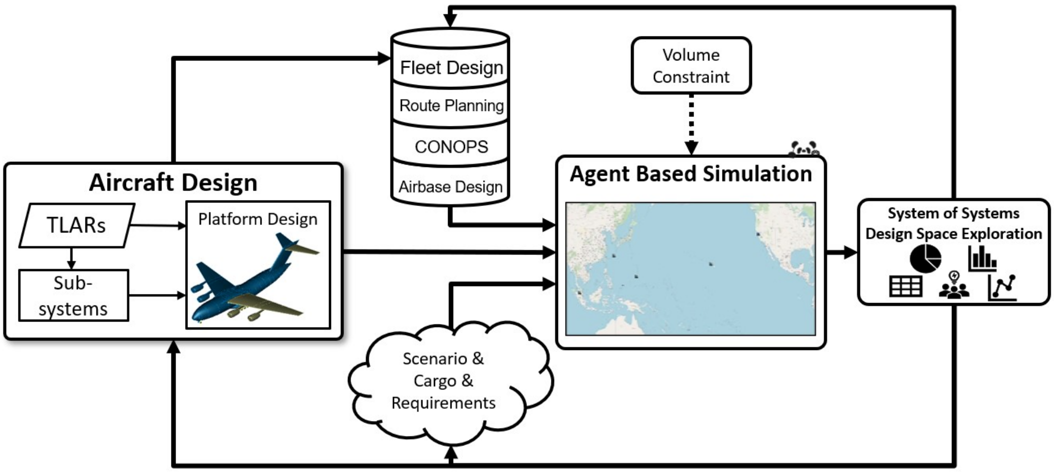


Fig. 1 System of Systems driven aircraft design framework

A. Scenario Description

In order to evaluate the performance of a heterogeneous fleet of strategic airlifters, it is essential to define scenarios that reflect the current and anticipated demands. Section II.A.1 and II.A.2 describe and detail two such scenarios. Additionally, an overview of the transportation assets is provided in Section II.A.3.

The scenarios presented are designed to place realistic yet high demand on the airlift network. Such high-stakes scenarios are crucial for defining both the requirements of a new aircraft and the requirements of the heterogeneous fleet in which they operate. To achieve this, the scenario requirements are derived from military rather than humanitarian needs, as these require transporting significantly larger volumes of cargo. For example, Operation Unified Response - a large humanitarian relief mission following the 2010 Haiti earthquake - required the airlift of 14,098 tons of relief supplies [3]. In contrast, large NRF deployments require moving 84,500 tons of cargo within 30 days [1].

Inspiration from previous research on the European airlift fleet was drawn to describe the scenarios. However, a key distinction between this study and other studies involving the deployment of the NRF, is that the described scenarios do not involve the deployment of the full NRF. An NRF deployment is structured into two phases: an initial phase involving very rapid movement of roughly one-third of the total cargo and a follow-up phase that deploys the remaining cargo over an extended period [4]. Therefore, the deployment of the NRF is dual-stage. However, most prior studies only considers the final deadline by which all cargo must be delivered. In contrast, this study emphasizes the initial phase, as this phase imposes more stringent requirements on both the fleet and individual aircraft and is furthermore unable to make use of other means of transport such as rapid sealift. By focusing on this phase, the analysis aims to capture the peak demands for airlift.

1. Scenario A: Medium-Heavy Cargo Deployment

Due to this study's focus on the constraint imposed by the cargo hold dimensions, it is essential to define the composition of the cargo in detail. These high-stakes scenarios include a mix of both palletized cargo and rolling stock equipment. The palletized cargo encompasses essential items, such as food, water, fuel, and other consumables necessary to sustain the rolling stock and its crew that can be loaded and transported on a standardized 463L pallet. The rolling stock consists of various vehicles ranging from trailers to soft-skin vehicles to heavy engineering equipment. The specific types and quantities of the rolling stock cargo were derived based on the structure of a U.S. Stryker Brigade Combat Team (SBCT) [5]. On the other side, the quantities and types of palletized cargo were computed based on logistical requirements and assumptions defined by Johnson and Brent [6] and further insights provided by Colclough [7]. These requirements are given in Table 9 and Table 10.

For this scenario, two SBCTs are transported. This choice aligns with anticipated cargo demands*, resulting in this scenario's requirement of moving approximately 35,000 tons of mixed cargo. The movement is structured to occur over a five-day period, as is required such a brigade [8] and is furthermore in-line with European requirements for a similar sized force. Furthermore, the cargo must travel roughly 3,800 nautical miles, effectively simulating a transatlantic crossing.

Figure 2 visualizes the transport network used for simulation, here the number serves as an identifier for the node which is used to identify the starting node of the airlift assets in Section II.A.3. Table 11 lists a detailed breakdown of the cargo, including mass, dimensions, and quantities.

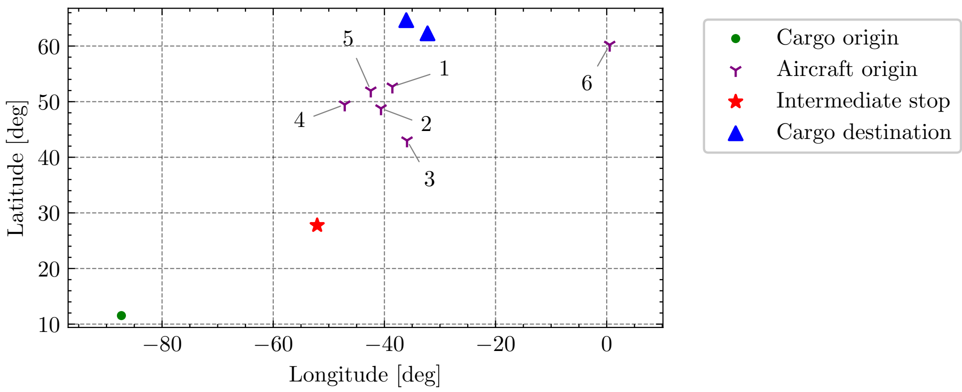


Fig. 2 Scenario A: Medium-Heavy Cargo Deployment

2. Scenario B: Extended-Range Heavy Cargo Deployment

The second scenario expands the area of research by differentiating itself from the first scenario by increasing the average mass of individual cargo and extending the range of the movement. Once again, cargo composition has to

*https://www.ndtahq.com/dod-places-variety-of-troops-on-prepare-to-deploy/

be detailed. This time, the specific types and quantities of the rolling stock are derived from a single U.S. Armored Brigade Combat Team (ABCT) [5], which includes heavier equipment than the previous scenario. The palletized cargo requirement is once again computed based on the same assumptions and insights given by Johnson, Brent [6], and Colclough [7] as given in Table 9 and Table 10.

This scenario models the movement of approximately 30,000 tons of cargo transported over an extended range of 5,200 nautical miles during a ten-day period. The transport network is visualized in Figure 3 and ones again the number serves as an identifier for later use. Furthermore, the cargo details are again given in Table 11 and a summary of both scenario requirements is shown in Table 1. Here, MTM/d refers to the airlift capacity, further detailed in Section II.B.5.

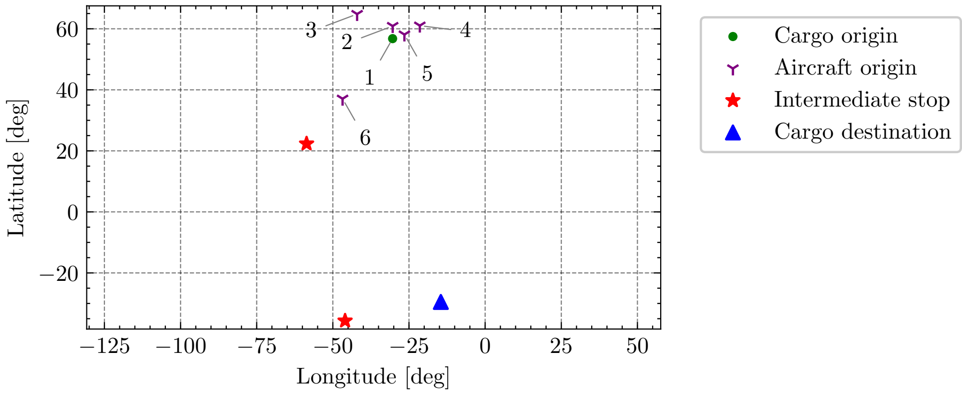


Fig. 3 Scenario B: Extended-Range Heavy Cargo Deployment

Table 1 Top-level requirements of both scenarios

Scenario	Cargo [tons]	Distance† [NM]	Depl. deadline [days]	MTM/d
A: Medium-heavy cargo deployment	34,954	3,822	5	26.7
B: Extended-range heavy cargo deployment	30,129	5,213	10	15.7

† Bird-flight distance between orign and destination

3. The Airlift Assets

The European strategic airlift fleet consists of the A400M, with 123 aircraft in service in 2024, set to expand to 170 in the near future. The fleet is supplemented by 11 C-17s - 8 operated by the United Kingdom and 3 shared through the Strategic Airlift Capability program. Although 5 AN-124s are available through the Strategic Airlift Interim Solution (SALIS) agreement, these aircraft are excluded from this analysis as the agreement will end in 2030, and the aircraft are aging [9]. The A400M and C-17 can both transport outsized cargo over strategic distances but differ significantly in capacity. The A400M can carry 37 tons over 2,000NM, while the C-17 can transport 77 tons over 2,730NM. Additionally, the C-17's wider cargo hold allows for double-file loading of cargo, unlike the A400M. The payload-range diagram and cargo hold dimensions of both aircraft are shown in Figure 4 and Figure 5, respectively.

Finally, the aircraft differ slightly in their flight velocity. The A400M cruises at roughly 36,000 ft altitude with Mach 0.70 while the C-17 cruises at 38,000ft around Mach 0.74 [10]. The current and future European fleets are decomposed in Table 2.

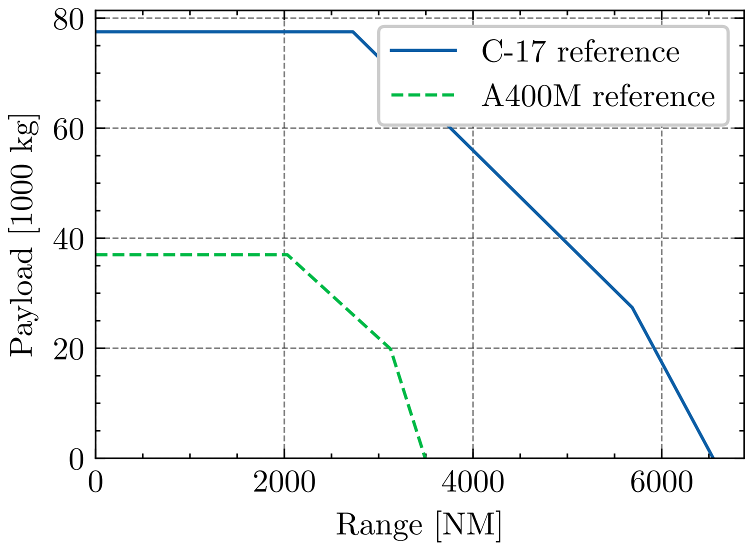


Fig. 4 Reference Payload-Range diagrams of the A400M and C-17 [10] [11]

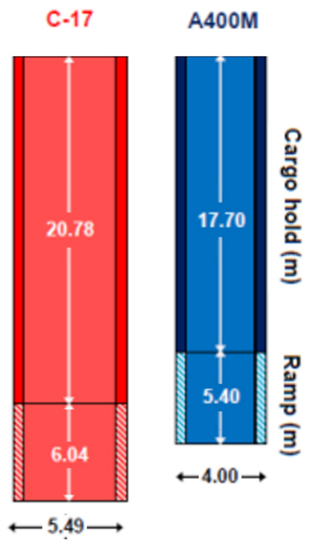


Fig. 5 Comparison of cargo hold dimensions between the A400M and C-17 [1]

Table 2 European airlift assets and their starting node

		Current fleet		Future fleet	
Nation	Starting node*	#A400M	#C-17	#A400M	#C-17
Germany	1	45		53	
France Air Base	2	24		50	
Spain	3	14		27	
United Kingdom	4	22	8	22	8
Belgium	5	7		7	
Luxembourg	5†	1		1	
Turkey	6	10		10	
Shared	1		3		3
Total		123	11	170	11

*The starting node defines the origin of the assets in simulation.
† Luxembourg operates its A400M from Belgium

B. Agent-Based Simulation & System of Systems

A System of Systems (SoS) refers to a group of independently functioning systems that interact to create the behavior of a larger, more complex system. As Maier [12] characterized, SoS are defined from the operational and managerial independence of its subsystems. In the context of airlift missions, the SoS is formed by the interdependence between the various aircraft that comprise the heterogeneous fleet, the airbases from which the aircraft operate, and the cargo that is transported. Together, the interactions between these systems shape the overall airlift system and cause so-called "emergent behaviors". The SoS approach is particularly useful for modeling and analyzing complex systems, making it easier to analyze and enhance early-stage design insights. The *SoSid Toolkit* is an Agent-Based Simulation environment developed to accelerate and simplify analysis of a SoS problem through simulation, as further described in [13]. Recently, Kalliatakis enhanced the SoSiD toolkit to model Humanitarian Aid and Disaster Relief (HADR) missions [14]. This enhanced toolkit is used to simulate the scenarios defined in subsection II.A.

Users input critical data such as GPS coordinates of airfields, runway lengths, fleet composition, and cargo specification - including origins and destinations. Furthermore, a simulation objective - such as minimizing the time or cost of the mission - is specified. Models of the aircraft that make up the heterogeneous fleet also have to be provided; this is done using the Common Parametric Aircraft Configuration Schema (CPACS), developed by DLR for aircraft data exchange between tools. Based on these inputs, the tool can simulate the movement of cargo between the origin and destination location. At the end of the simulation, the tool calculates SoS-level MoEs like mission completion time, success rate, mission cost, delivery rates, and airlift capacity. These metrics are used to assess the fleet's ability to perform the given scenarios and can furthermore be used to evaluate how fleet effectiveness changes when the TLARs of the aircraft within the fleet are changed.

1. Modeling of operations

The simulation models aircraft, airbases, and cargo as agents. Aircraft data is input in the aforementioned CPACS format, which includes payload-range diagrams, fuel consumption rates, flight altitudes and speeds, and cargo hold dimensions. These aircraft agents are used to move the cargo from origin to destination. Aircraft agents can land at airfields that meet operational requirements, such as being in range and having adequate runway length available. Airfields act as logistical hubs, offering refueling, maintenance, and cargo handling services to the aircraft agents. The simulation furthermore accounts for delays related to these ground operations, including takeoff and landing clearances, taxiing, servicing, refueling, and loading/unloading of cargo. Kalliatakis' enhanced toolkit is further enhanced by establishing that loading and unloading times are influenced by the cargo type being handled. For instance, rolling stock can be driven into an aircraft, while palletized cargo requires forklifts. Therefore, different setup and loading times were used when loading or unloading palletized cargo and rolling stock. These loading and unloading times are based on C-17 loading and unloading times for such cargo, as was found by Stucker et al.[15]. Finally, a special agent, the dispatcher agent, coordinates the airlift operations by determining which aircraft will transport what cargo to where and at what time. This agent catalogs optimal flight paths, allowing cargo to select the aircraft for each mission leg in a manner that minimizes the specified objective of the simulation - time in the case of rapid airlift. The decision-making logic of the dispatcher agent is illustrated in Figure 6.

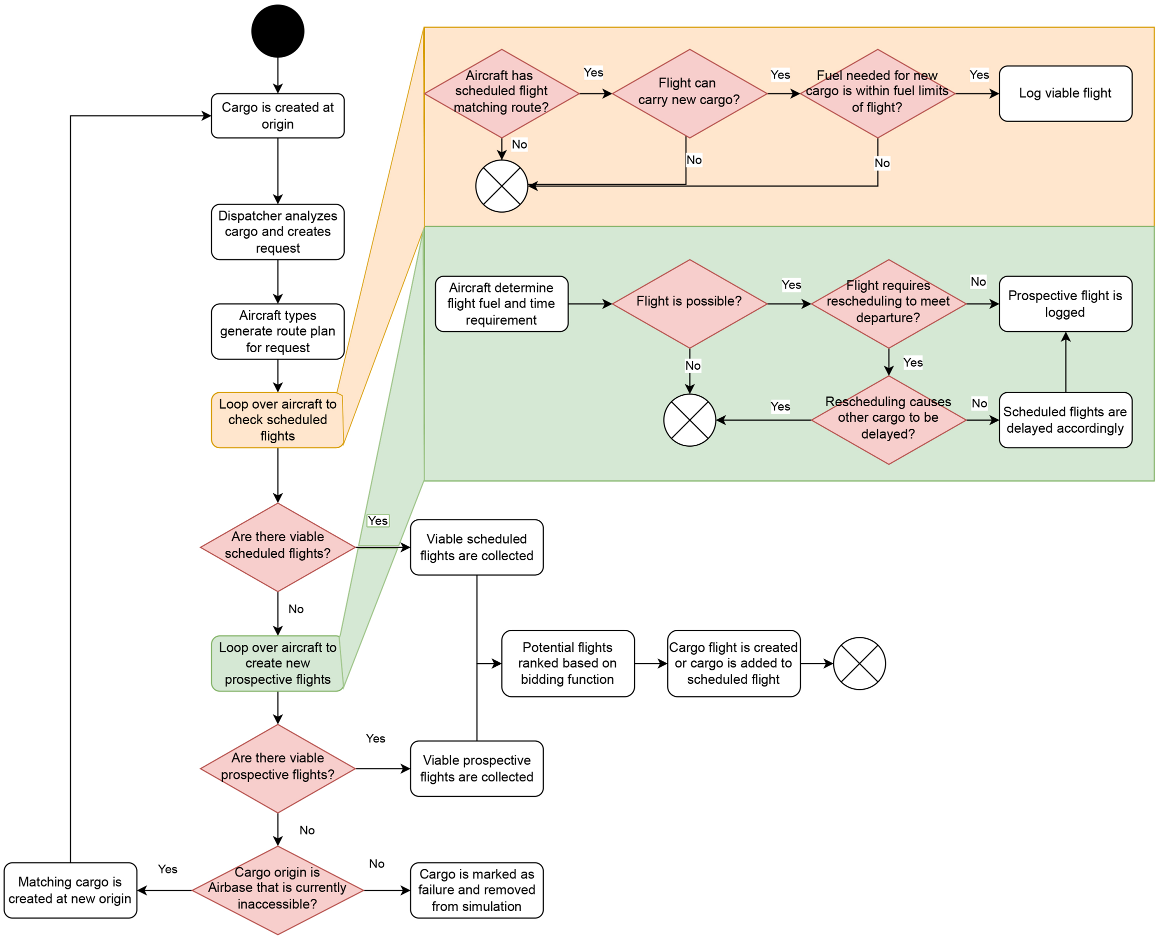


Fig. 6 Flow diagram of the SoSiD Toolkit agent-based simulation environment [14]

2. Volume constraint

Furthermore, this study improved the SoSiD toolkit by including a volume constraint, allowing for the assessment of aircraft "bulking out". Such a constraint is often ignored in research. However, a simplified volume constraint is sometimes included in HADR studies, such as in the work of Barwell and Wainer [16]. This study includes a simplified volume constraint using the Pallet Position Equivalent (PPE) method. This method requires aircraft models to specify the maximum pallet positions their cargo hold can take. Cargo is then expressed in equivalent pallet positions computed by Equation (1), where W_{pallet} and L_{pallet} refer to the width and length of a standard 463L pallet (2.74m x 2.2m). The algorithm then maximizes the amount of loaded cargo such that the aircraft allowable PPE is not exceeded.

$$PPE = \frac{W_{cargo}L_{cargo}}{W_{pallet}L_{pallet}} \tag{1}$$

This method works well for scenarios involving mainly palletized cargo, such as HADR scenarios, but is too simplistic for those that included bulky rolling stock. A significant limitation is that cargo height is ignored completely, even though this is essential for determining whether cargo can fit in the aircraft. Furthermore, it compresses cargo dimensions into a singular value, causing the method to overestimate the loading capacity. For example, the A400M can hold a maximum of 9 pallets. A Case M4K forklift, which has a length of 5.25m and a width of 2m, has a PPE of 1.71 (as computed with (1)), suggesting that five forklifts can be loaded (9 pallet positions / 1.71 PPE). However, in reality, only three would fit, considering the A400M's cargo hold is only 17.7m in length, as shown in Figure 5. Because the A400M is cannot load in a double-file configuration†, the length of the cargo is the constraining dimension, and thus, a singular value that expresses the width and length does not suffice. To overcome these limitations, this study uses the *knapsack loading algorithm*, which models cargo and the aircraft cargo holds as cuboids utilizing the input dimensions for width, height, and length. The algorithm processes a list of cargo, placing them sequentially into the cargo hold until no further cargo can fit in the hold while maintaining the payload mass constraint, thereby accurately accounting for loading limits based on the cargo hold boundaries. The algorithm is furthermore restricted from stacking and rotating cargo since rolling stock must be loaded lengthwise. The example above is visualized shown in Figure 7. Remember that this algorithm is used merely to give an indication of how much cargo can fit in the hold, and therefore it is assumed that during actual loading the shift in center of gravity remains within the required bounds.

