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DESIGN AND ASSESSMENT OF STRATEGIC AIRLIFTERS FOR RAPID DEPLOYMENT & HUMANITARIAN AID

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Abstract

Strategic airlift is an essential capability for rapid global movement of cargo, especially in humanitarian aid and disaster relief operations. Despite the collective purchase of A400M aircraft to enhance airlift capacity, a capability gap remains to exist due to its limited ability in transporting heavy outsized engineering equipment essential for such missions. This study uses Knowledge-Based Engineering aircraft design tools coupled with Agent-Based simulation tools to assess a fleet's ability to deploy heavy and outsized equipment. Furthermore, the study examines the often overlooked cargo hold volume constraint and quantifies its effects on airlift capacity. Results indicate that the current and future European fleets can't meet deployment timelines, with the volume constraint significantly reducing airlift capacity by about 20% for lighter cargo. A new aircraft design with a larger cargo hold, increased cruise speed and greater design payload mass could improve efficiency and reduce the required fleet size to meet the response deadlines.

Keywords: Airlift, System of Systems, Simulation, Aircraft design, Logistics

This paper is based on the research conducted in the master's thesis at TU Delft, as referenced in [1].

1 Motivation

Strategic airlift is a key capability required for rapid deployment of cargo and to aid in humanitarian aid and disaster relief (HADR) missions. Not only are a sufficient number of platforms required, but also a diverse fleet capable of transporting the heavy and outsized engineering equipment required by such efforts. Research that studies such airlift missions, often simplifies volume constraints by expressing all cargo in Pallet Position Equivalents (PPE). While this works well for missions that have a lot of palletized cargo, when including rolling stock such as vehicles, engineering cranes, excavators and more, this method proofs too simplistic. Furthermore, the transportation of heavy and outsized equipment requires aircraft capable of chartering such cargo over strategic distances, a capability in which the European fleet remains constrained. While the introduction of the A400M has undoubtedly improved the airlift capacity since the early 2000s, concerns persists regarding the fleet's ability to transport such heavy and outsized equipment. To cover this capability gap, the European Union in recent years has invested in the Strategic Air Transport for Outsized Cargo (SATOC) project which aims to address "critical shortfall for strategic air transport for outsized cargo by developing a European solution for the transport of outsized and heavy cargo" [2], reflecting Europe's desire for a new airlift platform. Two key questions arise:

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 the existing fleet?*

Section 2 describes the methodology this research follows the answer the above posed questions. Section 3 presents and discusses the results of the work, and Section 4 draws the final conclusions.

2 Methodology

This section outlines the methodology, a top-level overview of framework used to answer the research questions is shown in Figure 1. The required steps to answer these questions are:

1. Define realistic rapid reaction and humanitarian aid scenarios.
2. Develop models of the A400M and C-17 using the iterative aircraft design tool *OpenAD*.
3. Simulate airlift scenarios using the *System of Systems Inverse Design Toolkit* (SoSiD Toolkit), an Agent-Based simulation environment.
4. Assess the performance of airlift fleets based on System of Systems (SoS) level Measures of Effectiveness (MoEs) and study the effect of volume constraints on this assessment.
5. Generate new conceptual aircraft designs by modifying the Top Level Aircraft Requirements (TLARs) in the OpenAD model of the C-17.
6. Evaluate the new design using SoS-level MoEs, to determine which TLARs are most effective within an existing fleet.

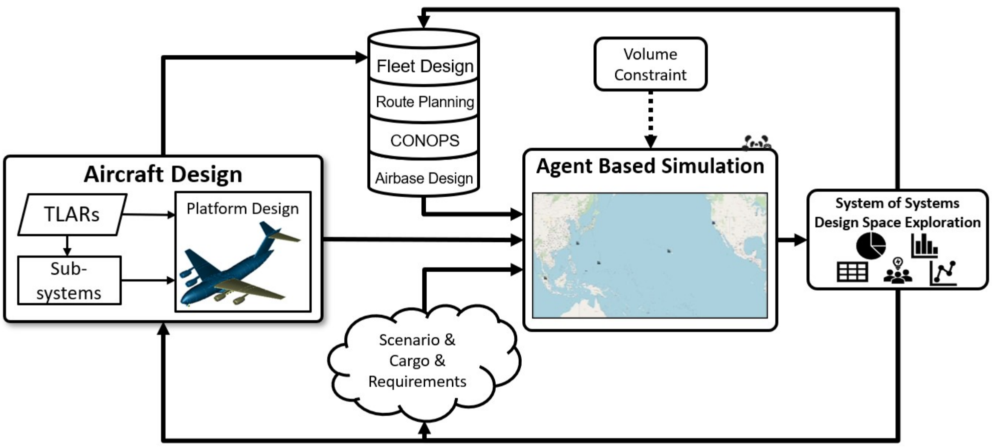


Figure 1 – System of Systems driven aircraft design framework

This above steps are further explained in detail. Section 2.1 describes the scenarios used in the simulations, followed by Section 2.2, which explains the agent-based simulation of airlift missions. Section 2.3 covers the creation and use of aircraft models and offspring designs, while Section 2.4 describes the Design of Experiments. Finally, Section 2.5 explains the setup of the Measures of Effectiveness.