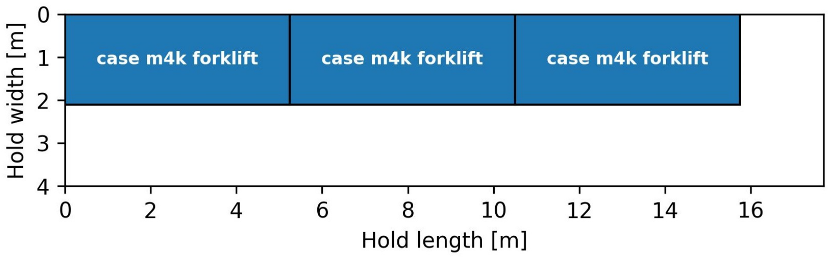


Fig. 7 Knapsack loading algorithm example: loading as many forklifts into the hold of an A400M

3. Mission cost

Operating costs of the various aircraft determine the total mission cost for the airlift operation. Operating costs are calculated using the cost per flight hour (CPFH) metric multiplied by the total flight hours of an aircraft. The CPFH is obtained through a linear regression relating aircraft maximum takeoff mass (MTOM) to CPFH for each aircraft type. This relationship is shown in Figure 8 and is based on data provided by the United States Air Mobility Command (AMC) for various airlift platforms [17]. The total flight hours per aircraft type result from the agent-based simulation keeping track of every flight and its duration.

†cargo loaded side-by-side

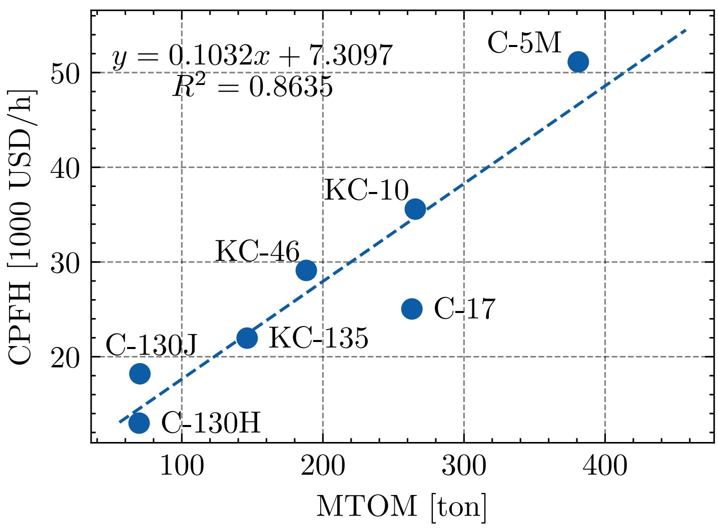


Fig. 8 Linear regression of CPFH data from the U.S. Air Mobility Command [17]

4. Acquisition cost

The acquisition cost of the various aircraft types is computed using the findings of a RAND study on the subject [18]. This study found Cost Estimation Relationships (CERs) based on bombers, transporters, and fighter aircraft. C_{PROG}, as seen in Equation (2), gives the program cost for 100 aircraft. Here, EW refers to the Operative Empty Weight (OEW) of the aircraft in pounds, and SPC refers to the cruise speed in knots. An additional factor of 5.19 was used to adjust for inflation from 1987 U.S. dollars to 2024 U.S. dollars. This cost can be broken down to a single aircraft and multiplied by the number of additional aircraft included in the expanded fleet to estimate the expanded fleet acquisition cost, assuming that a hundred aircraft are produced.

$$C_{PROG_{100}} = 2570 EW^{0.798} SPC^{0.736} 5.19 \tag{2}$$

5. Airlift capacity

The toolkit can compute the airlift capacity using the aforementioned million ton-miles per day metric. It does this by considering all the simulated flights, which cargo they carried over which distance, and at which time, as shown in Equation (3). The airlift capacity can later be compared against each other for volume-constrained and unconstrained simulations to quantify this constraint's impact.

$$MTM/D = \sum \frac{Tons\ Delivered \times Nautical\ Miles\ flown}{Days\ Required \times 1{,}000{,}000} \quad |\ \text{for all flights in the simulation} \tag{3}$$

C. Aircraft Design

OpenAD, a parametric iterative knowledge-based engineering tool developed by DLR for conceptual aircraft design (described by Wöhler et al. [19]), was used to model the aircraft that make up the European fleet of strategic airlifters. The tool operates based on input parameters, including design range and payload, cruise Mach number, runway length constraints, and a design mission. Furthermore, the tool can compute the required cargo hold sizes based on a list of cargo, their amount and dimensions, and whether they can be loaded in a double-file configuration. Additionally, OpenAD requires configurational details, such as landing gear and wing position, empennage configuration, the number of engines and their location, as well as the engine type. By using the built-in knowledge base, which relies primarily on publicly available aircraft design methodologies and in-house DLR methods, OpenAD can compute the aircraft geometry, performance characteristics, and component masses. The tool sizes the aircraft according to general sizing constraint diagrams. Furthermore, the tool includes modules that allow it to calculate engine performance, aerodynamic efficiency, and weight and balance. The computed aircraft data is then exported in the CPACS format and can be input into the SoSiD Toolkit without further processing.

1. Aircraft modeling using OpenAD

A model for both the A400M and C-17 is required for this study. Previously, Schmitz utilized OpenAD to create a model of the A400M [20]; therefore, only a model of the C-17 still needs to be constructed. To construct this model, the OpenAD knowledge base was adapted to align with the characteristics of heavy, outsized airlifters. Such airlifters differ significantly from civilian transport aircraft, of which the original knowledge base was composed. The A400M model by Schmitz [20] was built on the knowledge base of civilian transporters and is therefore not suitable to perform a design space exploration. Strategic airlifters are designed to maximize cargo hold volume and minimize aircraft turnaround time. Additionally, these aircraft have to operate from improvised runways. Therefore short takeoff and landing (STOL) requirements are often imposed. These requirements lead to design decisions such as the inclusion of a cargo ramp in the rear of the fuselage, podded landing gear capable of high flotation and landings in rough fields, high-wing configuration, and more. These decisions significantly impact the aircraft's component weights and aerodynamics. Hence, the knowledge base of OpenAD has been adapted to include such effects.

The reference mission to sizing aircraft was obtained from military standard MIL-STD-3013B [21], shown in Figure 9. A database of the C-17 measurements, requirements, and performance was assembled from publicly available sources. The model was then calibrated by applying adjustment factors to variables such as engine efficiency and aerodynamic drag coefficients, such that the payload-range diagram computed by OpenAD aligned with the reference payload-range diagram of the C-17. Furthermore, component masses for which a reference value was known were calibrated to overlap; those without a reference value were calibrated to overlap the empty weight. The final model is fully parametric, allowing for adjustments to the input TLARs, such as design range, payload, landing/takeoff requirements, and the list of to-be-transported cargo. This enables the exploration of offspring designs based on the C-17 platform and quantifying the impact of altering aircraft TLARs on the simulation results. The 3D geometry of the C-17 and A400M models, as generated by OpenAD, are shown in Figure 10. Furthermore, the top-level aircraft requirements of the C-17 used to construct the model are given in Figure 3. The payload-range diagram, in comparison with the reference payload-range diagrams for the C-17 and, additionally, the C-5 (for the purpose of validation), is presented in Figure 11.

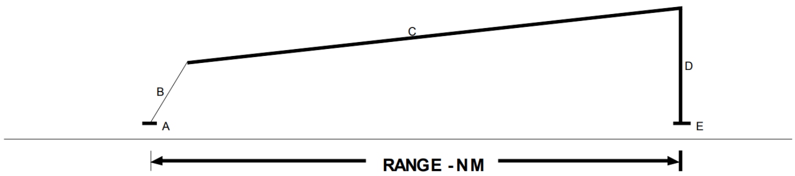
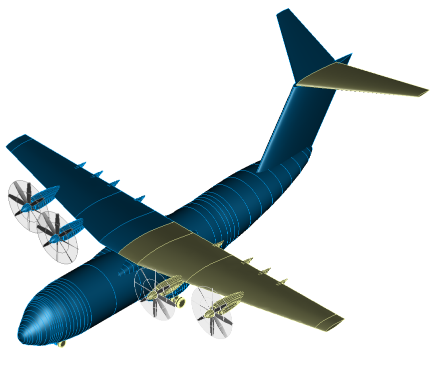


Fig. 9 Mission profile for a cargo transport mission, adopted from MIL-STD 3013B [21]

(a) C-17



(b) A400M

Fig. 10 3D geometries of the C-17 and A400M generated by OpenAD

D. Design of Experiments

To answer the second research question related to the key aircraft requirements for a new airlifter, a Design of Experiments (DoE) is set up. This DoE should be large enough to account for both small fleets of large aircraft and large fleets of small aircraft. The parameters considered in this DoE are established in Table 4, which shows the variables and their values. The parameters are chosen to lie around the C-17 focusing on the larger aircraft.

One of the parameters, the cargo hold configuration, stands out. This parameter holds variations in cargo hold dimensions, as shown in Table 5. Configurations are chosen to reflect hold sizes similar to those in use now but also arbitrary ones to increase the resolution of the grid. Considering OpenAD requires a list of cargo to compute the hold dimensions, this cargo hold configuration represents the dimensions as the result of said lists of cargo as it is easier to interpret. It is also worth noting that the cargo hold height does not influence the results as it is sized such that all cargo

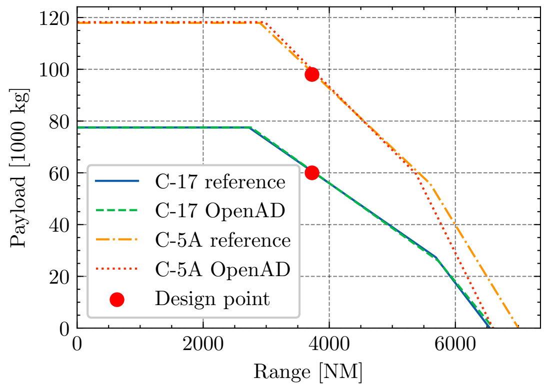


Fig. 11 OpenAD computed payload-range diagrams

Parameter	OpenAD	Reference
MTOM [kg]	265,970	265,352
OEM [kg]	128,290	128,418
W/S [kg/m^2]	753.5	751.9
T/W [-]	0.29	0.28
Approach speed [m/s]	55.5	59
Wing span [m]	50.1	50.3
Fuselage length [m]	48.4	48.8

Table 3 C-17 model top-level data

Table 4 Design of Experiments variables

Variable	Lower limit	Upper limit	Levels
Number of aircraft added to the future fleet†	11	66	8
Design payload [tons]	50	100	10
Design range [km]	3,000	8,000	10
Cruise Mach number [-]	0.75	0.85	3
Cargo hold configuration [-]	0	4	5

† The levels are not equally spread but are taken as: [11, 16, 22, 28, 33, 44, 55, 66]

fits inside of the cargo holds.

Table 5 The dimensions behind the cargo hold configurations

	Cargo hold configuration				
Parameter	0	1	2	3	4
Length [m]	17.2	32.1	24.5	39.14	44.02
Width [m]	4.3	4.3	5.35	5.35	5.35
Height [m]	5.35	5.35	6.0	6.0	6.0
Capable of double-file loading?	No	No	Yes	Yes	Yes

E. Measure of Effectiveness

MoEs are used to assess the outcomes at a SoS level. The effectiveness of a European fleet that includes conceptual aircraft designs can be evaluated based on key criteria such as mission success rate, mission cost, and fleet acquisition cost‡. To establish appropriate weights for these metrics, the *Fuzzy AHP* method described by Seethaler et al. [22] was utilized. This method, which is an analytical hierarchy process, determines the weights of various metrics by

‡This acquisition cost is only the cost of the new fleet, not the existing one. In other words, it is the number of additional aircraft added to the fleet multiplied by their acquisition cost

asking subject-matter experts (SMEs) or stakeholders to evaluate the relative importance of the metrics using linguistic variables. The SMEs were provided with a questionnaire outlining the definitions and implications of each metric, enabling them to rank the metrics relative to each other. The method allows these comparisons to be converted into numerical weights, following the procedure outlined by Seethaler et al. [22]. The responses collected from the SMEs , along with the resulting arithmetic mean value, are presented in Figure 12. The final equation used to compute the overall MoE is provided in Equation (4), where S_m denotes the mission success as a percentage of cargo delivered before the deadline, C_m represents the normalized mission cost, and $C_{a,f}$ represents the fleet acquisition cost, which refers to the cost to purchase the additional aircraft to be added to the future European strategic airlift fleet using the relation described in Section II.B.4.

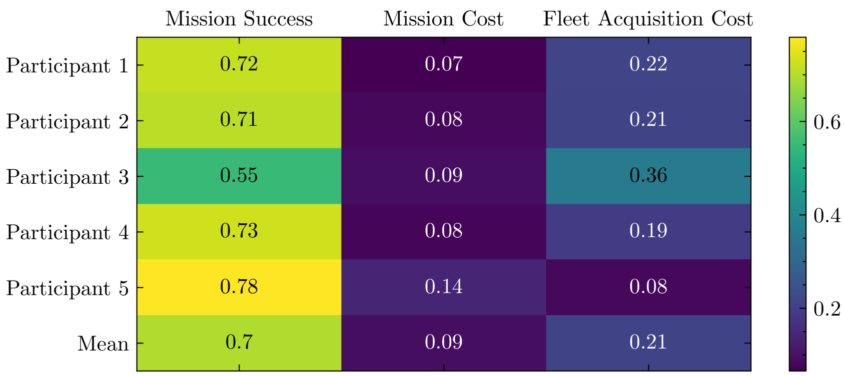


Fig. 12 SME responses and weights determined using the Fuzzy AHP method

$$MoE = 0.70S_m + 0.09(1 - \tilde{C_M}) + 0.21(1 - \tilde{C_{a,f}}) \tag{4}$$

III. Results

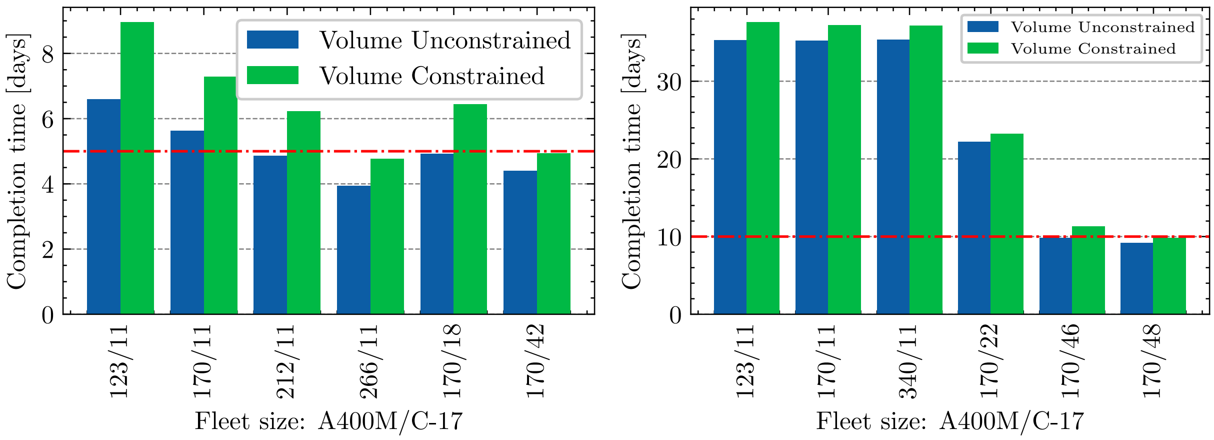
The results are split up into two sections: Section III.A assesses the current and future European strategic airlift fleet's ability to perform the given scenarios and investigates how the volume constraints affect this ability. Section III.B explores the design space for a new airlifter to be added to the future fleet, explores the influence of the parameters in the DoE, and details the optimal set of TLARs.

A. Assessing the airlift fleet and the effects of volume

For both scenarios, the mission completion times and the impact of volume constraints are shown in Figure 13. For scenario A, the first observation is that neither the current nor future fleets meet the deployment deadline under any circumstances. Without the volume constraint, the deadline is half a day off when using the future fleet. However, a delay of roughly 1.5 days is observed when accounting for the volume constraint. This trend between volume-constrained and unconstrained simulations continues for the other fleets in this scenario.

The plot further demonstrates that in order to meet the deployment deadline, the European fleet would require an expansion of 42 A400Ms or 7 C-17s without the volume constraint considered. When the volume constraint is applied, the additional fleet requirements increase to 96 A400Ms or 31 C-17s.

The airlift capacity, measured in MTM/d, is presented in Table 6, quantifying the volume constraint's impact on the airlift capacity. Specifically, imposing a volume constraint results in an average reduction in airlift capacity of approximately 20.4% compared to the volume-unconstrained scenario.



(a) Scenario A **(b) Scenario B**

Fig. 13 Volume-constrained and unconstrained mission completion times for various fleet configurations

Table 6 The effect of the volume constraint on the airlift capacity for scenario A

Fleet composition A400M / C-17	Volume-unconstrained airlift capacity [MTM/d]	Volume-constrained airlift capacity [MTM/d]	Difference [%]
123 / 11 (current)	19.27	14.20	-26.3
170 / 11 (future)	22.59	17.46	-22.7
212 / 11	26.20	20.46	-21.9
266 / 11	32.24	26.7	-17.2
170 / 18	25.81	19.75	-23.5
170 / 42	28.88	25.79	-10.7

For scenario B, neither fleets meet the deployment deadline, with delays of approximately 27 days for both fleets. The deadline is only achieved when 35 C-17s are added to the future fleet in the unconstrained case or 37 C-17s in the constrained case. The fleet requirements are similar to those of scenario A with one notable difference: expanding the fleet with additional A400M aircraft does not lead to any improvement in mission completion times, even when the fleet size is double to 340 A400Ms. This effect is clarified by examining the cargo deliveries over time, as shown in Figure 14.

It is clear that while the amount of cargo delivered in the initial days increased significantly, the delivery rate declines sharply after the first week. This decline occurs because the A400M is unable to contribute to the airlift operation after the initial period, during which bulk cargo and soft-skin vehicles are delivered. After this point, the remaining cargo primarily consists of heavy vehicles, which the A400M cannot transport due to its limited payload capacity and the extended ranges of in the scenario. As a result, the fleet's eleven C-17s are left to move the remaining heavy cargo on their own. Because even the C-17 can only charter a few cargo at a time, this results in significant delays. This demonstrates that fleet diversity is essential for a strategic airlift fleet.

The computed airlift capacities for these fleets are provided in Table 7. In this scenario, the difference in airlift capacity between the volume-constrained and unconstrained cases averages 5.5%, significantly less than in scenario A. Another effect of the heavier and denser cargo chartered in scenario B which causes the payload mass constraint to be reached before the volume constraint for many flights.

Table 7 The effect of the volume constraint on the airlift capacity for scenario B

Fleet composition A400M / C-17	Volume-unconstrained airlift capacity [MTM/d]	Volume-constrained airlift capacity [MTM/d]	Difference [%]
123 / 11 (current)	5.79	5.42	-6.4
170 / 11 (future)	5.79	5.48	-5.4
340 / 11	5.79	5.48	-5.4
170 / 22	9.18	8.74	-4.8
170 / 46	20.57	19.53	-5.1
170 / 48	21.93	20.64	-5.9

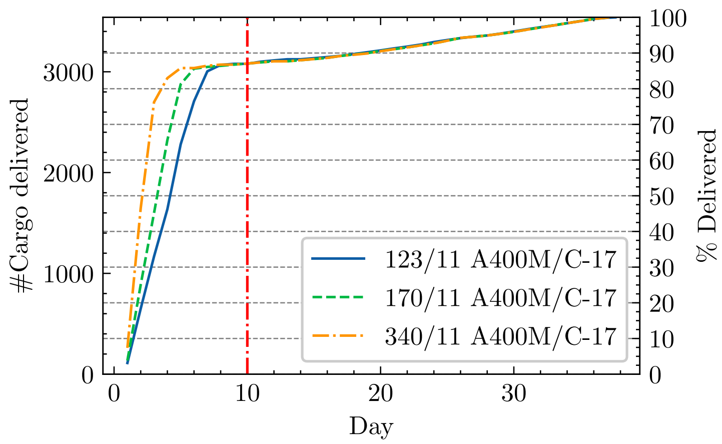


Fig. 14 Deliveries over time for varying A400Ms in the European fleet performing scenario B while volume-constrained

B. Design Space Exploration

In this section, the design space is explored, and the effects of the DoE parameters are explained. In order to make the analysis more manageable, the design space is gradually being built up. For this analysis, only the design space representing the arithmetic mean outcome of scenarios A and B is presented. Furthermore, Figure 19 shows the individual MoEs that comprise the overall picture.

The first notable observations can be seen in Figure 15, which shows the MoE as a function of the design range, design payload, fleet size, and cargo hold width. The data suggests that the fleets that have been expanded by 22 to 33 aircraft perform best. This required fleet size is substantially smaller than those observed when expanding the fleet by C-17 or A400M aircraft. Thus, instead of needing 37 extra C-17s to be able to perform both missions successfully, a new design can do both missions successfully with only a fleet requirement of 22 extra aircraft.

Another significant observation relates to the width of the cargo hold floor. The ability to load cargo in a double-file configuration greatly impacts the fleet effectiveness. The MoE improves significantly when double-file loading is possible, compared to configurations where it is not possible, highlighting the importance of this capability. This improvement is mainly due to the mission success parameter increasing significantly, as seen in Figure 19a. With a fuselage capable of double-file loading, success is significantly higher than fuselages with single-file loading.

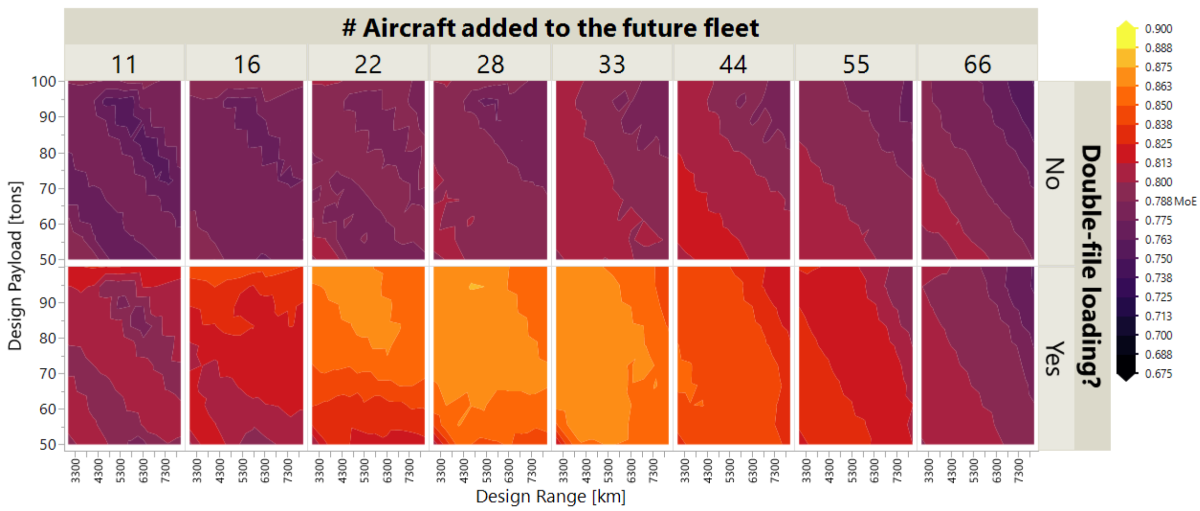


Fig. 15 The effect of cargo hold width (single file vs double file loading)

Building on the previous graph, the cargo hold configurations are expanded to include length, as shown in Figure 16. These configurations refer to those detailed in Table 5. For clarification, configurations zero and one do not support double-file loading, while the others do. Additionally, as the configuration number increases, the usable length of the cargo hold also increases.

Consistent with earlier findings, the fleet with an expansion of 22-33 aircraft demonstrates the best effectiveness.

Further observation reveals that configurations three and four yield nearly identical MoEs, indicating that the five meter hold length increase offers marginal improvement. Nevertheless, the longer the cargo hold is, the smaller the required fleet size is. Furthermore, when increasing the cargo hold length and decreasing the fleet size, a larger design payload is required to keep high mission success. Adversely, this increases fleet acquisition costs but only marginally. In terms of design range, its impact on the MoE is relatively minor. A design range around 5,000 km seems preferable as it minimizes acquisition and mission costs as this range allows to minimize the number of intermediate stops required, thereby increasing fleet effectiveness.

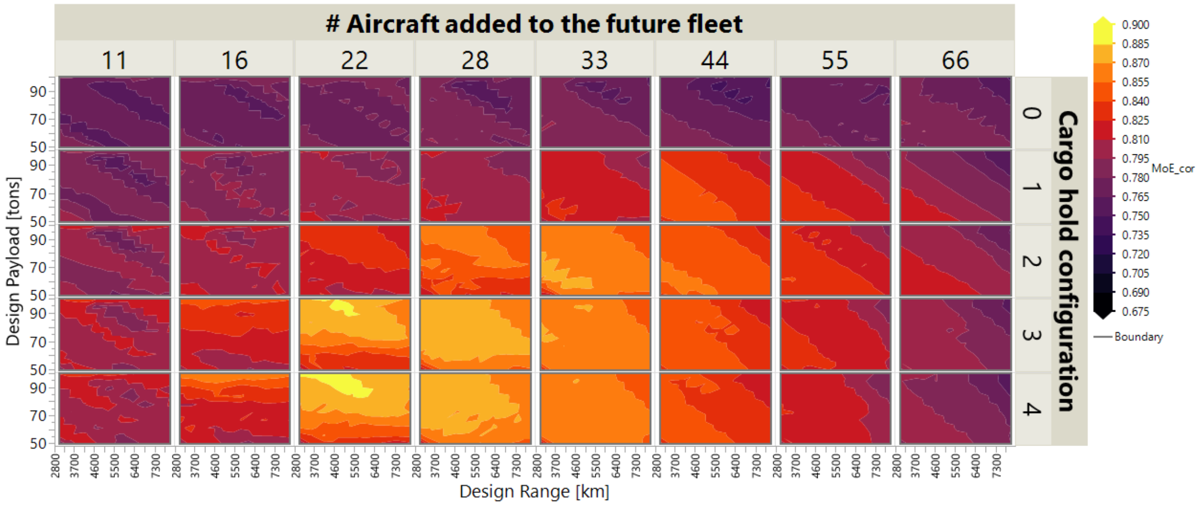


Fig. 16 The effects of the cargo hold configurations

Finally, the cruise Mach number is included in the analysis to get a holistic understanding of the design choice combinations, as shown in Figure 17. The results indicate that increasing the cruise speed generally enhances the overall MoE. However, the largest MoEs are found for Mach 0.8, after which the MoEs start to decrease again. Additionally, it becomes evident that smaller cargo holds and smaller fleet sizes become more viable as the cruise speed increases. This is due to the reduced number of required flights to complete the mission, which offset the increase in mission and acquisition cost associated with faster airplanes. For larger fleet sizes, the opposite happens; an increase in Mach number reduces the MoE. This is because, at these fleet sizes, mission success is guaranteed regardless of cruise Mach number. Therefore success has no further impact, and instead, acquisition costs increase which has a greater influence on the MoE than the reduced mission cost.

Finally, this figure highlights an optimal configuration. The aircraft that achieves the largest MoE features a medium design range, a high - though not maximum - design payload, and employs cargo hold configuration 3. The optimal aircraft geometry and corresponding payload-range diagram, as computed by OpenAD, are illustrated in Figure 18. Additional details and the TLARs for this optimal are provided in Table 8.

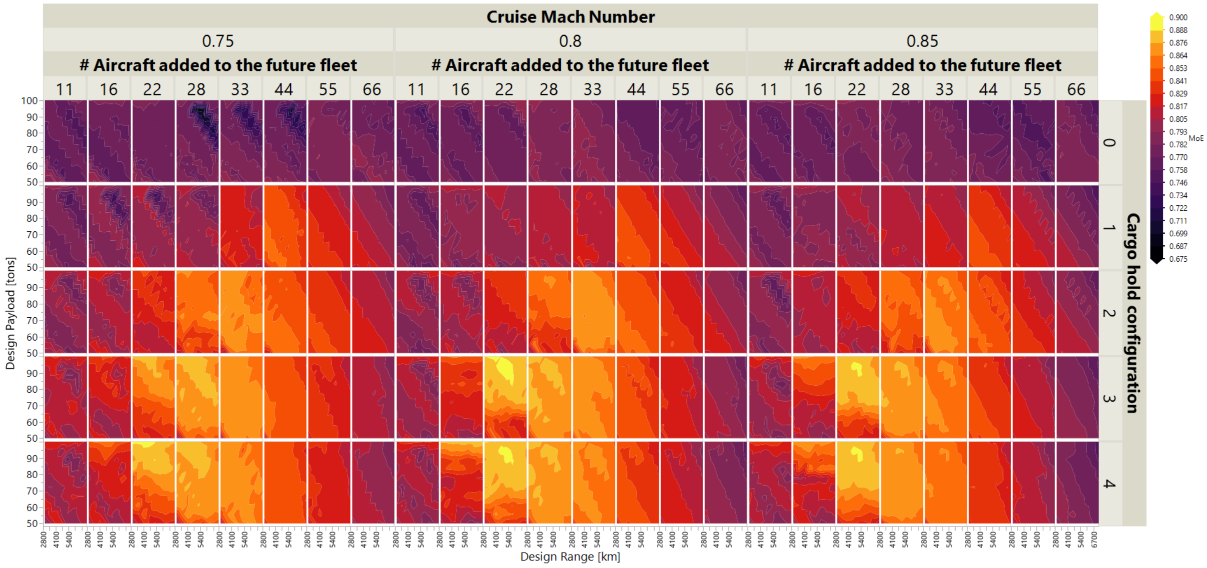
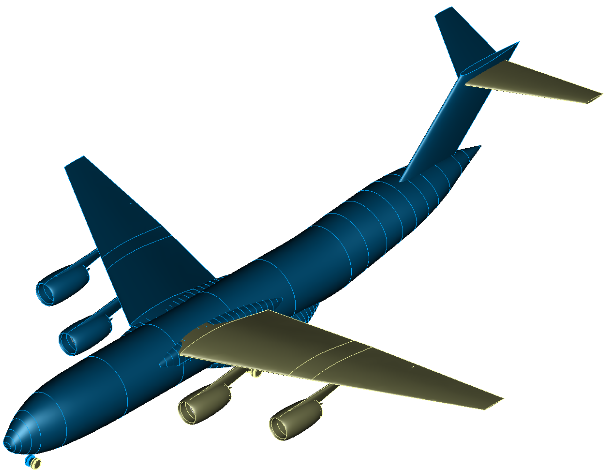
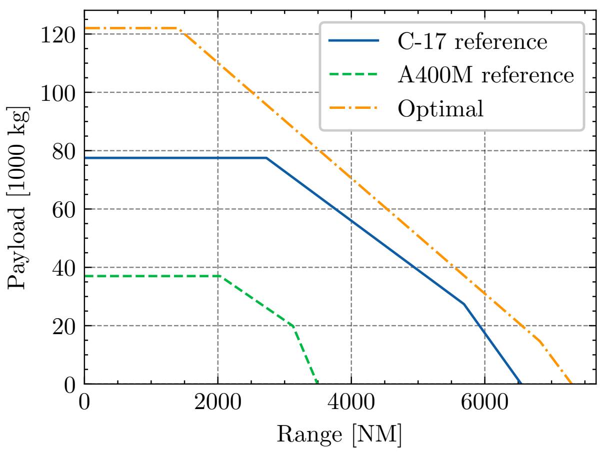


Fig. 17 Complete design space, averaged over both scenarios



(a) The optimal aircraft's geometry



(b) Payload-range diagram of the optimal aircraft compared to the A400M and C-17

Fig. 18 The optimal aircraft

IV. Conclusion

The research findings allow for answers to he proposed research questions, summarized as follows:

Question 1: *How does including a volume constraint impact the airlift capacity during rapid deployment scenarios?*

Regarding this first research question, the results demonstrate that the impact of volume constraints on the fleet requirements can be significant but varies depending on the scenario. In scenario A, including the volume constraint

Table 8 Summary of optimal aircraft data

Parameter	OpenAD value
Maximum take-off mass	326,910 kg
Operative empty mass	163.180 kg
Cruise Mach number	0.8
Design payload	94,444 kg
Design range	5,000 km
Cargo hold dimensions (WxLxH)	5.44m x 39.14m x 6.0m
W/S	765.5 kg/m^2
T/W	0.3
Additional aircraft req.	22
MoE	0.90

leads to an average reduction in airlift capacity of 20.4%. In contrast, scenario B sees a reduced impact with the volume constraint decreasing airlift capacity by 5.5% on average. This reduced impact is attributed to the increased density of individual cargo in scenario B, which causes the mass constraint to be reached before the volume constraint more often, thereby limiting the effect of the volume constraint.

Question 2: *What are key aircraft requirements for a new strategic outsized cargo airlifter to meet the requirements of rapid deployment scenarios and to work effectively in the existing fleet?*

In response to the second research question, the analysis of design parameters such as design payload and range, cruise Mach number, cargo hold configuration, and fleet size provided key insights. The results suggest that smaller fleets composed of larger aircraft, with respect to both cargo hold dimensions and payload capacity, outperform larger fleets of smaller aircraft. A critical requirement is the ability of aircraft to support double-file loading; cargo holds that do not allow for this capability perform significantly worse, even when their cargo hold length is increased significantly. Moreover, the design range is found to be of secondary importance compared to the design payload. A range of around 5,000 km is optimal and causes a reduced acquisition cost. A fleet of 22 additional aircraft is identified as the minimum necessary to meet the requirements of both scenarios. Although a fleet of 28 aircraft achieves a comparable MoE by reducing the number of required flights, and thereby, mission costs. Increasing the cruise Mach number also improves the MoE on average for smaller fleet sizes, as higher speeds enable more flights to be completed during the deployment. However, the effect plateaus at Mach 0.8, beyond which a decline in MoE is observed due to increased acquisition costs.

The optimal set of TLARs aligns with a design payload of 94.5 tons, a design range of 5,000 km, a cruise Mach number of 0.8, and a cargo configuration that supports double-file loading and has a cargo hold length of 39 meters. A fleet of 22 aircraft with these specifications is sufficient to meet the demanding requirements of both scenarios.

Although certain aspects of airlift operations, such as airfield ramp space constraints and multi-modal transport were not included in this analysis, the integration of aircraft design tools with agent-based simulations offers substantial potential for evaluating complex system of systems. This approach not only facilitates the analysis of airlift networks but also aids in defining optimal aircraft and fleet requirements to enhance existing strategic airlift fleets.

References

[1] Hages, L. D., "Quantifying the European Strategic Airlift Gap," *Air Force Institute of Technology*, 2013.

[2] PESCO, "Strategic Air Transport for Outsized Cargo (SATOC)," , 2024. (accessed: 26.03.2024).

[3] think defence, "2010 Haiti Earthquake Response Logistics," 2024.

[4] North Atlantic Treaty Organisation, "NATO Response Force," , 2024. (accessed: 26.03.2024).

[5] "The U.S. Military's Force Structure: A Primer," *Congressional Budget Office of the United States*, 2016.

[6] Johnson, M., and Coryell, B., "Logistics Forecasting and Estimates in the Brigade Combat Team," *United States Army*, 2016.

[7] Robert, C., "Interim Brigade Combat Team Ammunition Logistics Integrated Concepts Team," *Ammunition LAR Ft Lewis*, 2001.

[8] Vick, A., Orletsky, D., Pirnie, B., and Jones, S., "The Stryker Brigade Combat Team: Rethinking Strategic Responsiveness and Assessing Deployment Options," *RAND*, 2002.

[9] North Atlantic Treaty Organization, "Strategic Airlift," , 2024. (accessed: 26.03.2024).

[10] Smith, N., "A400M Grizzly: Strategic Delivery to the Point of Need," *European Aeronautic Defence and Space Company*, 2010.

[11] Nangia, R. K., Blake, W., and Zeune, C., "Relating & Comparing Operating Efficiencies of Civil Aircraft & Military Transports (Jets & Turbo-Props)," *27th International Congress of the Aeronautical Sciences*, Air Force Research Laboratory and Nangia Aero Research Associates, 2010.

[12] Maier, M. W., "Architecting principles for systems-of-system," *System Engineering*, 1998.

[13] Kilkis, S., Naeem, N., Shiva Prakasha, P., and Nagel, B., "A Python Modelling and Simulation Toolkit for Rapid Development of System of Systems Inverse Design (SoSID) Case Studies," *AIAA Aviation 2021 Forum, Virtual Event*, 2021.

[14] Kalliatakis, N., "An Agent Based Modelling and Simulation Framework to Support Strategic Cargo Airlift Evaluation," *Technical University of Delft*, 2023.

[15] Stucker, J. P., and Berg, R. T., "Understanding Airfield Capacity for Airlift Operations," *RAND*, 1998.

[16] Barwell, R., and Wainer, G., "Strategic Airlift Operationalizing constructive Simulations," *Carleton University*, 2020.

[17] Air Mobility Command, "Charter Guidance and rates for special Assignment airlift Mission, Joint exercise transportation Program, and Contingency Mission for the transportation Working Capital Fund: FY2024," 2023.

[18] Hess, R. W., and Romanoff, H. P., "Aircraft Airframe Cost Estimating Relationships: All Mission Types," *RAND*, 1987.

[19] Wöhler, S., Atanasov, G., Silberhorn, D., Fröhler, B., and Zill, T., "Preliminary Aircraft Design Within a Multidisciplinary and Multifidelity Design Environment," *Aerospace Europe 2020 Conference*, 2020.

[20] Schmitz, M., "Conceptual Aircraft Design Methodology for Disaster Relief Operations with a Variable Fidelity Interface," *Hamburg University of Applied Sciences*, 2023.

[21] Air Force Lift Cycle Management Center, "MIL-STD 3013B, Department of Defense Standard Practice Glossary of Defninitions, Ground Rules, and Mission Profiles to Define Air Vehicle Performance Capability," Tech. rep., U.S. Department of Defense, Septemer 2022.

[22] Seethaler, J., Strohal, M., and Stütz, P., "Finding Metrics For Combat Aircraft Mission Efficiency: An AHP-Based Approach," *DLRK 2020*, Deutsche Gesellschaft für Luft- und Raumfahrt - Lilienthal-Oberth e.V., 2020.

A. Appendix

Table 9 Assumed fuel usage for each vehicle type [6]

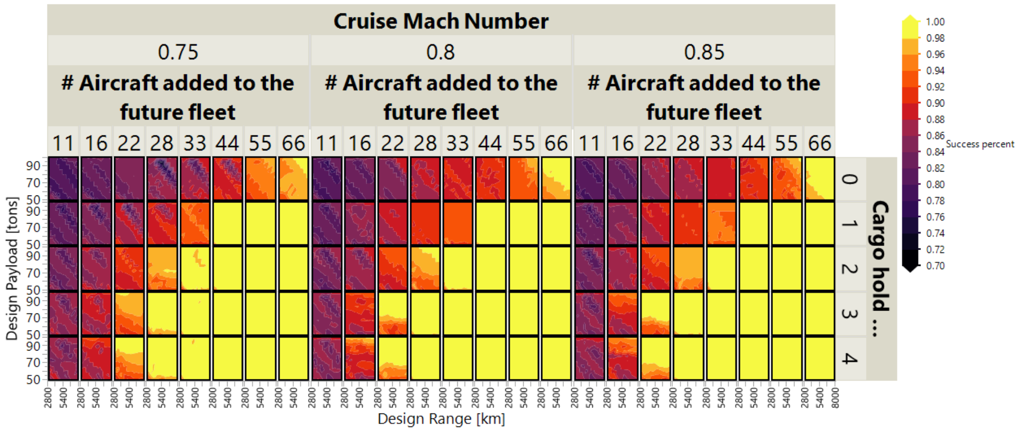
Vehicle type	Activate fuel usage [kg/h]	Idle fuel usage [kg/h]
Soft skin vehicle	39.75	3.79
Light & medium truck	39.75	3.79
Heavy truck & engineering vehicles	56.78	4.92
Medium-heavy hard skin vehicle	68.14	5.30
Very heavy hard skin vehicle	214.25	65.49

Table 10 Other assumptions used to compute the bulk cargo requirements of a SBCT and ABCT [5–7]

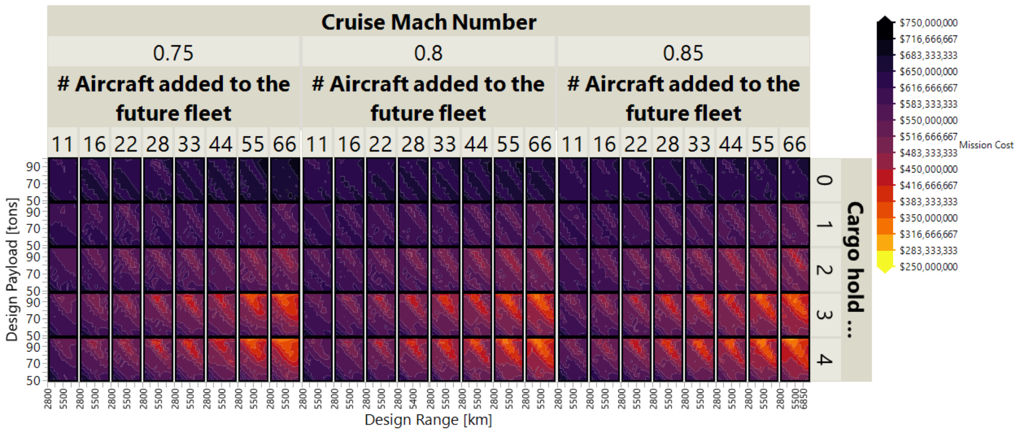
	SBCT	ABCT
Days before resupplied	5	10
Troops	4,081	4,535
Meals per day per person	3	3
Ammo consumption rate [ton/day]	5	5
Food pallet capacity [ton/pallet]	0.494	0.494
Water/fuel pallet capacity [ton/pallet]†	3.785	3.785
Pallet capacity for others [ton/pallet]	3	3
Cargo transported by strategic airlift††	59.68	59.68

† Based on H.A.R.P.S & Oasis tanker pallets

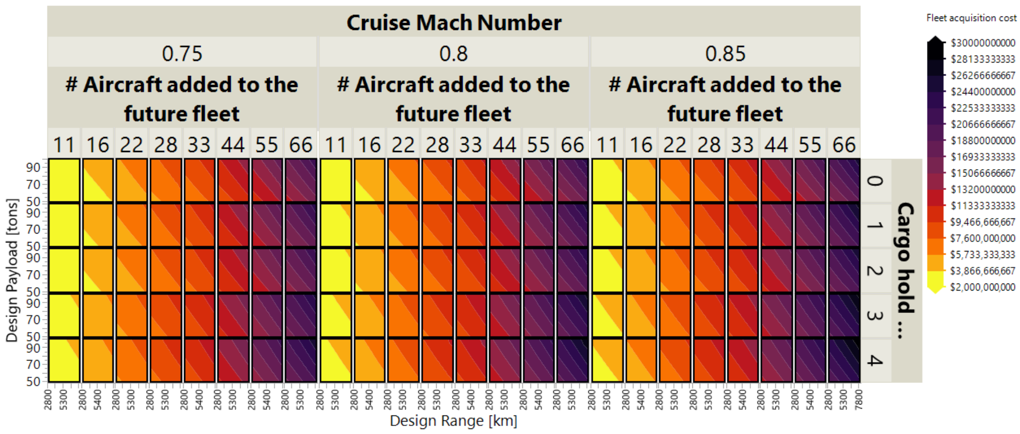
†† Computed as the carrying capacity of the combined A400M and C-17 fleet divided by that of the combined carry capacity of the tactical transporters, which include the A310, KC-10, KC-767, C-130-H, C-130-J, A340, and A330 MRTT



(a) Mission success rate



(b) Mission cost



(c) Expanded fleet acquisition cost

Fig. 19 Measures of effectiveness averaged over both scenarios

Table 11   List of cargo of the SBCT and ABCT [5]