2.1 Scenario description

To assess the performance of a fleet of strategic airlifters, scenarios which address the current and future European needs are required. Two scenario's, which are detailed in Section 2.1.1 and Section 2.1.2 respectively, are setup. Furthermore, the means of transportation of the cargo is discussed in Section 2.1.3.

2.1.1 Scenario A: Hurricane in the Bahamas

In this first scenario, a hurricane has severely impacted the Bahamas, requiring a rapid deployment of HADR supplies. The operation's primary objective is to deliver essential goods such as food, water, fuel and engineering vehicles, to aid in recovery efforts. To facilitate this, the European strategic airlift fleet is utilized. The palletized and rolling stock cargo is moved from Ramstein Air Base in Germany to a staging area at Fort Lauderdale, Florida. This staging area serves as a launch point for final deliveries to the Bahamas, leveraging its proximity to the region.
The logistics plan incorporates intermediate stops at major European airfields - which additionally serve as the origin points of the aircraft within the fleet - and Lajes Airfield to support refueling and maintenance, allowing for an extra intermediate stop before departing over the Atlantic if required. The deployment requires speed and therefore a 5 day delivery target is set. The scenario is visualized in Figure 2 where the blue color indicates the origin location, red indicates the intermediate stops and starting locations of the aircraft within the fleet and green indicates the destination.

Figure 2 – Scenario A: Hurricane in the Bahamas

2.1.2 Scenario B: Earthquake in Japan

The second scenario expands the parameters of the analysis by increasing both the distance and complexity of cargo requirements. Following a severe earthquake in Japan, the mission aims to deliver essential heavy equipment - such as excavators, cranes, and other-debris clearing machinery - from Ramstein Air Base in Germany to Yokota air base in Japan. Due to the large ranges involved and the logistical demands of transporting heavy, outsized, and specialized equipment, a delivery timeline of ten days is established. The scenario furthermore includes palletized cargo such as food, water and fuel. The mission is able to make use of intermediate stops at major U.S. cargo hubs in the Middle East and Singapore to manage refueling and maintenance if required. As in scenario A, the European airfields serve as starting points for the fleet of airlifters. The scenario is visualized in Figure 3 where, ones again, blue indicates the origin of the cargo, red indicates the intermediate stops and origin points of the aircraft that form the fleet, and green indicates the destination.

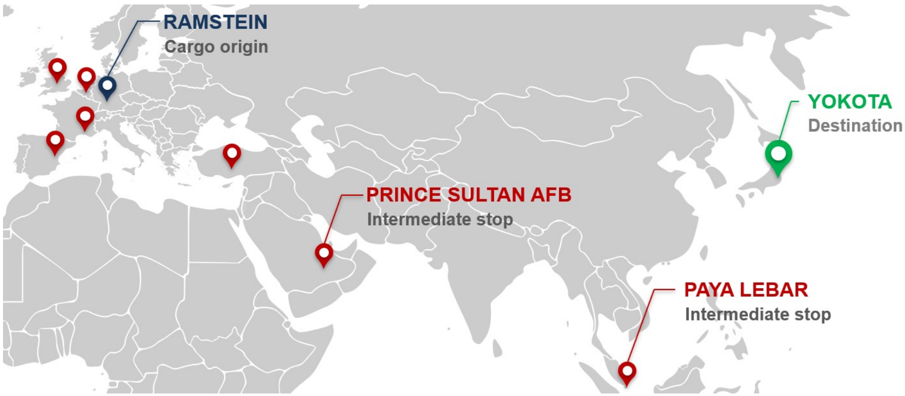


Figure 3 – Scenario B: Earthquake in Japan

Table 1 summarizes the requirements for both scenarios, with MTM/d (million ton-miles per day) used as a metric for measuring airlift capacity, further explained in Section 2.2.5.

Table 1 – Summary of the requirements for both scenarios

Scenario	Cargo mass [tons]	Rolling stock [%]	Mean cargo density [kg/m3]	Distance [nautical miles]	Deadline [days]	MTM/d
A	32,246.4	70.0	208.0	4,140	5	26.7
B	30,869.1	45.0	297.3	5,086	10	15.7

2.1.3 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-17's - 8 operated by the UK and 3 shared through the Strategic Airlift Capability program. Although Ukraine's AN-124s are available through the Strategic Airlift Interim Solution (SALIS) agreement, they are excluded from this analysis. The A400M and C-17 can both transport outsized cargo over strategic distances, but they differ significantly in capacity. The A400M can carry 37 tons over 3,300km, while the C-17 can transport 77 tons over 5,000km . additionally, the C-17's wider cargo hold allows for double-file loading, unlike the A400M. The payload-range diagram and cargo hold dimensions of both aircraft are shown in Figure 4 and Figure 5 respectively. The European fleet's are decomposed in Table 2 which shows the aircraft operators and their assumed operating bases.

Table 2 – European Airlift assets and their assumed operational base

		Current Fleet		Future Fleet	
Owning Nation	**Operation airfield**	**# A400M**	**# C-17**	**# A400M**	**# C-17**
Germany	Ramstein	45		53	
France	Bricy Air Base	24		50	
Spain	Zaragoza	14		27	
United Kingdom	RAF Brize Norton	22	8	22	8
Belgium	Melsbroek	7		7	
Luxembourg	Melsbroek	1		1	
Turkey	Erkilet	10		10	
Shared	Ramstein		3		3

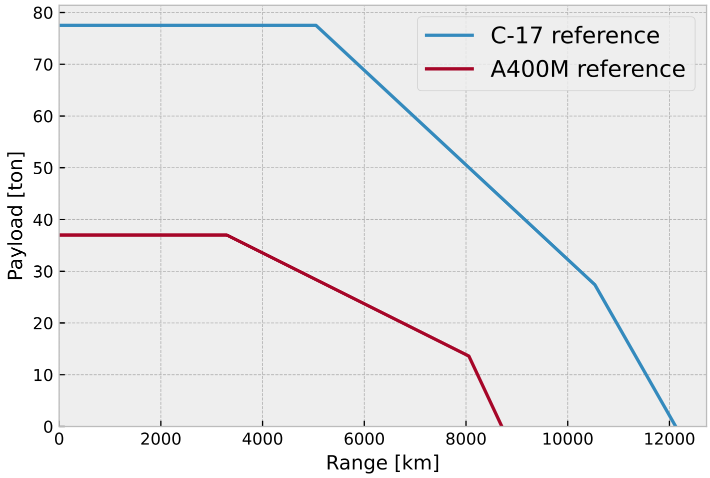


Figure 4 – Reference Payload-Range diagrams of the A400M and C-17 [3] [4]

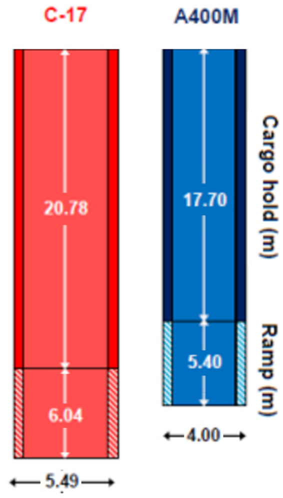


Figure 5 – Comparison of cargo hold dimensions [5]

2.2 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 characterized by Maier [6], 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 making up the heterogeneous fleet, the airbases from which they operate, and the cargo which they transport. Together, the interactions between these systems shape the overall airlift system through 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. This is particularly important for aircraft design as having more data and insights available at this early stage of development reduces the cost of the design process.

The SoSid Toolkit is an Agent-Based Simulation environment developed with the purpose of reducing time and technical difficulty of analyzing a SoS problem through simulation further described in [7]. Several use cases have already been explored in previous work using simulations built on the SoSiD toolkit. For instance, the Aerial Wildfire Fighting use case where the fleet effectiveness [8] and sensitivity of wildfire fighting tactics has been investigated [9]. In addition, the urban air mobility use case where aircraft architecture and fleet assessment studies [10] in addition to fleet life-cycle assessment have been performed using a SoS approach [11]. Recently, Kalliatakis enhance the toolkit to model HADR missions [12]. Users input critical data such as GPS coordinates of airfields, runway lengths, fleet composition, and cargo specifications, including origins and destinations. Simulation objectives such as minimizing time or cost, can also be specified. Aircraft models are provided in the Common Parametric Aircraft Configuration Schema (CPACS), developed by DLR for aircraft data exchange between tools.

Based on the input data, the tool simulates cargo movement between the origin and destination, generating SoS-level MoEs like mission completion time, success rate, cost, and deliveries rates. These metrics are used to assess the European fleet's ability to transport cargo and can be applied to conceptual aircraft designs to evaluate how fleet effectiveness changes with specific TLARs.

2.2.1 Modeling of operations

Within the simulation, aircraft, airbases, and cargo are modeled as agents. Aircraft data is inputted in CPACS format, which includes payload-range diagrams, fuel consumption rates, flight altitudes and speeds, and cargo hold dimensions. Aircraft agents can land at airfields that meet operational requirements, such as being in-range and having adequate runway length. Airfields act as logis-

tical hubs, offering refueling, maintenance, and cargo handling services. The simulation accounts for delays related to ground operations, including takeoff and landing clearances, taxiing, servicing, refueling, and loading/unloading of cargo. Notably, the tool differentiates loading/unloading times for palletized and rolling stock cargo, based on values from a RAND study [13].
Additionally, a dispatcher agent coordinates the airlift operations by determining which aircraft will transport what cargo where at what time. This agent catalogs optimal flight paths, allowing cargo to select the most efficient aircraft for each mission leg such that the arrival time at the destination is minimized. The decision-making logic of the dispatcher agent is illustrated in Figure 6