	Cargo	Mass [kg]	Dimensions (LxWxH) [m]	SBCT Amount	ABCT Amount
Soft & hard skin vehicles	Hard-skin vehicle type 1	16,470	7.27 x 2.96 x 3.12	131	3
	Hard-skin vehicle type 2	21,351	7.63 x 2.96 x 3.31	27	
	Hard-skin vehicle type 3	18,764	7.54 x 3.89 x 3.18	40	
	Hard-skin vehicle type 4	19,051	7.40 x 2.96 x 3.12	35	
	Hard-skin vehicle type 5	17,321	7.31 x 3.90 x 3.26	51	
	Hard-skin vehicle type 6	18,956	7.31 x 3.90 x 3.18	11	
	Hard-skin vehicle type 7	16,938	7.00 x 2.91 x 2.58	14	
	Hard-skin vehicle type 8	18,554	7.29 x 3.81 x 3.03	9	
	Hard-skin vehicle type 9	22,910	6.50 x 3.20 x 3.00		119
	Hard-skin vehicle type 10	12,340	5.30 x 2.70 x 2.50		60
	Hard-skin vehicle type 11	11,100	4.93 x 2.69 x 2.71		44
	Hard-skin vehicle type 12	64,600	9.83 x 3.66 x 2.44		87
	Soft skin vehicle type 1	3,490	5.00 x 2.18 x 1.88	10	18
	Soft skin vehicle type 2	3,525	5.13 x 2.16 x 2.54	18	21
	Soft skin vehicle type 3	3,490	4.57 x 2.18 x 1.88	365	323
Support equipment & trailers	Support vehicle type 1	28,848	6.81 x 3.24 x 3.27		18
	Support vehicle type 2	26,100	6.6 x 3.15 x 3.28		18
	Support equipment type 1	5,935	4.99 x 2.39 x 2.59	2	3
	Support equipment type 2	7,154	12.3 x 2.80 x 2.90	18	
	Truck type 1	7,484	6.42 x 2.44 x 2.68	39	58
	Truck type 2	8,889	6.94 x 2.68 x 2.85	220	175
	Truck type 3	24,040	10.80 x 2.52 x 3.30	118	177
	Truck type 4	16,920	10.19 x 2.44 x 2.59	26	
	Trailer type 1	662	3.35 x 2.17 x 1.33	260	162
	Trailer type 2	4,318	5.79 x 2.44 x 2.09	103	153
	Trailer type 3	1,270	4.11 x 2.03 x 2.11	54	
	Trailer type 4	8,300	6.10 x 2.44 x 2.59	30	
	Trailer type 5	7,386	10.56 x 2.92 x 2.21	14	19
	Trailer type 6	7,484	8.32 x 2.43 x 2.94	89	120
	Trailer type 7	1,800	3.00 x 2.60 x 3.30	8	7
Engineering equipment	Engineering vehicle type 1	24,040	10.80 x 2.52 x 3.30	4	
	Engineering vehicle type 2	58,967	7.91 x 3.65 x 2.88		7
	Engineering vehicle type 3	3,600	1.12 x 4.50 x 1.00		7
	Engineering vehicle type 4	62,300	9.83 x 3.66 x 3.08		4
	Engineering vehicle type 5	63,500	8.27 x 3.43 x 3.12		29
	Engineering vehicle type 6	16,800	9.21 x 2.44 x 3.70	6	13
	Engineering vehicle type 7	17,500	5.80 x 2.90 x 2.70	15	1
	Engineering vehicle type 8	4,350	5.25 x 1.99 x 2.04	7	6
	Engineering vehicle type 9	15,195	8.24 x 2.55 x 2.72		9
Palletized	463L Pallet of food	494	2.24 x 2.74 x 2.00	62	136
	463L Pallet of water	3,785	2.24 x 2.74 x 2.00	305	677
	463L Pallet of fuel	3,785	2.24 x 2.74 x 2.00	365	1,210
	463L Pallet of other items	3,000	2.24 x 2.74 x 2.00	6	11

Part II

Literature Review

3
Literature Review

3.1. Introduction

Strategic airlift is a fundamental aspect of modern operations, enabling the movement of personnel, equipment, and essential supplies across vast distances to areas in which they are needed the most. The significance of strategic airlift becomes especially apparent in time-critical missions where rapid response is crucial. For instance, while a rapid sealift vessel may take a week to cross the Atlantic, a strategic airlifter can accomplish the same journey in under a day. Strategic airlift is, therefore, an indispensable resource in both military and humanitarian operations, providing a unique level of readiness that no other form of transport can match.

Despite the evident importance of strategic airlift, recent developments have concentrated on smaller tactical airlifters, such as the Embraer C-390. The development of heavy strategic airlifters, such as the Boeing C-17 and Lockheed C-5, has stagnated, and no new models have been introduced in decades. Additionally, production lines of these heavy airlifters have been mostly closed down, leaving organizations that seek heavy airlift capabilities no options but to outsource their demand to third parties. This furthermore results in their owned fleets consisting mostly of smaller airlifters that are incapable of transporting heavy, outsized cargo[1].

This literature review examines the current landscape of strategic airlift capabilities, focusing particularly on the evolving demand for heavy airlifters in modern operations. Through the analysis of the historical airlift missions, academic research, and governmental reports, this review will discuss the importance of strategic airlift in today's world. Furthermore, this review will discuss the difference in design between civilian transporters and strategic airlifters, differences that are important during the design phase of such an aircraft.

To start, a brief history of airlift, including some significant airlift missions and the cargo which was chartered, is given in Section 3.2. The strategic airlift gap and prior research around this capability gap are investigated and evaluated in Section 3.3. Then, the differences between military and civilian transporters, as well as the design methods used in developing such aircraft is given in Section 3.4. then, a summary of the problem is provided and research questions are composed in Section 3.5. Finally, a research plan is made in Section 3.6

[1]Outsized cargo is large, bulky cargo that can fit only on a couple of types of cargo aircraft like the C-5 Galaxy, C-17 Globemaster III, and AN-124. Examples of such cargo are helicopters, large engineering equipment, and more [1]

3.2. A brief history of airlift

Airlift has become an essential component of military and humanitarian missions. This chapter explores the evolution of airlift by examining key phases in history. Furthermore, significant airlift missions are described to give an idea of the scale of both humanitarian and military airlift missions of the past.

3.2.1. World War I

The roots of airlift were formed during the early 20th century. During World War I, aircraft were used to support logistical demands. For instance, in 1916, a large British force was put under siege by the Turks, after which the British aviators used their aircraft to drop sacks of flour on their location to relieve them [2]. Of course, the aircraft used for such missions were not built purposefully for airlift but instead where simple reconnaissance and bomber aircraft [2]. Other than some small-scale logistical missions, logistics was primarily based around ground and sea transport [3], especially to transport heavy equipment. Aircraft simply were not capable enough at this time to transport large amounts of cargo.

3.2.2. World War II

This started to shift during World War II, which saw a significant increase in airlift capabilities. Due to the scale of the war, it demanded for the rapid movement of cargo and troops over longer distances. Hence air transport became more essential for supply chains that spanned across continents. Countries such as Great Britain and the United States (U.S.) rapidly developed their air transport capabilities and created large fleets of purpose-built aircraft designed to transport cargo [2]. An example is the C-47 Skytrain, an aircraft derived from the DC-3 civilian transporter[2]. This aircraft includes a cargo door at the rear of the fuselage, which allows it to more easily and rapidly load cargo; it was even capable of transporting jeeps, as shown in Figure 3.1. This shows that aircraft technology had advanced to the point where it could be used for more demanding logistical missions involving the transport of heavier and bulkier cargo.

Figure 3.1: A jeep being loaded into a C-47 aircraft in 1943[3]

[2]www.wikipedia.com

[3]www.worldwarphotos.info

3.2.3. After the war

After the world wars and specifically during the 1950s, further developments in airlift and its doctrine were made. One of the doctrinal changes created a distinction between tactical and strategical airlift; here, tactical airlift refers to the transport of troops and supplies over shorter distances, often directly into the area of need [4]. While strategic airlift is the long-range transport of cargo across continents [4]. From this point onward, airlifters were developed with these doctrines in mind, which resulted in some specific differences between the two types of airlifters.

Tactical airlifters are designed for shorter-range missions that require access to forward operating bases. This leads to the requirements for such aircraft to operate from short, austere, unimproved runways. The C-130 Hercules, which saw its maiden flight in 1954 and is still in use today, is an example of such an airlifter and is shown in Figure 3.2a. On the other hand, strategic airlifters are designed for long-haul, intercontinental missions. Therefore, this type of airlifter focuses on the ability to transport a lot of cargo at long distances, resulting in the requirement of larger cargo holds and larger design payloads. An early example of a strategical airlifter is the C-133 cargo master (shown in Figure 3.2b), which saw its maiden flight shortly after the C-130 in 1956.

(a) YC-130 Hercules[4] **(b)** C-133 Cargo Master[5]

Figure 3.2: Airlifters from the 1950's

During the 1960s, the U.S. Air Force was looking for a jet transport aircraft specifically designed to airlift outsized cargo [5], an ability the other strategic airlifters did not have. Therefore, the development of the C-5 Galaxy started, and the aircraft saw its first flight in 1968. This served another pivotal moment in strategic airlifter design as it was the first time an aircraft was purposely built with a fuselage capable of transporting pretty much all cargo in the inventory of the nation that operated it. To give an idea on how large the cargo hold of the C-5 is, Figure 3.3 shows a submarine being loaded into the aircraft. Furthermore, this aircraft is still in use today and was the U.S. only aircraft capable of transporting such heavy and bulky cargo until the introduction of the C-17 in 1993 [5].

[4] www.vintageaviationnews.com

[5] www.wikipedia.org

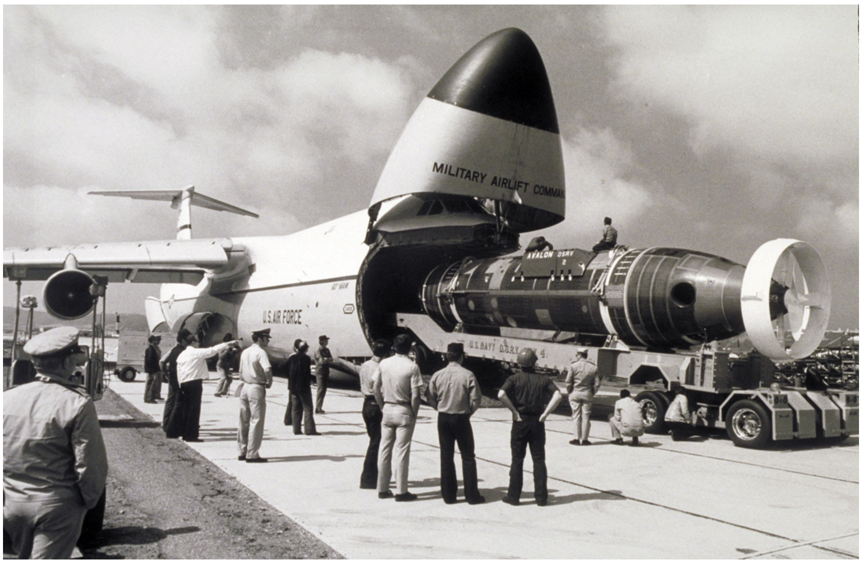


Figure 3.3: C-5 Galaxy loading a submarine in 1979[6]

3.2.4. Today

Today, the traditional distinction between tactical and strategic airlift remains relevant, yet emphasis is placed on multi-role capabilities that combine both sets of requirements. Modern airlifters are designed to handle a diverse range of missions, from short-range tactical deployments to intercontinental transport.

Aircraft like the Airbus A400M and Boeing C-17 are examples. The A400M is designed to bridge the gap between tactical and strategic roles [6], offering short take-off and landing capabilities while also providing the ability to transport cargo at strategic ranges and having a cargo bay capable of transporting outsized cargo [6]. Similarly, the C-17 combines larger airlifters' reach with the tactical airlifters' flexibility. This aircraft is therefore also able of short take-off and landing capabilities and is able to land on unprepared runways [7], making it ideal for military and humanitarian relief operations.

3.2.5. Historical Airlift Operations

This section examines a few selected historical airlift operations to provide insight into the scope and scale of both military and humanitarian airlift operations. Data on cargo volumes and composition is available for some of these to illustrate the logistical demands that shaped these missions.

Operation Vittles (1948-1949)

Operation Vittles is one of the most well-known airlift missions. In 1948, the Soviet Union put a landlock blockade on West Berlin, which left 2 million people in need of food, water, and other critical supplies. To avoid starting a war with the Soviets, Operation Vittles saw the delivery of these supplies through the use of airlift [8]. Over 461 days of the blockade, an astronomically large 2.3 million tons of relief equipment was transported over roughly 280,000 flights, a breakdown of the cargo is given in Table 3.1 [8]. Operation Vittles remains one of the largest and longest-duration airlifts of all time and was a considered a success.

Operation Provide Comfort (1991)

Following the Gulf War, a humanitarian crisis unfolded as approximately one million Kurds sought refuge in Iran and Turkey. In response, the United Nations Security Council authorized an international relief effort to aid these refugees [9]. This initiative, known as Operation Provide Comfort, commenced on April 3, 1991, with airdropped relief supplies to the refugees [9].

Initially, a fleet of only 20 American C-130 aircraft delivered around 600 pallets of aid daily from Turkey, but more was needed to meet the demands of the refugees. Strategic airlifters such as the C-5 galaxy

[6]www.theaviationgeekclub.com

Table 3.1: In-bound cargo to Berlin during the Berlin airlift [8]

Nation	Food [kg]	Coal [kg]	Other [kg]	Total cargo [kg]	Total flights
U.S.	296,319	1,421,119	66,135	1,783,573	189,963
UK	240,528	164,911	136,640	542,079	87,745
Total	536,847	1,586,030	202,775	2,325,652	277,682

played a crucial role in meeting the demands of the large amount of refugees and maintained a supply chain in which they transported thousands of tons of relief supplies from the U.S. to Germany and then to Turkey [9]. Over the course of 101 days, U.S. aircraft delivered more than 7,000 tons of humanitarian supplies in Operation Provide Comfort, offering critical support to the displaced Kurds [9].

Operation Allied Force (1999)
Operation Allied Force was a NATO operation that relied on rapid airlift to quickly deploy units, sustain the deployment, and supply civilians with relief supplies. During the operation, airlift was used to transport 32,000 passengers and 52,645 tons of equipment using primarily C-130s and C-17 aircraft [10]. C-17s were primarily used to transport outsized cargo. They moved 24 helicopters, 94 hard skin vehicles, and 22,000 tons of additional supplies over 468 missions [10]. A fleet of C-130s was furthermore used to transport 4,503 passengers and 5,171 tons of equipment for both military and humanitarian use cases [10]. Of the total amount of airlift sorties flown, over half were flown by the U.S. [11].

Operation Unified Response (2010)
In 2010, a 7.0 magnitude earthquake struck Haiti, claiming the lives of approximately 316,000 people and injuring another 300,000 more [12]. In the aftermath, Port-au-Price's airport quickly became a vital logistical hub for humanitarian aid. Although the airport reopened just days after the earthquake and U.S. military controllers took over, it faced logistical challenges due to the lack of infrastructure. Before the earthquake hit, the airport handled 12-15 flights daily and only during the daytime; it managed over 60 flights per day after the earthquake during 24/7 operations, all relying on a single runway [13].

Furthermore, the limited ramp spaces - enough to accommodate only two large aircraft and six smaller ones simultaneously - added to the operational difficulties on the ground [13]. Despite this, U.S. helicopters and cargo planes, including C-130s, C-17s, and even Russian AN-124s, delivered humanitarian aid supplies alongside airdrops [13]. When airport operations were returned to civilian controllers, 14,098 tonnes of humanitarian supplies had been delivered through airlift [13].

Operation Serval (2013)
In 2013, France launched Operation Serval, a military intervention in Mali that saw the deployment of a relatively small combined-arms force. Despite this modest deployment, France faced significant logistical challenges and relied heavily on allied and chartered airlift capabilities to overcome them. During the critical early weeks of the operation, approximately 75% of the airlifter cargo was transported by chartered aircraft belonging to two companies [14, 15]. At the time, France had also already received its first A400M aircraft.

The transported cargo included several hundred hard-skin vehicles, a significant portion of which had to be driven to Mali due to limited airlift availability [14]. This shows the strain a relatively modest deployment put on the airlift resources, even with allied support. Helicopters, small reconnaissance aircraft, trucks, and soft-skin vehicles were included in the airlifted cargo. A list of transported cargo is shown in Table 3.2. However this list does not include support equipment and palletized equipment and is, therefore, merely a top-level indication of the cargo requirements.

3.2.6. Takeaways
Some insights emerge from the historical operations discussed. The scale and complexity of such operations are highlighted. Thousands of tonnes of equipment are chartered in a short time. A striking difference between humanitarian relief and military missions is also the composition of the cargo. For humanitarian relief, most cargo is palletized, such as food, water, medical supplies, etc. In contrast, military operations see the movement of a combination of palletized cargo and non-palletized cargo, such as heavy

Table 3.2: Vehicles moved to Mali during Operation Serval as of april 2012 [14]

Vehicle type	Amount
Small aircraft	1
Helicopter	23
Soft skin vehicle	286
Hard skin vehicle	61
Truck	154

or outsized vehicles. This creates a unique distinction in the the requirements of both mission types and shows that airlifters must possess versatility and the ability to accommodate diverse payload types and sizes. It is also shown that infrastructure can impose significant challenges during operations, such as limited airport capacity. This could be a driver for additional requirements on airlifter design. Finally, these operations emphasize the significant role that the U.S. has in these missions, while European nations require more allied support when it comes to airlift. This is especially evident when there is a need to transport heavy or outsized equipment. This disparity indicates that a gap in the strategic airlift capabilities of the European fleet exists.

3.3. The Strategic Airlift Gap

The analysis of historical humanitarian and military airlift operations revealed a gap European airlift capabilities. This gap is not a recent development but has been a recognized concern for some time. One of the earliest formal acknowledgments of this deficiency came during the 2002 NATO summit in Prague, where insufficient strategic airlift was identified as a critical area needing improvement [16].

This gap became even more pronounced with the creation of the NATO Response Force (NRF), a high-readiness force designed to be deployed within days in response to global crises [17]. The NRF's rapid deployment capability relies heavily on strategic airlift, and many NATO members faced significant challenges in meeting these demands.

The first section, Section 3.3.1, of this chapter, examines how European nations have attempted to address this gap since the NATO summit in 2002. Then, Section 3.3.2 reviews past studies and analyses that look into the airlift gap and assess if the imposed solutions will bridge the gap. These studies are by now quite old, so Section 3.3.3 investigates whether the capability gap has been bridged or if the challenges of strategic airlift capacity remain an ongoing concern.

3.3.1. The response to the strategic airlift gap

Since identifying of the strategic airlift capability gap, European nations have undertaken several initiatives over the past decades to address and mitigate these shortcomings. These initiatives are described in the following subsections:

The A400M

One of the most substantial advancements in closing the capability gap has been the collective purchase of A400M aircraft by multiple European nations. While this fleet acquisition was intended to close the capability gap rapidly, the program faced significant delays in delivering an operational product [18]. The first deliveries of the aircraft were initially planned for 2009 [18]; however, in 2024, only about 75% of the purchased fleet has been delivered. Furthermore, the size of the purchased fleet has reduced over time. Initially, 291 aircraft were on order, but this was later reduced to 170 [19]. The current and future fleet of A400Ms is shown in Table 3.3.

Table 3.3: The composition of the collectively purchased A400M fleet in the 2024 and future fleet

Nation	# A400M in 2024	# A400M purchased
Germany	45	50
France	24	50
Spain	14	27
United Kingdom	22	22
Belgium	7	7
Luxembourg	1	1
Turkey	10	10
Total	123	170

Strategic Airlift Interim Solution (SALIS)

After the formation of the NRF, nations sought to mitigate the existing gap at the time by outsourcing their airlift demands to other nations until the A400M fleet had been delivered (hence, it is an interim solution), resulting in the SALIS contract being signed in 2006 [20].

SALIS provides NATO members access to five Antonov AN-124-100 aircraft. One of these aircraft is available at a 72-hour notice, another at a 6-day notice, another additional aircraft at a 9-day notice, and two additional aircraft are subject to availability [20].

Because the purchased fleet of A400M aircraft encountered significant delays, the SALIS contract had to be continuously extended and is still in effect as of 2024. The contract expires in 2030, after which the chartered aircraft will reach their end of life [21]. These pushbacks of the agreement have caused the cost tag of the interim solution to run up significantly. To give an indication of the cost tag of chartering these aircraft: Germany flew 100 sorties to transport heavy equipment to Afghanistan using the supplied aircraft and paid an estimated 218,000$ per mission [22]. France and the United Kingdom also used these aircraft and paid an estimated 265,000$ per mission [22]. Even the U.S. had to lease the AN-124s to carry outsized cargo, which cost them about 366,000$ per mission in 2003 [22]. Compare these mission prices with the total cost of acquiring an AN-124, which is valued at 80M$ [23]. Furthermore, prices increase significantly more when crises happen as the demand for airlift increases [24].

Strategic Airlift Capability (SAC)
Another significant measure European nations took to address the strategic airlift capability gap is the collective purchase and operation of three C-17 Globemaster III aircraft by twelve participating countries through the SAC agreement [25]. This collaborative approach is designed to mitigate the financial burden of purchasing such expensive aircraft individually. The C-17s are utilized to fulfill the airlift demands of allies, the European Union, and the individual member's national needs [25].

Resulting fleet of airlifters
The aircraft obtained through all three of these initiatives combined create a portfolio of airlifters all of various classes and sizes. Figure 3.4a shows the payload-range diagrams of the three types, and Figure 3.4b compares their cargo hold dimensions.