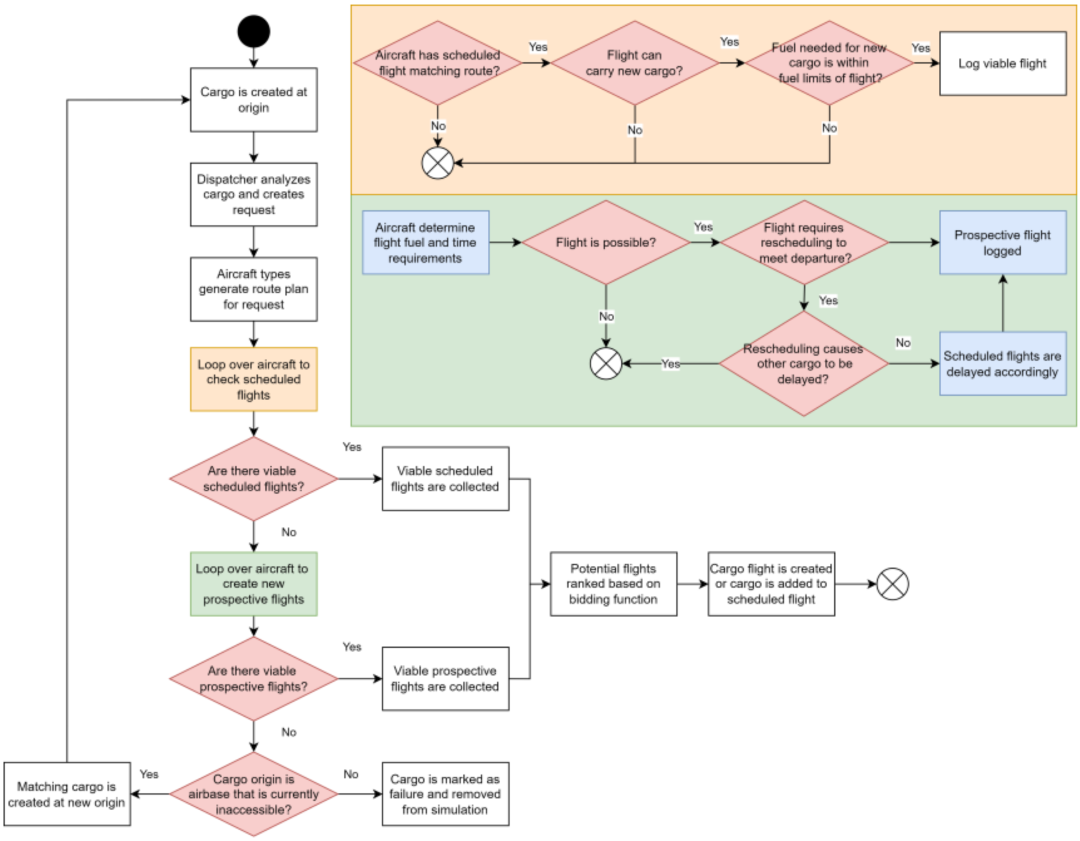


Figure 6 – Flow diagram of the SoSiD Toolkit agent-based simulation environment [12]

2.2.2 Volume constraint

In this study, the tool was enhanced to include a volume constraint, allowing for the assessment of aircraft "bulking out". Other research on humanitarian aid studies, such as the one by Barwell and Wainer [14] include 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 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. The algorithm maximizes cargo loading without exceeding the aircraft's allowable PPE.

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

While the PPE method works for scenarios involving mainly palletized cargo, it is too simplistic for scenarios involving oversized and outsized rolling stock. A significant limitation is that cargo height is ignored, which is essential for determining if cargo fits in the aircraft. Furthermore, it compresses cargo dimensions into a singular value causing the method to overestimate the loading capacity; for example, the A400M's nine pallet positions suggest five case M4K forklifts (5.25m in length and 2m

in width) could be loaded, but only three would fit in reality. The A400M is unable to load side-by-side and therefore, the length of the vehicle is the constraining factor and thus a singular value expressing the width and length does not suffice.
To overcome these limitations, this study uses the *knapsack loading algorithm*, which models cargo and aircraft 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 fits. Thereby accurately accounting for loading limits based on the cargo hold boundaries. Note that it is restricted from stacking or rotating cargo since rolling stock must be loaded lengthwise. The aforementioned example is visualized in Figure 7.

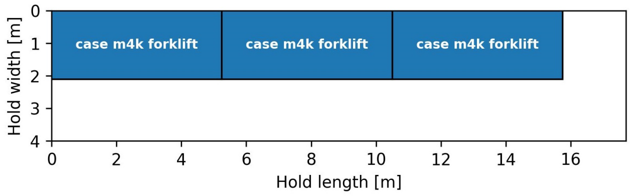


Figure 7 – Knapsack loading algorithm result after loading as many case M4K forklifts into the cargo hold of an A400M

2.2.3 Mission cost

Fuel and operating costs determine the total mission cost for airlift operations. In the simulation, fuel costs are fixed at $ 714 (U.S.) per ton [12]. Operating cost are calculated using the cost per flight hour (CPFH) metric multiplied with the total flight hours for each aircraft. The CPFH for each aircraft, including offspring designs, is obtained through a linear regression which correlates the aircrafts maximum takeoff mass (MTOM) with its CPFH. The relationship is visualized in Figure 8 and is based on data provided by the U.S. Air Mobility Command [15]. The total flight hours for each aircraft are furthermore tracked by the agent-based simulation, which records every flight conducted along with its duration.

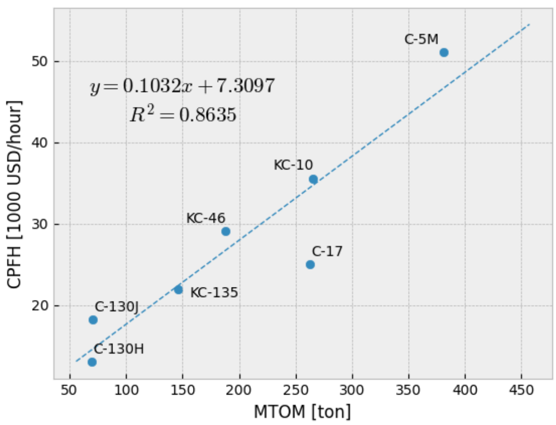


Figure 8 – Linear regression of CPFH data from the U.S. Air Mobility Command [15]

2.2.4 Acquisition cost

The acquisition cost for various aircraft types is computed using the findings from a RAND study on cost estimation relationships (CERs) based on bombers, transporters, and fighter aircraft [16]. $C_{PROG_{100}}$, in Equation (2), provides 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 multiplied by the number of additional aircraft included in the expanded fleet to get an estimate for the expanded fleet acquisition cost.

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

2.2.5 Airlift capacity

Finally, the toolkit can compute the airlift capacity by using the aforementioned million ton-miles per day metric which serves as a standard measure for evaluating airlift capacity. It does this by considering all the simulated flights, which cargo they carried over which distance, and the time it took to finish the flight. Equation (3) shows how the metric is computed. The airlift capacity can later be used to evaluate the difference between volume-constrained and unconstrained scenarios.

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

2.3 Aircraft Design

OpenAD, a parametric iterative knowledge-based aircraft design tool developed by the German Aerospace Center (DLR) for conceptual aircraft design (described by Wöhler et al. [17]), was used to model the aircraft within the European airlift fleet. The tool operates based on a set of input parameters, including design range and payload, cruise Mach number, runway length constraints, and a design mission. Furthermore, it is able to compute the cargo hold sizes based on a list of cargo, their amount and dimensions, and wether or not they can be loaded in a single or double-file configuration. Additionally, OpenAD requires configurational details, such as landing gear, empennage and wing configurations, as well as the number, position and type of the engines.
By using the built-in knowledge base, which relies primarily on publicly available aircraft design methodologies and in-house DLR methods, openAD is able to compute the aircraft's geometry, performance characteristic, and component masses. The tool sizes the aircraft according to general sizing constraint diagrams and 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.

2.3.1 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 [18]; therefore, only a model of the C-17 remains to be constructed. To construct the C-17 model, the OpenAD knowledge base was adapted to align with the characteristics of heavy, outsized airlifters. Such airlifters differ significantly compared to civilian transport aircraft. Strategic airlifters are designed such that cargo hold volume is maximized while aircraft turnaround time is minimized. Additionally, these aircraft have to operate from as many airfields in the world as possible, therefore short takeoff and landing requirements are often imposed. This leads to design decisions such as the inclusion of an aft cargo ramp, podded landing gear capable of high flotation and landings in rough fields, high mounted wings and more. These decisions have a significant impact on component weights and aerodynamics of the aircraft. These factors have been included in the knowledge-base of OpenAD as further described in [1].
The reference mission for sizing the C-17 model was obtained from military standard MIL-STD-3013B [19], and is shown in Figure 9. A database of the C-17 measurements, requirements, and performance was assembled from publicly available sources and input into OpenAD. The model was then calibrated by applying adjustment factors to the unknown variables, such as engine efficiencies and aerodynamic drag coefficients, such that the payload-range diagram computed by OpenAD aligned with the reference payload-range diagram of the C-17.
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 cargo to be transported. This parametric model

enables the exploration of offspring designs based on the C-17 platform such that the impact of the TLARs on the MoEs can be studied. The 3D geometries of the C-17 and A400M models as computed by OpenAD are shown in Figure 10. Furthermore, top-level aircraft parameters of 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 validation purposes), is presented in Figure 11.