3.3.2. Past studies

Several studies and simulations have been conducted in the past decades to study the airlift capabilities of Europe and NATO. These studies mostly focus on the deployment of the NRF as such a scenario is logistically very demanding for an airlift network and, therefore, is a driver of requirements. Some of these studies are listed in the following subsections:

Belgian Royal Defense College Report (2004)
The Belgian Royal Defense College performed one of these studies in 2004. They studied the strategic airlift requirements by asking ”How much, how far, and how fast” cargo had to be moved using the EU's Headline Goal Task Force [7] guidelines [24]. The study concluded that the EU must deploy roughly 20% of the required equipment using airlift at distances that span up to 4,000km from EU borders [27]. An estimate is made that 10 passenger, 60 medium logistics (equivalent to the C-130 or C-160), and 14 heavy aircraft sorties (equivalent to the C-17 Globemaster III) are required *daily* to transport 60,000 personnel with 40,000 tons of equipment over 60 days [18].

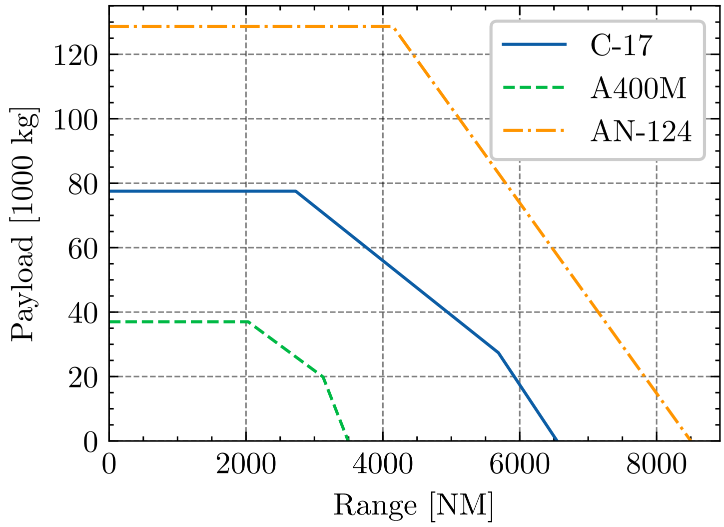
Joint Air Power Competence Centre Study (2005)
Another study was performed by the Joint Air Power Competence Centre (JAPCC) in 2005. They investigated the requirements to deploy the NRF after they became operational in the same year. The study compared the airlift capabilities at the time against the requirements they identified to make such a deployment. They note the importance of airlift over sealift for deploying such cargo over a small time-span by stating the following:

> *”A fundamental component in the deployability jigsaw is having the capability to be able to “lift” the required force rapidly to the required destination in the required timescale. Clearly, sealift plays a vital part in all this but the real premium in today's uncertain world rests upon having a strong military airlift capability. Without the airlift, the readiness timescales for deployment are unlikely to be met, particularly when one considers the distances involved and the likely deployment scenarios.”* [28]

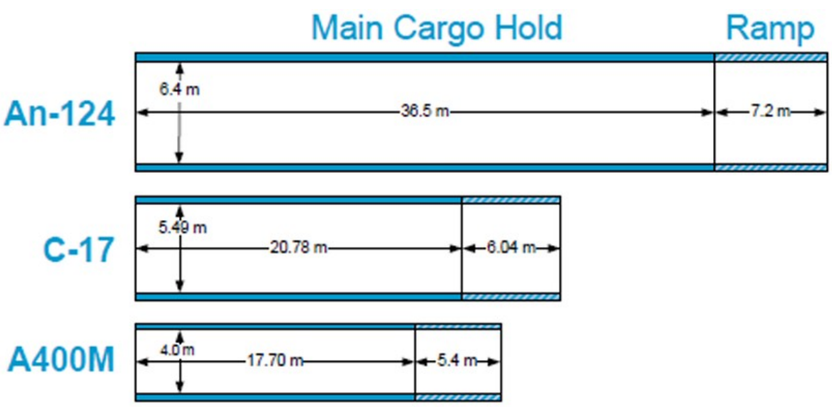
The study investigated two typical NRF deployment cases. The first case focused on central Africa at a distance of 3,300 nautical miles. On the other hand, the second scenario models a coastal scenario by deploying the NRF to the Bahamas at a distance of 4,100 Nautical miles [28].

It is challenging to come up with the requirements to deploy the NRF as they are required to perform vastly different missions and the composition of the NRF can change to tailor to the needs of these different missions. For this reason, the study took a balanced approach and used the NRF's Combined Joint

[7] The Headline Goal Task Force is a group of experts that deals with capability development for the EU [26]



(a) Payload-range diagrams of the A400M, C-17 and AN-124 [6]



(b) Cargo hold dimensions of the AN-124, C-17 and A400M compared [18]

Figure 3.4: The European strategic airlifters compared

Statement of Requirements (CSJOR) [28] and data from the NATO MOVEX 04 exercises, which simulated an NRF deployment, to identified the requirements. This resulted in the requirement to move around 22,000 personnel and 91,000 tons of equipment within 30 days per scenario [28].

In both scenarios, the study used all available airlift assets, including those of the U.S. and also tactical airlift platforms. Furthermore, the fleet also included the AN-124 aircraft available through SALIS but did not include the C-17s supplied by SAC as it was not yet operational at the time. Additionally, sealift was ignored for the study. Therefore the types of aircraft considered in the scenarios were A-310, TU-154, KDC-10, KB0707, C-5, C-17, VC-10, C-130, and AN-124s.

Next, the scenarios were modeled in NATO's Allied Deployment and Movement System (ADAMS). The study's first key finding is that despite the inclusion of U.S. air assets, NATO could not deploy the NRF within the required timescale [28]. They concluded that NATO members, excluding the U.S. and possibly the UK, possess insufficient strategic military airlift capabilities to deploy the required equipment in the required timescale [28]. However, it was found that the European fleet didn't have any issues moving standard foot troops and cargo as the European fleet of aircraft possessed a sufficient amount of smaller tactical airlifters [28]. They stress the important of diversifying the airlift fleet with heavy lifting strategic airlifters by stating:

"Massive use of light transport aircraft cannot compensate for the lack of the heavy type assets necessary to move outsized and heavy equipment" [28]

While the exact composition of the forces used is not specified if at all defined, the study showed that about 60% of the total equipment that had to be transported was outsized and required the use of C-17, C-5, or AN-124 [28]. Finally, the study notes that the A400M will provide a useful increase in load-carrying capability and that it represents a crucial capability improvement for the deployment of the NRF [28]. However, the aircraft itself was not included in any of the scenarios and therefore this statement is merely theorizing the effect it would have.

Objective Force Mobility Study (2007)
Another study of interest involved the deployment of a U.S. light brigade, a heavy brigade, and a Stryker brigade. The deployment of these forces should happen in the time-span of 4 days for a brigade, a division in 5 days, and five divisions within 30 days as is required by the U.S. transformation plan at the time [29].

While this force is not the NRF and the deployment timeline is different from that of the NRF, the size of the force is comparable to a small NRF deployment [18]. It is roughly equivalent in size of the Very High Readiness Joint Task Force (VJTF), which is part of the NRF, and has similar deployment timelines to it. Once again the exact composition of the brigades is not given, if at all defined, but the requirements of these brigades are shown in Table 3.4.

Table 3.4: Cargo demands for the U.S. Transformation Plan [29]

Brigade	Cargo [tons]
Heavy	29,000
Stryker	15,000
Light	7,300

The study concludes that to deploy the heavy brigade, 478 C-17 sorties are required. 243 Sorties are required for the Stryker brigade and 141 for the light infantry brigade [29]. In addition to these results, the study emphasizes the fact that deployments often happen in areas that do not have extensive infrastructure like the U.S. or Europe does. Therefore, the STOL capabilities of transporters such as the C-17 provide great capabilities for rapid deployments [29]. Additionally, the study mentions that the use of sealift in such a deployment can be limited due to the limited number of harbors available, and because sealift platforms require deep-water ports to offload equipment [29].

Air Force Institute of Technology Study (2013)
In a 2013 study, the Air Force Institute of Technology (AFIT) investigated not only the size of the capability gap in the European airlift capabilities at the time, but unlike other studies, also whether this gap would be filled in the future with the introduction of the A400M fleet.

The study simulated three separate scenarios for the deployment of the NRF. The requirements for this deployment were based on the requirements from the previously described 2005 JAPCC study [18]. Furthermore, this study used the same scenarios as the ones used in the 2005 JAPCC study and additionally added a third scenario which was modeled by the European Aeronautic Defense and Space Company (EADS): the multinational effort in Mali in 2013. The deployment time for the Mali scenario was set at 10 days and was derived from past studies of EU Battle Groups and the EADS study itself [18].

In terms of the cargo, the study modeled it in the same way as the JAPCC study and therefore modeled 60% of the total cargo mass as outsized cargo [18], thus cargo is merely seen by its mass and not by its dimensions as appears to be the same in all other studies. This outsized cargo can only be carried by the C-5, C-17, A400M, and AN-124 in the simulation [18], while all remaining cargo can be carried by all aircraft. Table 3.5 shows the requirements of each scenario.

These scenarios were then simulated using three separate fleets of aircraft. First, a one-to-one replica of the European fleet at the time was used. Second, a projected future European fleet that included the A400M aircraft was used [18]. Additionally the AN-124 aircraft were removed from this fleet as the SALIS arrangement was believed to end after a significant number of A400M aircraft were delivered. These two fleets are shown in Table 3.6.

Table 3.5: AFIT scenario requirements [18]

Scenario	Distance [NM]	Personnel	Cargo [tons]	Outsized [%]	Depl. Time [days]
Bahamas	4,267	25,000	69,853	60	30
Rwanda	3,297	20,000	84,368	60	30
Mali					
Eur. Battalion x3	2,025	4,900	22,577	45.69	10
Afr. Battalion x1	1,015	816	2,004	6.36	10
Afr. Battalion x1	856	816	2,004	6.36	10
Afr. Battalion x1	541	816	2,004	6.36	10

Table 3.6: Fleet compositions used in the AFIT study [18]

	”Current” fleet†	Future fleet
Aircraft	Total (Europe)	Total (Europe)
C-17	10	10
A400M		170
A310	10	10
A330	14	14
KDC10	3	3
KC767	2	4
C-130J	62	70
C-130H	107	107
AN-124	4	

† Current refers to the fleet at the time of writing the study, namely 2013

The third and final fleet involved the modeling of a hypothetical expansion of SAC by adding more C-17s to this fleet [18]. These scenarios were then simulated using the USAF AMPCALC, a deterministic model based on Air Force Pamphlet 10-1403 ”The Algebra of Airlift” [18].

The report concludes that the European fleet at the time was unable to complete any of the scenarios within the required times [18]. In fact, most scenarios required nearly double the required time. When the A400M was introduced, however, the study found that the projected future fleet does manage to complete most scenarios except for the Rwanda scenario [18]. Finally, the study concludes that an expansion of the SAC by buying more C-17 aircraft would require fewer aircraft to achieve the same goals which would result in a more cost-effective solution and a solution that would put less strain on the logistical network [18].

3.3.3. Is the airlift gap closed?

The studies agree that when all A400Ms have been delivered, the resulting fleet would have sufficient airlift capacity to close the airlift gap. The AFIT study, the only study that included the future A400M fleet in computations, found that airlift capacity was sufficient in nearly all simulated scenarios. However, some doubts remain to exist about these conclusions. For example, a 2009 USAF study states:

”While capable of outsize cargo, the A400M cannot transport the heavy tanks or artillery pieces required to meet NRF goals.” [24]

Furthermore, after France used the first A400Ms in Operation Serval, they also voiced their concerns, stating that:

”The A400M, the first aircraft of which were delivered were tested in Mali, is the beginning of a solution for strategic transport. This device has many qualities and will considerably improve our projection

capabilities. But he's not a heavy lifter. [...] Even when the A400Ms have all been delivered, we will still need large aircraft." [15]

This statement suggests, just like the JAPCC study, that airlift diversity is important but currently lacking in the European fleet. Thus, while research indicates that the airlift gap will be closed with the introduction of the A400M fleet, there is some skepticism, especially concerning the heavy lift capabilities of the aircraft. This is furthermore backed by the fact that the European Union is running the Strategic Air Transport for Outsized Cargo (SATOC) project, which seeks to completely close the capability gap by filling the "critical shortfall for strategic air transport for outsized cargo by developing a European solution for the transport of outsized and heavy cargo" [21].

Study limitations

Because of these statements and a new project being launched, which could result in the development of a new European airlifter, it appears that the past studies have overestimated the abilities of the future fleet. Such overestimation may be due to some significant simplifications in their simulations and computations. The assumption that aircraft cannot "bulk out" is one of the assumptions made by all previous studies (albeit the precise methodology used for some research is not publicly available). Bulking out refers to the constraint an aircraft's cargo hold dimensions put on the airlift mission. By ignoring this constraint, calculations, and simulations merely look at a single constraint per flight: the payload mass constraint. However, while the mass constraint is crucial, so is aircraft bulking out, as this can result in many more flights being flown, therefore reducing airlift capacity. This is particularly true when transporting outsized cargo over long distances, considering that approximate 60% of the NRF's equipment is outsized. For example, while the A400M is capable of loading 37 tons of cargo before reaching its mass constraints, it can only load a single NH90 helicopter that weights 6.2 ton in its 17.7m long cargo hold. Figure 3.5 looks at how constraining the cargo hold dimensions can be when chartering outsized cargo such as helicopters.

Figure 3.5: An NH90 helicopter being loaded in the A400M [8]

Secondly, the studies ignore other important aspects such as airfield ramp constraints and ground operations which can again cause an overestimation of airlift capacity. A RAND study previously investigated the impact of these airfield constraints. The impact of limited maintenance crew availability, limited fuel at

[8]mediacentre.airbus.com

airfields, and limited ramp spaces saw a reduction of 20% in airfield throughput [30].

Finally, the results of these studies rely heavily on the scenario requirements. In 2013, the requirements have changed after the VJTF was introduced as part of the NRF. Deployment of the NRF now occurs in two phases: an initial very rapid deployment phase, where a significant portion of cargo is moved in just a few days - according to the Le Touquet agreements, between 5-10 days [31] - anywhere in the world, and a second phase which sees the remaining cargo moved in a significantly longer time-span of 30 days [17]. The aforementioned studies do not model both these deployment phases as they were written before to the VJTF was introduced. However, depending on how much cargo will be transported during the first deployment phase, this phase can be significantly more constraining on airlift capacity than the second phase. Consider that in 2023, the VJTF was centered around Germany's 37th Panzergrenadier brigade, a heavy brigade. An estimate of the main cargo, excluding support equipment, and palletized cargo is shown in Table 3.7. This estimated cargo, which does not include all the cargo considering support equipment and palletized cargo is ignored, makes up around 13,000 tons the total NRF equipment. Add the support equipment and palletized cargo to this load, and you would look at probably about one-third of the total mass of cargo that has to be deployed in the first phase of the deployment, thus resulting in more or less the same requirements as was used in the Objective Force Mobility Study for a heavy brigade. Therefore, this initial deployment phase is the most constraining on the airlift network and, thus, also on the fleet and aircraft requirements.

Table 3.7: Top-level equipment that makes up the 2023 VJTF [32]

Battalion	Central vehicle	Mass [tons]
212th Battalion	44x Puma IFV	A: 31.45 C: 43.0
371st Battalion	44x Marder I	1A3: 33.5 1A5: 37.4
391st Battalion	44x Marder I	1A3: 33.5 1A5: 37.4
929th Battalion	44x Marder I	1A3: 33.5 1A5: 37.4
393rd Battalion	44x Leopard 2A6	62.0
375th Battalion	A: 24x PzH 2000 B: 8x M270 C: COBRA Radar	A: 55.3 B: 24.0 C:32.0
345th Battalion	A: 24x PzH 2000 B: 8x M270 C: COBRA Radar	A: 55.3 B: 24.0 C:32.0
30th Battalion	40x NH90	6.2
701st Battalion	A: Keiler MiRPz B: Dachs 2A1	A: 53.0 B: 43.0
131th Battalion	N.A	N.A
13th Battalion	Fennek	10.4

3.4. Aircraft and Fleet Design Methods

Before World War II, no distinction was made between civilian and military aircraft. Instead a single aircraft type was used to carry out the full spectrum of missions [33]. However, when the requirements for the different missions became clearer, transport aircraft began to be split into specific classes, each designed for specific missions [33]. The difference between military and civilian transport aircraft began to take shape. To gain insight into the differences between civilian and military transport aircraft, this chapter will investigate the design features and methods used in their development cycle.

Section 3.4.1 discusses the important differences between commercial and military transport aircraft. Section 3.4.2 follows with a short discussion about knowledge-based engineering and how it is used for aircraft design. Finally, Section 3.4.3 discusses the System of Systems and System of Systems Engineering concept and how these can be applied to conceptual aircraft design.

3.4.1. System Engineering

At first glance, military transport aircraft might appear similar to civilian transport aircraft. However, civilian freighters are often derivatives of passenger transporters, meaning their primary design focus is around the passenger. In contrast, military transporters are built around the cargo [34]. Figures 3.6, 3.8, and 3.7 illustrate various military transport aircraft, both tactical and strategic. From these images, several commonalities in their design become more evident.

(a) Lockheed C-5 Galaxy [9] **(b)** Antonov AN-124 Condor[10]

Figure 3.6: Large strategic military transport aircraft

(a) Boeing C-17 Globemaster III[11] **(b)** Airbus A400M Atlas[12]

Figure 3.7: Strategic/tactical military transport aircraft

[9] www.blogspot.com
[10] www.interestingengineering.com
[11] www.wikimedia.org
[12] www.wikimedia.org

(a) Lockheed C-130 Hercules[13]

(b) Embraer C-390 Millenium[14]

Figure 3.8: Tactical military transport aircraft

High-wing configuration
A prominent feature among military transporters of all classes is their high-wing configuration. This design offers several advantages. Firstly, high-mounted wings provide greater ground clearance for wing-mounted engines, minimizing the risk of damage from debris during operations on austere airfields [33]. Secondly, it allows the fuselage to be positioned closer to the ground, facilitating the rapid loading and unloading of cargo in locations with minimal or no specialized equipment [35]. In larger designs that require longer landing gear struts, such as the AN-124 and C-5, this advantage is kept by such designs including kneeling landing gear.

Furthermore, some aircraft, including the A400M and C-390, mount the wings ”on top” of the fuselage. This prevents the wing structure from passing through the cargo hold, ensuring a uniform cargo hold height [34]. When the wing is not mounted on top of the fuselage, the cargo hold height becomes non-uniform, as is the case for the C-17 Globemaster III, as can be observed in Figure 3.9b.

Fuselage differences
Military transporters incorporate unique features to streamline cargo handling. For instance, the cargo hold floor is often lowered to truck-bed height, simplifying loading operations and accommodating taller cargo [34, 35]. Furthermore, a cargo ramp is added to the rear of the fuselage to facilitate the rapid loading and unloading of a wide range of vehicles [36]. This ramp allows for so-called ”drive-on, drive-off” capabilities where cargo can quite literally be driven into the cargo hold, see Figure 3.9a. The aft cargo ramp also allows these aircraft to perform airdrop missions, which can be crucial in rapidly deploying troops or humanitarian aid supplies over a disaster zone.

The aft cargo ramp cuts severely into the fuselage structure, leaving little structural depth for the empennage attachment. Therefore, the fuselage structure is reinforced. Appendix D of Torenbeek [34] can be used to compute the weight gains due to these cutouts.

Furthermore, when including the aft cargo ramp, the fuselage must camber tail upward. This creates an adverse interference with flow fields caused by the downwash of the wing, wheel fairings, and rear fuselage, causing vortices to be created, as shown in Figure 3.10a. Depending on the fuselage up-sweep angle, these vortices can create a substantial drag penalty and safety concerns when airdropping cargo or paratroopers [34, 37]. In fact, for the C-130, the drag due to these vortices is estimated to be 11% of the total drag [38]. The drag penalty estimate can be seen in Figure 3.10b [34].

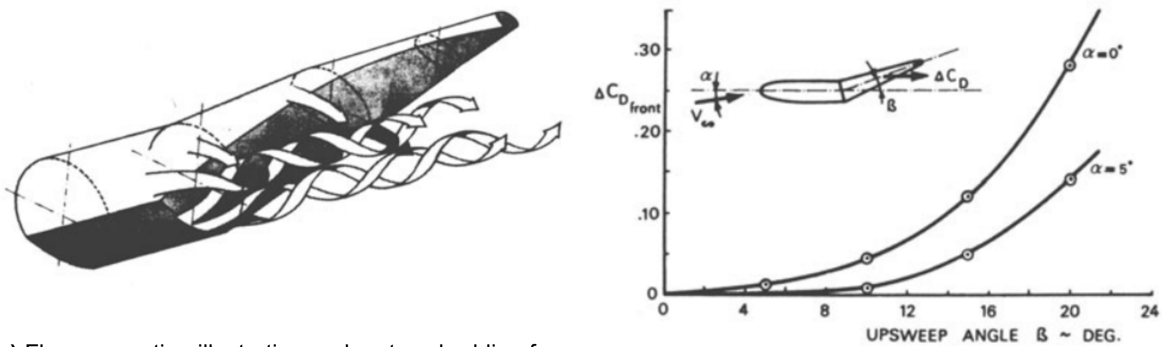
Some of the largest designs, such as the C-5 and AN-124, also include a ”knight's visor” nose. This nose can open up, and a ramp which is located behind the nose can fold out to allow for a second access point

[13] www.wikimedia.org
[14] www.cockpit.aero
[15] www.ytimg.com
[16] live.staticflickr.com

(a) U.S. C-5 Galaxy loading rolling stock[15]

(b) C-17 Globemaster III Cargo hold[16]

Figure 3.9: A C-5 Galaxy with an open "knight visor" nose and the cargo bay of a C-17 Globemaster III



(a) Flow separation illustration and vortex shedding from a highly upswept fuselage [34]

(b) Drag penalty versus increased up-sweep angle [34]

Figure 3.10: Aerodynamic effects of high fuselage upsweep angles

to the cargo hold. This way, cargo can be loaded and unloaded even faster [34]; such a nose can be seen in Figure 3.9a. The downside of including of a knight visor nose is that a high-mounted cockpit is required. Such a high-mounted cockpit produces additional drag [34].

Finally, to allow for wider cargo to fit into the cargo hold, some military transporters deviate from the traditional round fuselage design as found in civilian transport aircraft. Because the floor is lowered and has to be as wide as possible to accommodate outsized cargo, the fuselage cross-section is sometimes rectangular-shaped. This shape comes at the cost of additional drag [35].

Landing gear

As shown prior, military airlifters often include short take-off and landing (STOL) requirements. Furthermore, they are often required to land at austere, unprepared airfields. These requirements, in particular, substantially impact the design of the landing gear.

Take for example the landing gear of the C-17 Globemaster III, as shown in Figure 3.11. First, the aircraft has 6 tires per side, which is relatively many for an aircraft with a max take-off weight (MTOM) of roughly 265 tons. For example, the Airbus A350-900 has a similar maximum take-off weight at 270 tons and only has 4 tires per side. This difference facilitates landings on soft fields, as an increased number of wheels will increase the surface area over which the load is spread, thereby holding the aircraft from sinking into the soft field [39]. Secondly, Figure 3.11 shows that there are two struts for the six tires, which are configured three-abreast. This feature fulfills the requirement of landing in rough fields as both sets of wheels can now move independently up and down from each other.

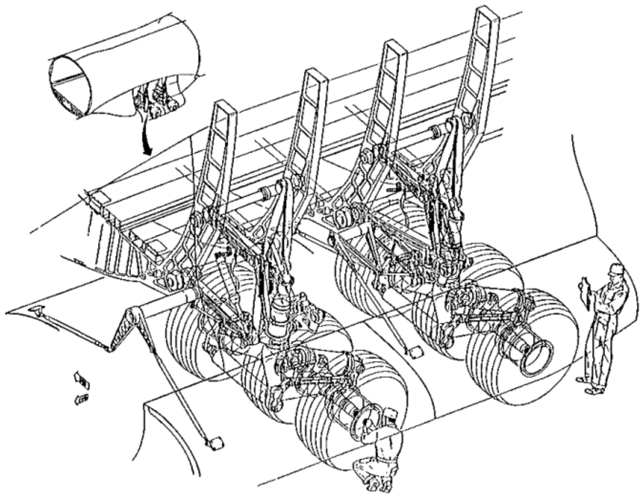


Figure 3.11: The main landing gear of the C-17 [7]

Also, the requirement to rapidly handle cargo impacts the landing gear. As mentioned before, the floor inside the fuselage is attempted to be placed as low as possible to ease the loading and unloading of cargo. This leads to short struts being used for the landing gear; however for some large designs, this is simply not possible. Therefore, these larger designs include so called ”kneeling” capabilities in its landing gear, as shown in Figure 3.12. Furthermore, the landing gear is stored in fuselage mounted landing gear pods due to the high wing design. This provides two advantages: a wider track to prevent tip over, and it prevents the landing gear from folding into the fuselage, which would constrain the cargo hold dimensions. Additionally, this landing gear fairing often also stores the APU [35], when looking carefully the APU exhaust can be seen in Figure 3.6a.

Figure 3.12: C-5 Galaxy’s kneeling landing gear [17]

The STOL requirement sees military airlifters having significantly larger sink speeds than civilian transporters. For example, the C-17’s landing gear is designed to land at sink speeds of 15 ft/s [7], while passengers consider 4-5 ft/s a bad landing [35]. In fact, this sink speed is quite close to that of carried-based naval aircraft which land at around 20 ft/s sink speed [35]. Such high sink speeds require a heavier load bearing structure of the landing gear, thereby increasing weight.

[17] www.theaviationist.com

Finally, some airlifters additionally benefit from features such as cross-wind positioning, allowing the landing gear to essentially yaw which makes it easier to land with rough crosswinds [39] as well as self-jacking abilities allowing ground crew to replace tires when no jacking equipment is available [39]. All these requirements and features together create the most sophisticated landing gear designs seen in aircraft. Currey in his book about landing gear design [39], indicates the weight increases due to these various features, these are shown in Table 3.8. However, other aircraft design books like Raymer [35] also provide methods which include these capabilities.

Table 3.8: Scaling parameters for various landing gear capabilities as obtained by Currey [39]

Capability	Mass scaling parameter
Rough-field capable	1.15
High-flotation	1.11
Kneeling	1.19
Crosswind positioning	1.04

Based on the points above, it is clear that military transporters are significantly different from civilian transporters. The need for rapid loading/unloading and the accommodation of non-standard cargo create a larger, heavier, and unconventionally shaped fuselage. Paired with the additional capabilities such as STOL and landings at unprepared runways, further increase the weight and complexity of the structure. All these factors combined, therefore, render military transporters not only heavier and more structurally complex than civilian transporters, but they also produce more drag.

3.4.2. Knowledge-Based Engineering

System engineering involves a wide range of methods, principles, and human expertise in designing complex systems. In the field of aircraft design, knowledge of multiple disciplines, such as aerodynamics, propulsion systems, structures, and more, is vital to the design process. To effectively use all of this knowledge, it is often stored and categorized in so-called ”knowledge databases”.

Knowledge-based engineering (KBE) tools use knowledge databases as a central piece to automate an aircraft’s design cycle. It isn’t uncommon for aircraft manufacturers and research institutes to have their own KBE tools that are based on their knowledge databases. Some examples include NASA’s Flight Optimization System (FLOPS), Dassault Systems ICAD, and Technosoft Adaptive Modeling Language (AML) [40].

The German Aerospace Center (DLR) also developed a tool called *OpenAD*. OpenAD is a multidisciplinary iterative aircraft design environment capable of evaluating and assessing various aircraft concepts and technologies [41]. A user can provide the tool with an input file that houses a set of Top-Level Aircraft Requirements (TLARs), configurational decisions, and other settings, which are then used to compute aircraft geometry, aerodynamic performance, and more [41]. The input and output files are formatted using the Common Parametric Aircraft Configuration Schema (CPACS) [42]. The structure of OpenAD is shown in Figure 3.13 and some various aircraft configurations generated by OpenAD in the past are shown in Figure 3.14. Such tools provide a great way to come up with accurate descriptions of conceptual aircraft designs rapidly.

3.4.3. System of Systems and System of Systems Engineering

Airlift systems require the coordination of multiple subsystems to achieve the overall objective of the airlift mission: the delivery of a vast amount of cargo within a specified deadline. System of Systems Engineering (SoSE) is an approach that can address such complex systems by not viewing each system as its isolated entity, but rather as a system that is part of a broader, interconnected network of systems known as a System of Systems (SoS).

The principles of SoSE are particularly relevant to airlift missions as these missions involve a variety of different, independent systems such as various aircraft types, ground equipment, airbases, and cargo, which all work together to achieve the common goal: deliver cargo to the area of need as fast as possible. The dynamics of this interconnected network are therefore of interest and must be optimized to ensure the

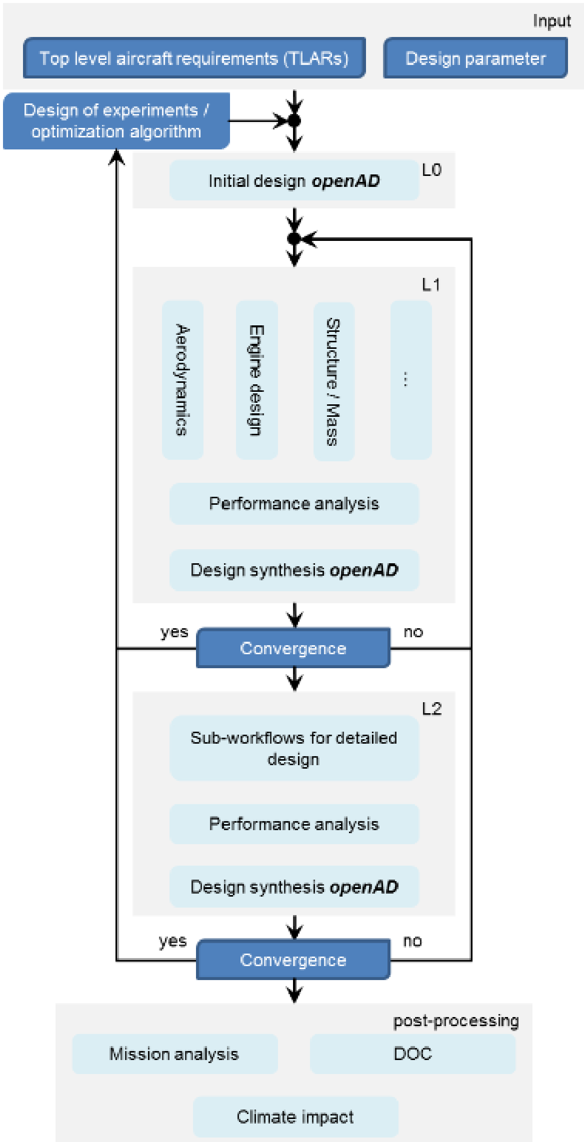


Figure 3.13: Flow diagram of OpenAD [41]

success of the airlift mission and can additionally be used to drive aircraft design requirements. NATO defines SoS and SoSE as:

System of Systems is a "set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities" [45]

System of Systems Engineering is "the process of planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into a system-of-systems capability that is greater than the sum of the capabilities of the constituent parts" [45]

Additionally, according to the "Architecting System of Systems" paper by Maier [46], one of the pioneers of SoSE, a SoS has five characteristics:

1. Operational Independence: Systems in a SoS operate independently
2. Managerial Independence: Systems in a SoS are managed independently
3. Geographical Distribution: Systems in a SoS are geographically distributed
4. Evolutionary Development Process: a SoS evolves incrementally

Figure 3.14: Various aircraft geometries generated by OpenAD [41, 43, 44]

5. Emergent Behaviors

Here, emergent behaviors are defined as:

> *"Emergent system behavior can be viewed as a consequence of the interactions and relationships between system elements rather than the behavior of individual elements. It emerges from a combination of the behavior and properties of the system elements and the systems structure or allowable interactions between the elements, and may be triggered or influenced by a stimulus from the systems environment"* [45]

The first two of the five characteristics defining a SoS are primary, while the others can be seen as secondary. All the primary characteristics and some secondary ones are met in terms of airlift scenarios. For instance, operational and managerial independence nd geographical distribution is clear as within a logistic network all airlift platforms which make up the heterogeneous fleet of airlifters work independently, make their own decisions, and are located at different locations.

An example of emergent behaviors and their importance for aircraft and fleet design have been demonstrated in a prior report [47]. The report identified that a small airlift network delivers the cargo the fastest, not by taking the route that minimizes the arrival time of the cargo, but instead of taking the route that is most fuel-efficient, as this results into aircraft flying shorter legs and thereby can carry more cargo per leg which in the broader network results in a reduction in delivery time. This is just a simple example showing that such emergent behaviors are essential in the context of transport networks, as the performance of a single system only matters when it also synergizes with the performance and capabilities of the broader network. For this reason, using measures of effectiveness over measures of performance is preferred to quantify how well a network performs given a goal. Furthermore, this can be helpful when identifying the set of optimal requirements of new systems that would be introduced in the broader network, such as a new aircraft type.

Mavris D. of Georgia Institute of Technology is also involved in this domain, a series of papers discussing the development of various systems that make up an overall SoS environment have been published by him and his team, the most recent of which simulates the disaster relief efforts during the 2016 Cyclone ”Winston” [48], this scenario is shown in Figure 3.15. Here, strategic airlifters bring supplies, personnel, and assessment UAVs to a forward operating base. After arrival, the UAVs are assembled and deployed to assess the damage done by the cyclone and estimate the impacted population and the cargo they need [48]. Airlifts are then performed to deliver relief supplies to the most severely impacted regions first. After five days, the maritime assets that carry additional supplies arrive. This research looks at the evaluation of various compositions of air fleets to investigate what maximizes their measures of effectiveness, which include the rate of deliveries and the amount of days to deliver 10,000 packages [48].

Another example is shown in the paper by N. Kalliatakis [49], which uses an agent-based simulation environment to simulate the movement of supplies to a large group of people during a disaster relief

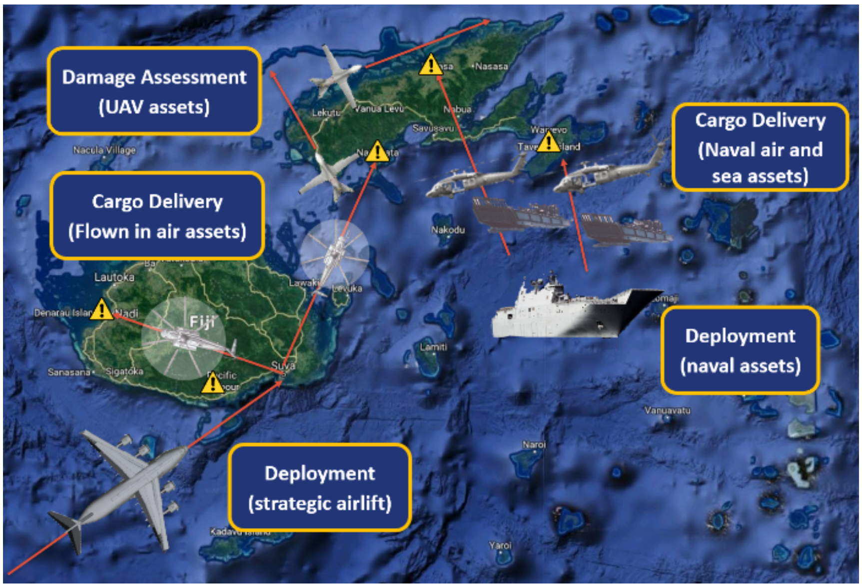


Figure 3.15: Humanitarian aid and disaster relief response to tropical cyclone Winston in 2016 [48]

mission. The paper utilizes measures of effectiveness such as mission success rate, total mission cost, and mission completion time to identify which factors, such as design range and payload of an aircraft system, are of interest to an airlift platform. The paper identified that smaller design ranges and payloads are preferred to achieve optimal designs, a surprising result.

A final example is the research of V. Nugnes [50], which used the aforementioned aircraft design tool OpenAD and linked it to an ABMS environment to investigate how the optimal seaplane design looked like such that it would be a competitive alternative mode of transport to the existing fleet of ferries to transport passengers on the Greek islands. SoSE and measures of effectiveness allowed an MDO tool to optimize an aircraft design so that the measures of effectiveness were maximized. A flow diagram of this process is shown in Figure 3.16.

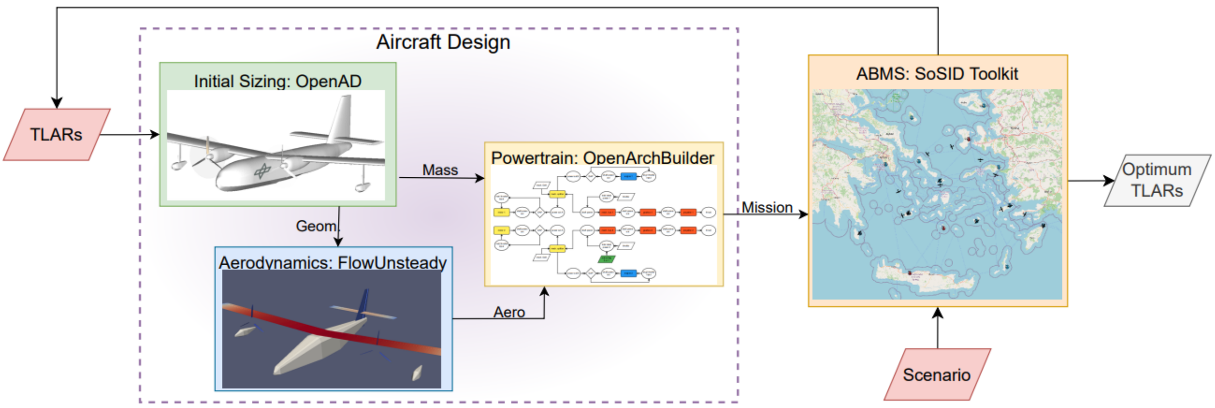


Figure 3.16: System of Systems aircraft design framework flowchart [50]

SoSE provides a great way to investigate and determine requirements for fleets and aircraft that have to work in a complex network of other systems.

3.5. Problem statement

In summary of this literature review: Past studies have shown that European countries suffered from a critical airlift capability gap during the past few decades. Over the past decades, the Europeans have steadily closed the gap, mainly by the collective purchase of a large fleet of Airbus A400M aircraft. The literature review however showed that in 2024, the gap remains to exist at smaller scale and is mainly characterized by the ability to transport heavy and outsized equipment such as the cargo needed by the NRF.

Some limitations in prior studies have been identified that could affect the accuracy of their results. For instance, all publicly available studies ignore the effect of aircraft ”bulking out”, meaning that the constraining cargo hold dimensions of airlifters are not considered during simulation. This results in unrealistic scenarios where aircraft can charter much more cargo per flight as would be possible in reality. An example was given using the A400M chartering NH90 helicopters: The A400M, with its carrying capability of 37 tons, can charter around 5 of these helicopters when one only looks at the mass of the cargo. However, When taking into account that the A400M’s cargo hold is only 17.7m long, this drops to the aircraft being able to charter only a single NH90 in reality. Thus, simulations would be affected by having significantly more flights, which in turn reduces the airlift capacity of a fleet of airlifters and thus the resulting fleet requirements are underestimated. The effect of such a constraint remains unknown.

Secondly, it is clear that Europeans are looking for solutions to close the remaining capability gap. For instance, they have launched the SATOC project, which seeks to develop a new airlift capable of transporting heavy, outsized cargo. However, it is unclear what the requirements for such a new aircraft should be. Consider also that such a new aircraft has to work alongside the A400M and C-17, which make up Europe’s future airlift fleet. This makes defining requirements even more difficult. The literature review showed that System of Systems Engineering is a useful tool for precisely this purpose. Therefore, the SoS analogy can be used to investigate the effects that top-level aircraft requirements (TLARs) have on the performance of the airlift network when a new aircraft with those TLARs is integrated into the existing heterogeneous fleet of airlifters.

3.5.1. Research Question

Given the problem description, this study seeks to address critical gaps in understanding strategic airlift capabilities, specifically by focusing on the impact of volume constraints and the requirements for new aircraft to be introduced into the existing fleets. Two research questions are posed:

”How does the inclusion of volume constraints impact the strategic airlift capacity during rapid reaction scenarios?”

”What are key aircraft requirements for a new strategic outsized cargo airlifter to meet the requirements of rapid deployment scenarios and to work effectively in the existing fleet?”

3.6. Research Plan

To answer the two established research questions, a parametric KBE aircraft design tool and a mission analysis tool that utilizes the agent-based simulation concept will be used. The KBE tool of choice is the OpenAD tool of the German Aerospace Center, a tool that has been used many times before to generate passenger transport aircraft and other configurations. The tool has never been used to generate airlifters, however, and therefore requires modifications. The main modifications of interest were established in Section 3.4.1 and relate to the fuselage, landing gear, overall structure, and the onboard systems. These differences between strategic airlifters and commercial transporters can cause an increase in component masses, different center of gravity locations and additional drag.

The future European fleet of strategic airlifter is composed of both the A400M and C-17. Previously, a model of the A400M was already built, therefore OpenAD will be used in this study to recreate the C-17 as this aircraft provides excellent outsized cargo capabilities and the ability for STOL which can both be important for airlift scenarios. Furthermore, the aircraft provides a good middle ground in airlifter size as in terms of its capabilities it lies between the A400M and larger C-5. Furthermore, considering that one of the posed research questions seeks to study the effects of changes in TLARs on the effectiveness of the airlifter in an airlift mission, the model must be parametric. To build the model, a database of information is to be gathered about the geometry, performance and other specifications of the aircraft. The TLARs of the aircraft can be inputted into OpenAD, and the geometry can initially be fixed. Constraints can then slowly be lessened so that component masses can be calibrated based on the obtained database. Furthermore, aerodynamic and performance metrics can be calibrated such that the model produces a good fit with the aircraft reference payload-range diagram, which in terms of the simulation is the most essential aspect of the airlifter. When a good fit is obtained, geometrical constraints can be removed after which OpenAD can generate the geometry and other data on purely the TLARs and configurational inputs. Thus, new TLARs can be specified, after which OpenAD can generate an offspring design, which can then be simulated in the fleet of airlifters to assess how the new fleet performs the airlift scenarios.

For the mission analysis part, the German Aerospace Center's System of Systems Inverse Design Toolkit ”SoSID”, or ”toolkit” in short, will be used as it is an agent-based model written in the Python programming language. As previously mentioned in Section 3.4.3, this tool has been modified to simulate humanitarian aid and disaster relief scenarios. While military missions are different from humanitarian ones, the main differences are related to scale, and therefore, this tool serves as a good baseline. Some modifications could be required to improve accuracy, for example regarding various loading and unloading times dependent on cargo types. A set of realistic yet demanding scenarios that capture the main elements of a logistics network must be set up. This way, results would reflect fleet and aircraft requirements that can handle realistic future demands. Furthermore, it is essential to set up a list of cargo and detail the cargo as much as possible, considering the effects of a volume constraint are to be included in the analysis. Finally, for this exact reason, the mission analysis tool must be adapted to include a good algorithm that captures the cargo hold dimension constraint well.

System of systems are important in order to draw final conclusion about aircraft and fleet requirements, and therefore, measures of effectiveness are to be used to quantify how capable a given fleet is at performing a given scenario.

Part III

Supporting Work

4 Strategic airlifter modeling using OpenAD

The iterative aircraft design tool OpenAD was utilized to model the aircraft in the European strategic airlift fleet. Although a model of the A400M had previously been developed by Schmitz [51], a model of the C-17 Globemaster III was yet to be available. Therefore, such a C-17 model had to be created, and is to serve two purposes: it represents the aircraft in the European fleet and, therefore, needs to be as realistic as it can be to model this existing aircraft. Secondly, it provides a baseline model from which derivative designs can be generated by adjusting the TLARs that are input, therefore it needs to be parametric.