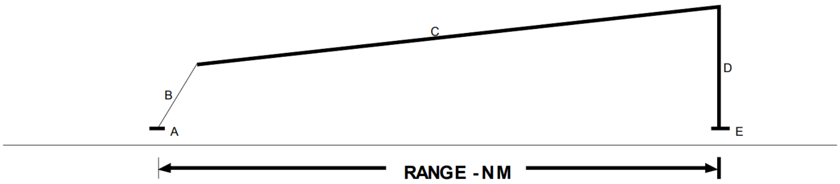
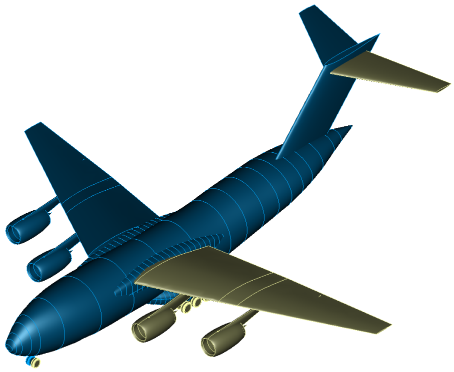
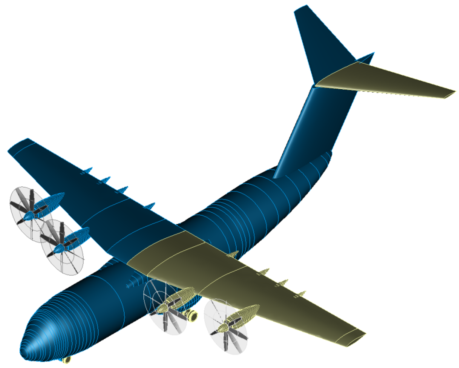


Figure 9 – Mission profile for a cargo transport mission, adapted from MIL-STD 3013B [19]



(a) C-17



(b) A400M

Figure 10 – 3D geometries as generated by OpenAD

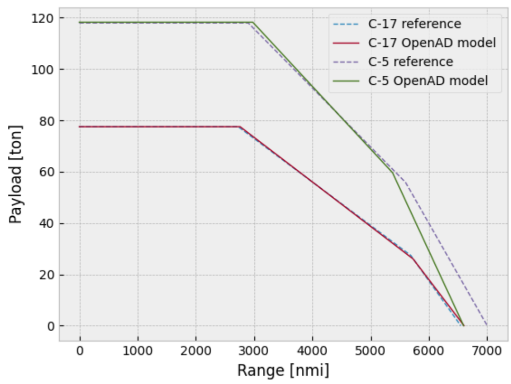


Figure 11 – OpenAD Computed payload-range diagrams

Parameter	OpenAD	Reference
MTOM [kg]	265,970	265,352
OEM [kg]	128,290	128,418
W/S [kg/m^2]	753.5	751.7
T/W [-]	0.29	0.28
$V_{approach}$ [m/s]	55.5	59
Wing span [m]*	50.1	50.3
Fuselage length [m]	48.4	48.8

* Excluding wing tips

Table 3 – C-17 model top level data

2.4 Design of Experiments

To answer the second research question, a Design of Experiments (DoE) is set up. This DoE should be large enough to account for both small fleets of large aircraft, as well as large fleets of small aircraft. The parameters considering for this DoE are established in Table 4, which shows the variables and their values.

Table 4 – Summary of the DoE variables

Variable	Lower limit	Upper limit	# levels
Number of aircraft added to the future fleet [1]	11	66	8
Design payload mass [tons]	50	100	10
Design range at the design payload mass [km]	3,000	8,000	10
Cruise Mach Number [-]	0.75	0.85	3
Cargo Hold Configuration [-]	0	4	5

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 and arbitrary ones that increase the resolution of the grid. It is worth noting that the cargo hold height has no influence on the results as it is sized such that all cargo fits inside all the cargo holds.

Table 5 – The dimensions behind the cargo hold configurations

Cargo Hold Configuration	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

2.5 Measure of Effectiveness

To assess the outcomes at a system of systems level, measures of effectiveness (MoEs) are utilized. The effectiveness of a European fleet which includes conceptual aircraft designs can be evaluated based on key criteria such as mission success rate, mission cost, and fleet acquisition cost[2]. To establish appropriate weights for these metrics, the *Fuzzy AHP* method, an analytical hierarchy process, as described by Seethaler et al. [20], was used. This method determines the weights of various metrics by 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 eachother. The method allows to convert these comparisons into numerical weights, following the procedure outlined by Seethaler et al. [20]. The collected responses from the SMEs, along with the resulting mean value are presented in Figure 12. The final equation used to calculate 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 additional aircraft to be added to the future European strategic airlift fleet.