The existing A400M model created by Schmitz [51] is only partially parametric, limiting its capacity to produce derivative designs and generate geometries. Moreover, this model has been shown to have difficulties with accurately predicting payload-range diagram of airlifters. Considering that the payload-range diagram is critical for the agent-based simulation of the aircraft and imposes performance limitations that affect the airlift capacity, a model with an improved ability to predict payload-range diagrams is required. Schmitz's model also utilized a knowledge base built around commercial transport aircraft, with some component mass and aerodynamic estimations driven by the number of passengers specified in the input file. This passenger-centric knowledge base needs to be aligned with the requirements for strategic airlifters as these aircraft are built around the cargo instead. Finally, the model is tuned for turboprop-driven aircraft, while all existing heavy strategic airlifters are built around turbojets instead.

To address these issues and further increase the fidelity of OpenAD, the knowledge base was adapted to include design considerations for strategic airlifters. These changes are discussed in Section 4.1. The calibration process of the model is furthermore discussed in Section 4.2

4.1. Adaptations made to the knowledge base

This section will review the adaptations that were made to the knowledge base of OpenAD to align it with the design considerations required by strategic airlifters. The adapted components are discussed below:

4.1.1. Fuselage

The first notable difference between a strategic airlifter and a commercial aircraft is the fuselage. The function of the fuselage is not only to be spacious, which allows for the transport of large vehicles and helicopters, but also to make sure loading and unloading of the aircraft can be done as fast as possible to minimize turnaround time. To do so, these airlifters include a cargo ramp at the back of the fuselage, allowing for "drive-on, drive-off" capabilities such that loading of vehicles, for instance, can be done as fast as possible. However, this comes with drawbacks as the inclusion of such a cargo ramp creates a cutout in the fuselage structure that weakens the structure. Therefore, the structure has to be reinforced in specific area's causing the structural weight of the fuselage to increase. Additionally, the ramp causes the aft fuselage to be flattened and swept up, which increases the drag due to flow separation due to the large upsweep angles.

To minimize the turnaround time, the cargo hold floor is lowered as much as possible. One effective way of doing so is by choosing a high-wing configuration, allowing for the whole fuselage to be closer to the floor. However, this means that the landing gear should be fuselage-mounted also so as to minimize weight. If the landing gear were stored inside of the fuselage, however, this would minimize the usable cargo hold volume and restrict the dimensions of the cargo that is able to be loaded into the hold. Thus, to mitigate this drawback, the landing gear is mounted in belly-mounted wheel fairings. Once again, this does not come without drawbacks; while it solves the issue of limiting the cargo hold dimensions, the wheel fairing causes an increase in both fuselage structural weight as well as the produced drag.

Raymer [35] provides Equation (4.1) to compute the fuselage mass for a cargo transport aircraft. This equation is included in the knowledge base because it includes both a penalty for having an aft cargo door through the $K_{door,aft}$ parameter, and a penalty for having fuselage-mounted main landing gears K_{lg}.

$$m_{fus} = 0.328 K_{door,aft} K_{lg} (W_{dg} N_z)^{0.5} L^{0.25} S_f^{0.302} (1 + K_{ws})^{0.04} (L/D)^{0.1} \quad \text{[lbs]} \quad (4.1)$$

The knowledge base of openAD is already capable of computing the drag increases due to the belly fairing; it does not include the drag increase due to the large aft fuselage upsweep angle, however. To account for the fuselage upsweep drag, use is made of Equation (4.2) provided by Kundu [52]. This equation allows to compute the form factor increase produced by the upsweep angle Φ. This delta can be added to the overall form factor of the fuselage, which openAD then uses to compute the drag of the fuselage.

$$\Delta C_{FF_{upsweep}} = 1 + (0.0422\Phi^2 + 0.373\Phi - 0.051)/100 \quad \text{[-]} \quad (4.2)$$

In addition to the structural weight and drag, the fuselage differs from commercial aircraft in terms of the way it is sized. While the cargo hold of a commercial aircraft is built around standardized crates with an additional passenger housing area, the cargo hold of a strategic airlifter usually joins both compartments into one and is built around the cargo itself. The cargo can include both palletized and non-palletized items such as vehicles and helicopters. The outer wall of the cargo hold is often equipped with foldable seats to facilitate the transport of troops. Large strategic airlifters additionally include the ability for cargo to be loaded in a double-file configuration where vehicles, for instance, are placed side-by-side. Therefore such a capability has to be kept in mind.

OpenAD was adapted such that a list of cargo, their dimensions, quantities, and whether or not the cargo is able to be loaded in a double-file configuration, can be input from which the cargo hold dimensions can then be computed. Tavernetti [7] provides the cargo that was used to size the cargo hold of the C-17, the same cargo was then used as an input into OpenAD also to size the fuselage of the C-17 model. Given this information, the required minimum length of the cargo hold can be computed using Equation (4.3).

$$L_{hold} = (n_{cargo_i} + 1) t_{clearance} + \frac{n_{cargo_i}}{n_{files_i}} L_{cargo_i} \mid \text{for the cargo item which maximizes} \frac{n_{cargo}}{n_{file}} L_{cargo} \quad (4.3)$$

Additionally, the width of the cargo hold floor can be computed using Equation (4.4). Obtaining the cargo hold width and height is more tricky, however. The cargo hold must encapsulate the entire set of cargo, and the required floor width must fit within the hold. A set of points K can be setup that includes the points defining the bounding box of the cargo offset by a clearance width and height, as well as a set of points that span the cargo hold floor. The minimum area ellipse that en-capsules this set of points K, known as the outer Löwner-John ellipse, can then be computed to obtain the dimensions of said ellipse using an algorithm described by Todd and Yildirim [53]. Then, the ellipse's major axis describes the width of the cargo hold whilst the minor axis describes the height of the cargo hold. Additionally, the center point of the ellipse can be used to obtain the z-offset of the cargo hold floor. Finally, to obtain the outer dimensions of the fuselage, the structural depth has to be considered. Equation (4.5) [54] can be used to compute the structural depth; here, it is assumed D_{inner} is the average of the cargo hold width and height. The illustration in Figure 4.1 shows the process described above, the red crosses indicate the set of points K.

$$w_{floor} = MAX(w_{cargo} n_{files} + (1 + n_{files}) t_{clearance}) + 2 w_{seat} \quad (4.4)$$

$$D_{outer} = 1.045 D_{inner} + 0.084 \quad \text{[m]} \quad (4.5)$$

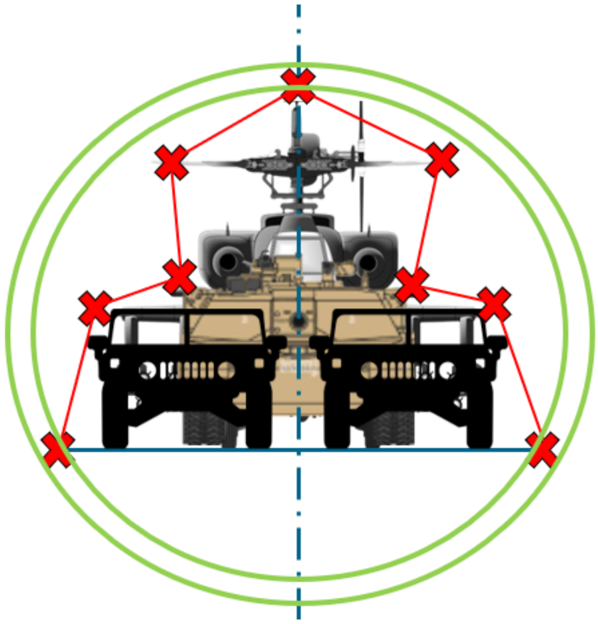


Figure 4.1: Example of cargo hold cross section calculation using a list of cargo. Red crosses indicate the points used to compute the outer Löwner-John ellipse

4.1.2. Landing gear

It was already touched upon that the landing gear is often stored inside of a fuselage-mounted fairing due to the high-wing configuration and the fact that the cargo hold needs to be as open as possible. However, besides these remarks, the landing gear differs in its capabilities and function. Most strategic airlifters, such as the C-17, C-5, and A400M, include the capability of short take-off and landing (STOL). This capability requires the landing gear to be structurally strong as the impact loads for this ability can be. For instance, the landing gear of the C-17 is designed for sink speeds of 15 ft/s [7], which is large compared to the sink speed of commercial transporters of 4-5 ft/s [35]. Furthermore, the landing gear must be designed for landings on unprepared airfields. This requires the landing gear to have rough field and high flotation capabilities, both of which cause an increase in the structural weight and complexity of the landing gear. This is because, for landing gears that are able to land on rough fields, there is not a single suspension and shock absorber but multiple to allow all tires to move independently. Furthermore, landing gears capable of high flotation need more tires as to spread the load over a larger area to avoid sinking into soft ground.

In his book [39], Currey describes all these features and more specialized capabilities such as kneeling and crosswind coupling. However, proposed methods that include weight increases due to these capabilities do not distinguish between the nose and main landing gear. Therefore, the equations provided by Raymer [35] were used instead.

Equations (4.6) and (4.7) provide a way to compute the mass of the main and nose landing gears for cargo transport aircraft. Here, K_{mp} and K_{np} allow the inclusion of the effect of kneeling landing gear, an ability the C-17 does not have: hence, this is assumed to be equal to one. N_l is the ultimate landing load factor, which include the effect of the increased landing loads. This value is assumed to equal a relatively high value of 7.5 as this is close to the loads used for carrier-based navy aircraft, which are relatively close in terms of sink speed relative to STOL-capable airlifters. Additionally, L_m and L_n include the effects of the reduced lengths of the landing gear considering they are close to the ground as they are fuselage-mounted. Finally, N_{mss}, N_{mw}, and N_{nw} are the amount of shock struts and wheels, which, therefore, account for the effects of having high flotation and rough field capable landing gear.

$$m_{MLG} = 0.0106 K_{mp} W_l^{0.888} N_l^{0.25} L_m^{0.4} N_{mw}^{0.321} N_{mss}^{-0.5} V_{stall}^{0.1} \quad \text{[lbs]} \quad (4.6)$$

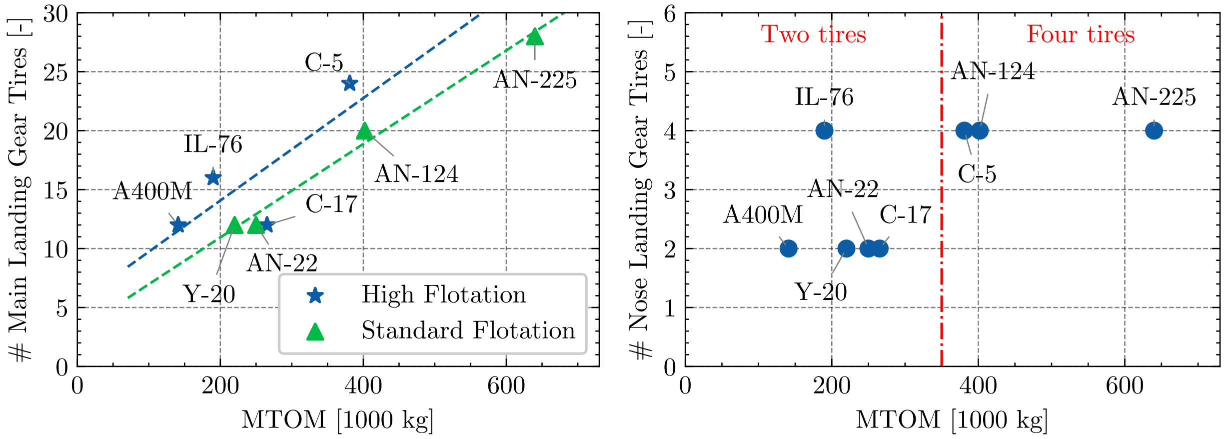
$$m_{NLG} = 0.032 K_{np} W_l^{0.646} N_l^{0.2} L_n^{0.5} N_{nw}^{0.45} \quad \text{[lbs]} \quad (4.7)$$

The number of nose gear wheels N_{nw} and main landing gear wheels N_{mw} depend on the landing gear's high flotation requirement. Figure 4.2 shows the relationships used to take into account this requirement. For the main landing gear, a categorical linear regression is used to acquire the number of main landing gear wheels relative to the MTOM of the aircraft as shown in Equation (4.8), while for the nose landing gear, the rule shown in Equation (4.9) is used which follows from the relation between number of nose gear wheels and MTOM. Finally, the number of shock struts N_{mss} is assumed to follow Equation (4.10). The relation follows from the fact that the C-17 has one shock strut per 3 main gear tires.

$$N_{mw} = \begin{cases} 2\lfloor\frac{4e^{-5}MTOM+5.7029}{2}\rceil, & \text{if high flotation gear} \\ 2\lfloor\frac{4e^{-5}MTOM+3.0124}{2}\rceil, & \text{otherwise} \end{cases} \quad \text{[-]} \quad (4.8)$$

$$N_{nw} = \begin{cases} 2, & \text{if } MTOM \leq 340,000kg \\ 4, & \text{otherwise} \end{cases} \quad \text{[-]} \quad (4.9)$$

$$N_{mss} = \lceil\frac{N_{mw}}{3}\rceil \quad \text{[-]} \quad (4.10)$$



(a) A categorical linear regression to obtain the number of main gear tires

(b) Nose landing gear

Figure 4.2: Relationships between the number of wheels versus the MTOM

With the increased mass of the landing gear accounted for, its positioning is the final difference related to the landing gear. For a strategic airlifter, the landing gear must be positioned so that the aircraft does not tip over when the most aft center of gravity is reached. Unlike commercial aircraft, however, this aft center of gravity location is not the same aft location used to position the wing because consideration has to be made that during the loading of heavy equipment, which can weigh up to roughly 65 tons, the center of gravity shifts quite far aft but does not remain in this location as the cargo is loaded such that the final center of gravity of the loaded aircraft remains near the center of gravity at OEM. Thus, this aft location of the center of gravity only matters for the landing gear location, not the wing location. It was accounted for by placing a 65-ton point mass at the most rear cargo hold location when computing the lengthwise location of the cargo hold.

4.1.3. Engine

The engines used in military strategic airlifters are usually derivatives of engines designed for civilian transport use, which is especially true for jet engines. For instance, the C-5M galaxy uses the F138-GE-100 engine, which is also used by many civilian transporter aircraft such as Boeing 747 and Airbus A330. The most significant difference is that the military engines have different requirements, such as, for instance, landing in sandy terrain. Therefore, these engines mass is slightly different from those developed for commercial use cases. OpenAD computed the mass of the engine core using a linear regression that relates the engine core mass with the produced thrust retrieved from a database of civilian engines. This regression was adapted by changing to engines in the database with engines used in military transporters, tanker and surveillance aircraft instead[1]. The newly obtained regression is shown in Figure 4.3, and the engine mass can be computed using Equation (4.11).

$$m_{gasturbine} = (0.0689T_{ISA} + 406.19)n_{engines} \quad \text{[kg]} \quad (4.11)$$

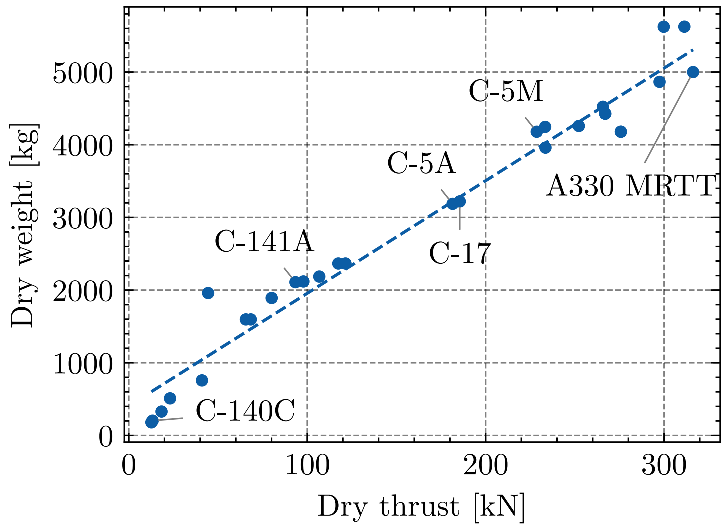


Figure 4.3: Linear regression relating gas turbine mass to produced thrust

4.1.4. Empennage

The knowledge base of openAD was adapted by changing the mass calculations of the empennage. Strategic airlifters almost always use a T-tail configuration with very few exceptions. This is because these aircraft often have the STOL requirement, which requires them to have large high lift devices, which can cause significant downwash on the tail. This can be mitigated by using a T-tail. Additionally, due to the inclusion of the aft cargo ramp in the fuselage, there is limited room to include the structure of a conventional horizontal tail. The knowledge base was adapted to include methods that account for the load factor and tail leverage arms. For the horizontal tailplane (htp), Equation (4.12) [35] is used, while for the vertical tailplane, Equation (4.13) [35] is used.

$$\begin{aligned} m_{htp} = {} & 0.0379K_{uht}(1 + F_w/B_h)^{-0.25}W_{dg}^{0.639}N_z^{0.1}S_{ht}^{0.75} \\ & \times \frac{1}{L_t}K_y^{0.704}\frac{1}{\cos(\phi_{25})}A_h^{0.166}(1 + S_e/S_{ht})^{0.1} \end{aligned} \quad \text{[lbs]} \quad (4.12)$$

$$\begin{aligned} m_{vtp} = {} & 0.0026(1 + \eta_{VTP})^{0.225}W_{dg}^{0.556}N_z^{0.536}L_t^{-0.5} \\ & \times S_{vt}^{0.5}K_z^{0.875}(cos(\Lambda_{vtp,0.25}))^{-1}AR_{vtp}^{0.35}(\frac{t}{c})_{vtp,root}^{-0.5} \end{aligned} \quad \text{[lbs]} \quad (4.13)$$

4.1.5. Systems

Finally, an airlifters systems are mostly the same as commercial aircraft. The only exception is the inclusion of a Counter Measures Dispenser System (CMDS) capable of launching flares and chaff. This system's masses have been based on publicly available data on the AN/ALE-47 CMDS unit. Equation (4.14) and (4.15) are used. It is assumed that the aircraft carries 120 flares and chaff and that one AN/ALE-47 unit holds 30 units of flare or chaff.

[1] The engine data was obtained from www.jet-engine.net

$$m_{chaff} = 2.27n_{dispenser} + 0.135n_{chaff} \quad \text{[kg]} \quad (4.14)$$

$$m_{flares} = 2.27n_{dispensers} + 0.37n_{flare} \quad \text{[kg]} \quad (4.15)$$

Additionally, most strategic airlifters use an APU. However, due to the inclusion of the aft cargo ramp, the APU cannot be located at the rear of the fuselage. Therefore, the APU often located in the landing gear fairing. The knowledge base was adapted to reflect this difference.

4.2. Calibration

In addition to changes in component properties, the new model is calibrated towards the C-17. For this purpose, a database of requirements, measurements, TLARs, and a list of to-be-chartered cargo was built and input into OpenAD. The calibration process aimed to match the generated geometries, structural component masses, and performance parameters of the aircraft. The process emphasized gaining a good fit for the payload range diagram. The calibration is done by adding a multiplication factor to the outcome of certain modules at every iteration. The process is shown in Figure 4.4.

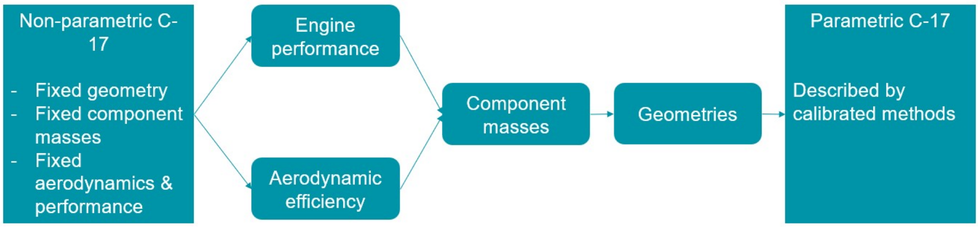


Figure 4.4: Calibration process [51]

First, the geometries of the aircraft were fixed. Given the payload-range diagram, the engine efficiency, aerodynamic factors, and fuel tank volumes could be calibrated by adding a factor to the engine's overall efficiency factor and one to the overall drag calculation. The payload-range diagram is the only publicly available information on the performance of the C-17, it is therefore not possible to compare final performance metrics such as drag coefficient and engine efficiency to the real aircraft. However, in the end, only a -1% adjustment was required for the drag computation. An larger adjustment factor of -17% was used on the engine efficiency computation which resulted in an efficiency of around 40% for the C-17's engines. The engine model is based on a generic engine model developed for OpenAD. This model requires the bypass ratio, overall pressure ratio, and turbine inlet temperature as input. Finally, the fuel tank volume computations are adjusted by a factor of 1.15 to obtain a near perfect fit with the reference payload-range diagram.

Afterwards, the component masses were calibrated to obtain a good fit for the aircraft's operative empty mass (OEM). No reference values for the fuselage and systems mass were obtained, so these components ended up receiving the largest calibrations factors. Using the reference mission shown in Figure 4.5 obtained from MIL-STD 3013B [55], the maximum take-off mass (MTOM) followed and fit well.

Finally, the geometry was unfixed and calibrated to fit the measurements from the database. In the end, the geometry is fully described by methods in the knowledge base and only requires top-level configurational and planform input such as the aspect ratios, taper ratios, thickness to chord ratios, dihedral angles, and inclination angles. For the horizontal and vertical tailplane, the reference areas were tuned using the volume coefficients of the respective wing. With the calibration process over, a parametric model of the C-17 is obtained.