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

[2] This acquisition cost accounts only for the new fleet, not the existing one, and is calculated by multiplying the number of additional aircraft added to the fleet by their respective acquisition costs

Figure 12 – SME responses and weights determined using the Fuzzy AHP method

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

3 Results

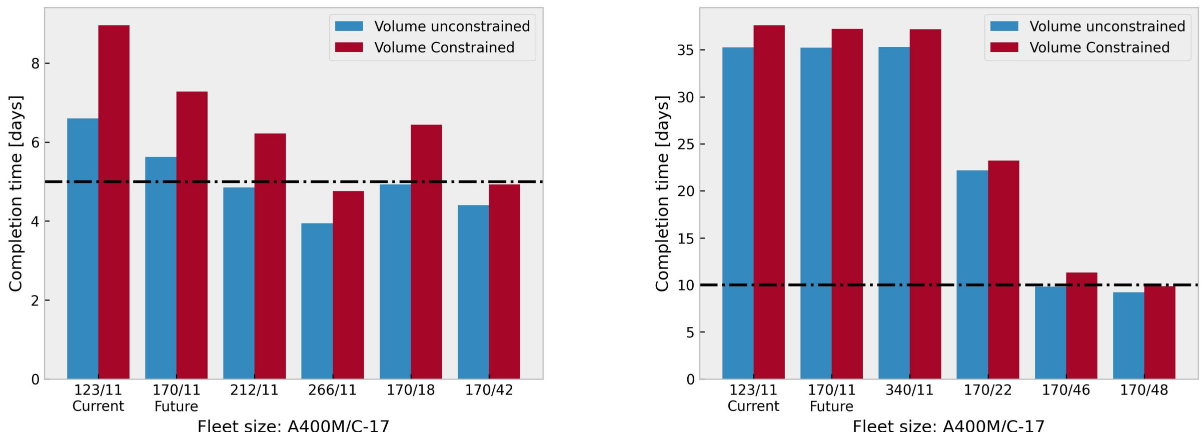
The results are split up into two sections: Section 3.1 assesses the current and future European strategic airlift fleet's capability to perform the given scenarios and studies the effects that a volume constraint has on this assessment, while Section 3.2 explores the design space for a new airlifter to be added to the future fleet to come up with an optimal set of TLARs.

3.1 Assessing the airlift fleet and the effects of volume

For both scenarios, the mission completion times and the impact of volume constraints are show in Figure 13. For scenario A, the first observation is that neither the current nor future fleets meet the deployment deadline under any circumstances. In the absence of the volume constraint, the deadline is nearly met by the future fleet. However, when accounting for the cargo hold volume, a delay of roughly 1.5 days is observed. This trend between volume-constrained and unconstrained simulations continues for the other fleets in this scenario.
The plot further demonstrates that, 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, which additionally quantifies the impact of the volume constraint 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.

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

Fleet size [A400M/C-17]	Volume-unconstrained airlift capacity [MTM/d]	Volume-constrained airlift capacity [MTM/d]	Difference [%]
123/11	19.27	14.20	-26.3
170/11	22.59	17.46	-22.7
212/11	26.20	20.46	-21.9
266/11	32.24	26.70	-17.2
170/18	25.81	19.75	-23.5
170/42	28.88	25.79	-10.7



(a) Scenario A (b) Scenario B

Figure 13 – Volume-constrained and unconstrained mission completion times for various fleet configurations

For scenario B, neither fleets meet the deployment deadline, with delays of approximately 27 days for both fleets. The deadline is only achieved when an additional 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. 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 is 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 is not capable of transporting. As a result, the fleet's eleven C-17s are left to move all these vehicles on their own, and even they are only capable of carrying a limited number at a time. This observation shows that the 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. This is due to the nature of scenario B. In this case, the individual cargo is heavier, causing the payload mass constraint to be reached before the volume constraint on many flights.

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

Fleet size [A400M/C-17]	Volume-unconstrained airlift capacity [MTM/d]	Volume-constrained airlift capacity [MTM/d]	Difference [%]
123/11	5.79	5.42	-6.4
170/11	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

3.2 Design Space Exploration

In order to make the analysis more manageable, the design space is built-up gradually. For the purposes of this analysis, only the design space that represents the arithmetic mean outcome of

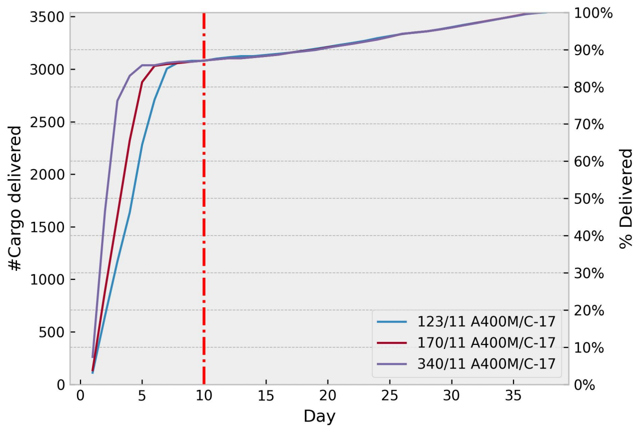


Figure 14 – Deliveries over time for varying A400Ms in the European fleet performing scenario B while volume-constrained

scenarios A and B is presented, however Appendix A shows the individual MoEs that make up the overal 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 which are expanded by 22 to 33 aircraft perform best. This required fleet size is substantially smaller than what was observed when expanding the fleet by C-17 or A400M aircrafts.
Another significant observation relates to the width of the cargo hold floor. The ability to load cargo in a double-file configuration has a great impact on 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.