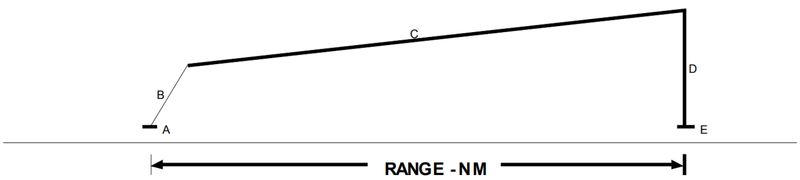


Figure 4.5: Mission profile for a cargo transport mission, adopted from MIL-STD 3013B [55]

5
The C-17 Model & Validation

This chapter will discuss the obtained C-17 model and its validation. To validate the C-17 parametric model and the models ability to predict the performance of other airlifters, the new model is compared with the old model made by Schmitz [51] using reference data for both the C-17 and C-5A aircraft. As mentioned before, this old model is only partially parametric; therefore, the fuselage and wing geometry had to be fixed. The TLARs input for both aircraft are provided in Table 5.1.

Table 5.1: TLARs used to obtain the models for the C-17 and C-5A

Parameter	C-17	C-5A
Take-off field length [m]	2,359	2530
Landing field length [m]	1,066	1,500
Design payload [kg]	60,000	96,500
Design range [km]	6,900	6,900
Cruise Mach number [-]	0.75	0.75

Furthermore, Table 5.2 shows the computed wing loading and thrust loading, as well as the reference value for both aircraft. Due to the fixed geometry provided to the old model, both aircraft obtain a relatively large wing loading. Additionally, the thrust loading computed by the old model is larger than the reference for the C-5.

Table 5.2: Old and new model computed constraints compared with eachother

	C-17			C-5A		
Parameter	Old model	New model	Reference	Old model	New model	Reference
W/S	816.5	753.5	751.9	803.8	687.0	661.5
T/W	0.29	0.29	0.28	0.33	0.28	0.27

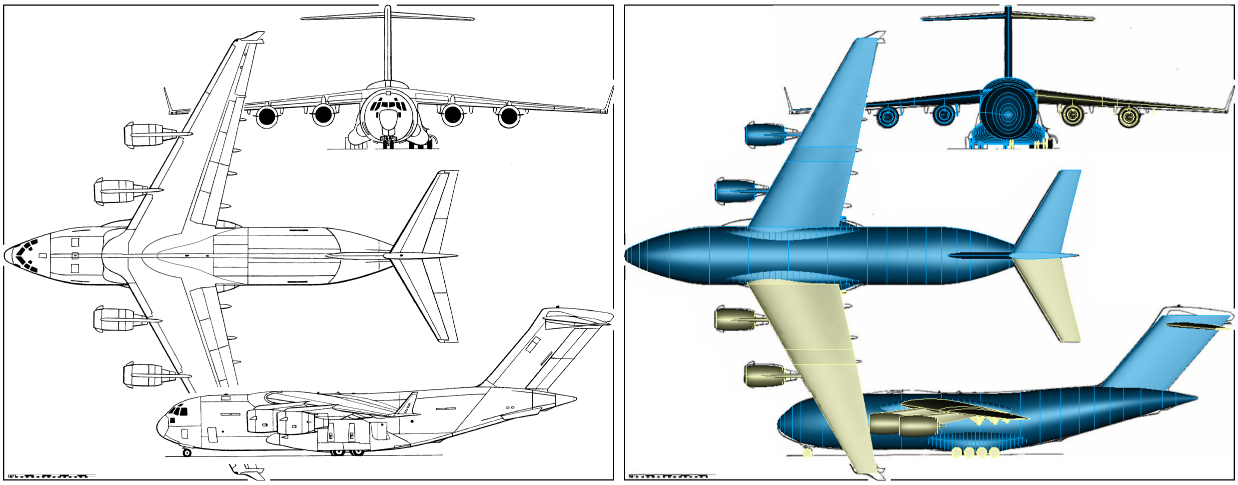
5.1. Geometry

To validate the geometry of the C-17, the final geometry computed by the new model is over-layed with a three-view reference image as shown in Figure 5.1.

5.2. Mass breakdown & comparison

The breakdown of the OEM and the MTOM for both aircraft and models is given in Table 5.3. When comparing the old and new models using the C-17 reference, the old model underestimates the OEM and

[1] www.skybrary.aero



(a) C-17 three-point reference view[1]

(b) C-17 OpenAD geometry over-layed onto reference geometry

Figure 5.1: C-17 geometry compared to reference geometry

overestimates the MTOM. The underestimation of the empty mass is expected because this model used the knowledge base for commercial transporters, which, therefore, does not include all the component mass increases seen in strategic airlifters. Thus, the fuselage and landing gear mass are lighter on the old model, but this decrease in component masses is offset by the increase in furnishing mass, which largely depends on the number of passengers.

For the C-5A, a different trend is seen. Here, the old model estimates the OEM slightly larger than the new model, but both are off by a couple percent relative to the reference value. Regarding MTOM, the old model vastly overestimates the mass while the new model is off by roughly 4% thereby significantly improving the accuracy.

Furthermore, the reason that the old model estimates the OEM relatively close to the estimate of the new model is for all the wrong reasons. For instance, the new model is very good at predicting the landing gear mass and engine assembly mass, while the old model significantly underestimates this mass. Again, the old model, furthermore, significantly overestimates the furnishing mass which has a compensating effect.

When it comes to the old models ability to estimate the MTOM, for both aircraft they are significantly overestimated. The main reason is the fact that the mission fuel mass is very much greater, indicating that the engine efficiency is underestimated and the aerodynamic drag is overestimated. This is an artifact of the calibration process by Schmitz, keeping in mind that the model was calibrated for the A400M, which is driven by turboprops.

5.3. Drag breakdown

The computed drag of all components for both aircraft and models is given in Figure 5.2. For both aircraft, the computed total drag of the old model is significantly larger than that of the new model. The lift-induced component of drag differs the most. This is due to the substantially larger estimated MTOM as is computed by the old model - shown in Table 5.3. In terms of the zero-lift drag, the largest difference is seen in the horizontal tailplane while the remaining components remain more or less the same.

Table 5.3: OpenAD old and new model component masses compared for the C-17 and C-5A inputs

	C-17			C-5A		
Component	Old model	New model	Ref.	Old model	New model	Ref.
Wing	26,778	30,846	29,572	45,591	51,162	
Total empennage	8,051	6,343	6,350	11,031	8,298	4,976
Horizontal tailplane	4,710	3,035		6,350	3,746	
Vertical tailplane	3,341	3,308		4,681	4,552	
Engine assembly	20,255	18,845		35,640	25,857	23,301
Engine core (4)	14,990	12,952	12,880	26,606	17,675	15,333
Systems	9,715	13,366		13,139	16,408	
Power distribution sys.	2,597	2,449	2,449	3,510	3,104	
Landing gear	7,992	10,551		15,785	17,614	17,276
Main gear	7,253	9,234	9,979	14,453	14,387	14,061
Nose gear	739	1,317		1,332	3,260	3,224
Fuselage	31,660	37,720		56,808	59,538	
Furnishing	7,613	3,370		14,637	5,810	3,100
Operator items	2,120	4,330		2,681	6,879	
OEM	117,210	128,290	128,418	199,780	195,230	181,437
Design payload	60,000	60,000		96,500	96,500	
Mission fuel mass	111,030	78,564		167,730	107,330	
MTOM	288,240	265,970	265,352	462,160	397,940	381,018

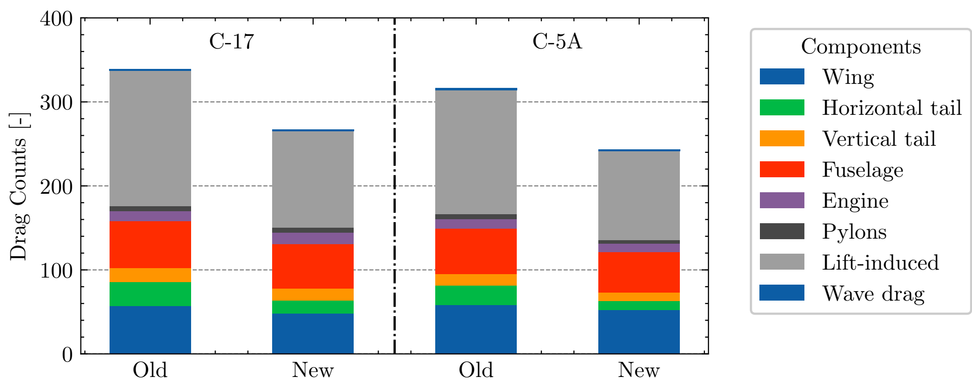


Figure 5.2: Breakdown of the drag in cruise of the C-17 and C-5A for both the old and new model

5.3.1. Impact of fuselage upsweep drag

Furthermore, the impact of including fuselage upsweep drag is not directly evident from the drag breakdown. To have a better comparison, the zero-lift drag during cruise for the complete aircraft as well as the fuselage is computed using the new model with, and without the added fuselage upsweep drag. Furthermore, the mission fuel mass required to complete the reference mission is also computed. This data is presented in Table 5.4. It is clear that the inclusion of the fuselage drag has a significant impact on the zero-lift drag of the fuselage, but also on the complete aircraft. Furthermore, the inclusion of the upsweep drag increases the mission fuel mass by about one ton; this is one ton less payload the aircraft can charter.

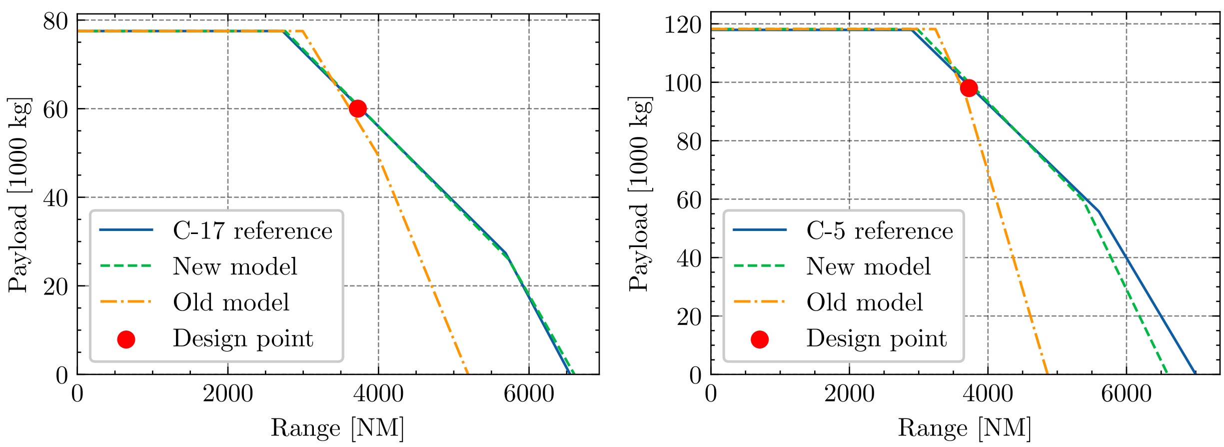
5.4. Payload-range diagrams

Finally, the payload-range diagrams of both aircraft and models can be compared. As stressed before, the payload-range diagram is the most essential information for the simulation aspect of this work; Therefore,

Table 5.4: Impact of fuselage upsweep drag

Parameter	C-17 Without upsweep drag	C-17 With upsweep drag	C-17 Diff.	C-5A Without upsweep drag	C-5A With upsweep drag	C-5A Diff.
Cruise C_{D_0} [count]	150.19	152.26	+1.38%	134.65	136.44	+1.40%
Cruise $C_{D_0,fuselage}$ [count]	51.03	52.04	+3.75%	46.75	48.62	+4.0%
Mission fuel mass [kg]	77,667	78,654	+1.15%	106,290	107,330	+0.98%

a good fit is required. The comparison is shown in Figure 5.3. The old model produces a very poor fit in terms of payload-range diagram. This deficiency was already noted by Schmitz during the development of said model [51] and was one of the main reasons why a new model was required, thus this comes as no surprise. The new model, on the other hand, produces a rather good fit for the C-5A, with the only discrepancy between the computed payload-range diagram and the reference payload-range diagram being the ferry range. Thus, indicating that the fuel tank volume estimate is too small but the overall performance such as drag and engine efficiency is captured rather well.



(a) C-17 **(b)** C-5A

Figure 5.3: Old and new OpenAD models compared based on the payload range diagrams of the C-17 and C-5

6 Agent-Based Simulation adaptations

The agent-based simulation tool previously developed by Kalliatakis N. [49] was built for humanitarian aid missions. Humanitarian mission rely mostly on the transport of palletized cargo, hence the tool does not take into account reduced ground times when handling non-palletized cargo which is the main type of transported cargo during military missions. Therefore, the tool was adapted to differentiate loading and unloading times of palletized and non-palletized cargo. The preparation times as well as the loading and unloading times of such cargo for the C-17 can be found in a RAND study [56], and is shown in Table 6.1. To compute the loading or unloading time, equations (6.1) and (6.2) are used. In these equations N_{PC} refers the amount of palletized cargo that is being loaded or unloaded, and N_{NPC} refers to the amount of non-palletized cargo being loaded or unloaded.

Table 6.1: Loading and unloading times [56]

Activity	Time [min]
Set up work	
Set up for loading work	6
Set up for working pallets	5
Set up for working rolling stock	6
Loading work	
On-load rolling stock	7.5
Off-load rolling stock	4.5
On-load pallet	2
Off-load pallet	2

$$T_{loading} = 6 + 5(if\ N_{PC} > 0) + 6(if\ N_{NPC} > 0) + 2N_{PC} + 7.5N_{NPC} \quad \text{[min]} \quad (6.1)$$

$$T_{unloading} = 6 + 5(if\ N_{PC} > 0) + 6(if\ N_{NPC} > 0) + 2N_{PC} + 4.5N_{NPC} \quad \text{[min]} \quad (6.2)$$

References

[1] Katia Vlachos-Dengler, “Carry That Weight: Improving European Strategic Airlift Capabilities,” *RAND*, 2007.

[2] Michael Fricano, “The Evolution of Airlift Dcotrine and Organization,”

[3] Ian M. Brown, “Transportation and Logistics,” 2018.

[4] Jcabo Maywald, Adam Reiman, Alan Johnson, and Robert Overstreet, “The myth of strategic and tactical airlift,” *Air University*, 2017.

[5] John Leland and Kathryn Wilcoxson, “The Chronological History of the C-5 Galaxy,” 2003.

[6] Neil Smith, “A400M Grizzly: Strategic delivery to the Point of Need,” 2010.

[7] L Tavernetti, “The C-17: Modern Airlift Technology,” *American Institute of Aeronautics and Astronautics*, 1992.

[8] Daniel F. Harrington, *The Air Force Can Deliver Anything: A History of the Berlin Airlift*. USAFE Office of History, 1998.

[9] Daniel L. Haulma, “Criss in Iraq: Operation PROVIDE COMFORT,” *Air Force History and Museums Program*, 1996.

[10] Schatz, R, “Theater Airlift Lessons from Kosovo,” *United States Air University*, 2000.

[11] John E. Peters, STUART Johnson, Nora Bensahel, Timothty Liston, and Traci Williams, “European Contributions to Operation Allied Force Implications for Transatlantic Cooperation,” *RAND*, 2001.

[12] G Cecchine, F Morgan, M Wermuth, T Jackson, A Schaefer, and M Stafford, “The U.S. Military Response to the 2010 Haiti Earthquake,” *RAND*, 2013.

[13] Think Defence, “2010 Haiti Earthquake Response Logistics,” 2024, (accessed: 27.03.2024).

[14] Michael Shurkin, “France’s War in Mali: Lessons for an Expeditionary Army,” *RAND*, 2014.

[15] Yves Krattinger and Dominique de Legge, “Rapport d’information n° 673,” *LE SÉNAT*, 2014.

[16] North Atlantic Treaty Organization, “Prague Capabilities Commitment (PCC),” 2002, (accessed: 26.03.2024).

[17] North Atlantic Treaty Organisation, “NATO Response Force,” (accessed: 26.03.2024).

[18] Lee Hages, “Quantifying the European Strategic Airlift Gap,” *Air Force Institute of Technology*, 2013.

[19] European Defence Agency, “Landscaping stud for the European air transport fleet initiative - final report,” *Marshall Solutions*, 2011.

[20] North Atlantic Treaty Organization, “Strategic Airlift,” (accessed: 26.03.2024).

[21] PESCO, “Strategic Air Transport for Outsized Cargo (SATOC),” (accessed: 26.03.2024).

[22] John Brosky, “U.N. Support Mission in Afghanistan Underscores European Airlift Failings,” *Defense News*, 2002, (accessed: 26.03.2024).

[23] Aerocorner, “Antonov An-124 Ruslan,” *Defense News*, (accessed: 26.03.2024).

[24] James Hood, “NATO Strategic Airlift: Capability or Continued US Reliance?” *Air Command and Staff College*, 2009.

[25] North Atlantic Treaty Organization, “Strategic Airlift Capability (SAC),” (accessed: 26.03.2024).

[26] Council of the European Union, “European Union Military Committee Working Group (EUMCWG),” (accessed: 27.03.2024).

[27] Alain De Neve, “No Future for European Military Technology?,” 2004.

[28] Massai Carlo, “Deploying the NRF: Meeting the Airlift Challenge,” *JAPCC*, 2005.

[29] “Objective Force Mobility - 4-5-30,” 2007, (accessed: 26.03.2024).

[30] James P Strucker and Laura M Williams, “Analyzing the Effects of Airfield Resources on Airlift Capacity,” *RAND*, 1999.

[31] Gustav LKindstrom, “Enter the EU Battlegroups,” European Union Institute for Security Studies, 2007.

[32] Bundeswehr, “Bundeswehr website,” 2024, (accessed: 26.03.2024).

[33] Yao Xinchi, “Differences in Large Aircraft Design Between Military and Civil Perspectives,” 2023.

[34] Egbert Torenbeek, “Synthesis of Subsonic Airplane Design,” 1982.

[35] Daniel Raymer, *Aircraft Design: A Conceptual Approach*. American Institute of Aeronautics and Astronautics, 1992.

[36] Jan Roskam, “Airplane Design: Part IV. Layout Design of Landing Gear and Systems,” 1985.

[37] Chitrarth Prasad, Daniel Garmann, and Datta Gaitonde, “Edge Curvature Effects on the Wake of a Simulated Aircraft Fuselage,” *American Institute of Aeronautics and Astronautics*, 2023.

[38] Brian Smith, Patrick Yagle, and John Hooker, “Reduction of Aft Fuselage Drag on the C-130 Using Microvanes,” *American Institute of Aeronautics and Astronautics*, 2013.

[39] S. Norman Currey, *Aircraft Landing Gear Design: Principles and Practices*. American Institute of Aeronautics and Astronautics, 1988.

[40] Antoon VAN DER LAAN, “Knowledge based engineering support for aircraft component design,” *Delft University of Technology*, 2008.

[41] Sebastian Wöhler, Georgo Atanasov, Daniel Silberhorn, Benjamin Fröhler, and Thomas Zill, “PRELIMINARY AIRCAFT DESIGN WITHIN A MULTIDISCIPLINARY AND MULTIFIDELITY DESIGN ENVIRONMENT,” *German Aerospace Center (DLR)*, 2020.

[42] Marko Alder, Erwin Moerland, Jonas Jepsen, and Bjorn Nagel, “Recent Advances in establishing a Common Language for Aircraft Design with CPACS,” *Aerospace Europe Conference*, 2020.

[43] Tobias Dietl, Samuel Schnell, Prajwal Shiva Prakasha, Björn Nagel, and Olaf Brodersen, “Development of a Conceptual Design Tool for Supersonic Transport with a Variable Fidelity Interface,” *Deutscher Luft- und Raumfahrtkongress*, 2022.

[44] Benjamin Fröhler, Michael Iwanizki, and Thomas Zill, “Conceptual Design of a Blended-Wing-Body for a Short/Medium Range Mission Enhanced by High-Fidelity Aerodynamics,” *Deutsche Luft- und Raumfahrtkongress*, 2021.

[45] North Atlantic Treaty Organisation, “System of Systems Characterization and Types,” 2014.

[46] M. W. Maier, “Architecting principles for systems-of-system,” *System Engineering*, 1998.

[47] Dani Hotters, “Enhancing a System of Systems Driven Military Cargo Aircraft Design Framework,” *Delft University of Technology*, 2024.

[48] Dimitri Mavris, Yaw Tung Tan, Mika Xu, Yohan Auguste, and Michael G Balchanos, “A Parametric and Interactive Approach to Defense Acquisition Decision Making Using Disaster Relief Tabletop Exercises,” *Georgia Institute of Technology*, 2024.

[49] Nikolaos Kalliatakis, “An Agent Based Modelling and Simulation Framework to Support Strategic Cargo Airlift Evaluation,” *Delft University of Technology*, 2023.

[50] Vincenzo Nugnes, “A system of systems aircraft design framework: Demonstration using a seaplane transport network in the greek islands,” *Delft University of Technology*, 2024.

[51] Matthias Schmitz, “Conceptual Aircraft Design Methodology for Disaster Relief Operations with a Variable Fidelity Interface,” *Hamburg University of Applied Sciences*, 2023.

[52] Ajoy Kumar Kundu, *Aircraft Design*. Cambridge University Press, 2010.

[53] J Michael Todd and E alper Yildirim, “On Khachiyan’s algorithm for the computation of minimum-volume enclosing ellipsoids,” *Science Direct*, 20007.

[54] Jan Roskam, “Airplane Design: Part II. Preliminary Configuration Design and Integration of The Propulsion System,” 1985.

[55] Air Force Lift Cycle Management Center, “MIL-STD 3013B, Department of Defense Standard Practice Glossary of Defninitions, Ground Rules, and Mission Profiles to Define Air Vehicle Performance Capability,” U.S. Department of Defense, 2022.

[56] James P Strucker and Laura M Williams, “Understanding Airfield Capacity for Airlift Operations,” *RAND*, 1999.