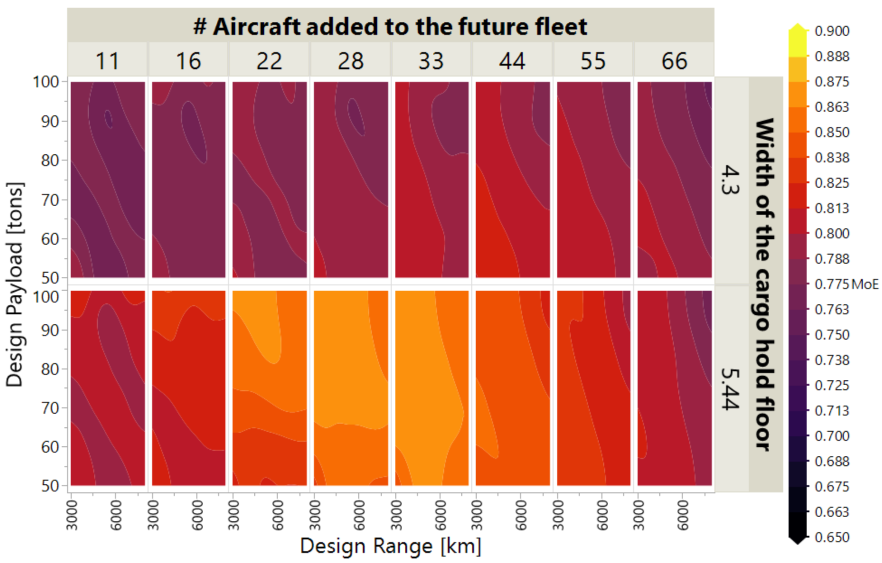


Figure 15 – The effect of cargo hold width (single file vs double file)

Building on the previous graph, the cargo hold configurations are expanded to include width and 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 aircraft demonstrates the best effectiveness. A further observation reveals that configurations three and four yield nearly identical MoEs, indicating that beyond a certain point, increasing cargo hold length offers diminishing returns in

terms of overall fleet effectiveness. Nevertheless, longer cargo holds are seen to generally enhance effectiveness: the longer the cargo hold is, the smaller the required fleet is.
Additionally, for longer cargo holds, smaller design payloads start performing a little better for the fleet of 22 aircraft. In terms of design range, its impact on the MoE is relatively minor. The analysis suggests that smaller design ranges are preferable due to the reduction in acquisition cost. However, slightly longer design ranges can contribute to reduced mission costs by minimizing the number of intermediate stops required, thereby increasing fleet effectiveness.

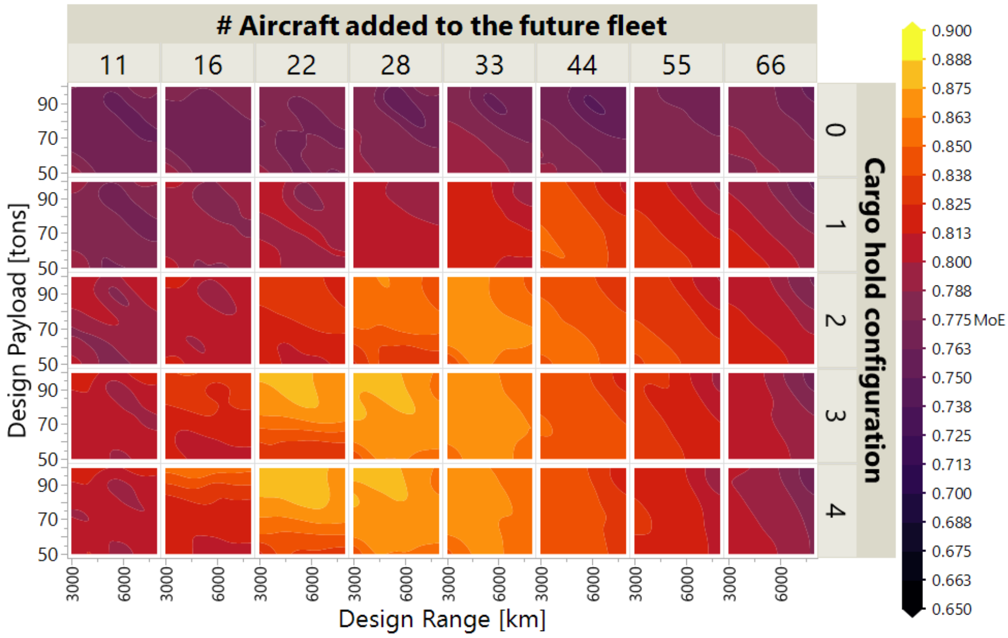


Figure 16 – The effects of the various cargo hold configurations

Finally, to get a holistic understanding of the design choice combinations, the cruise Mach number is included into the analysis, 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, which somewhat offset the increase in mission and acquisition cost associated with faster airplanes.
Furthermore, this figure highlights an optimal configuration. The aircraft which 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. The optimal aircraft is similar to the C-5 Galaxy.

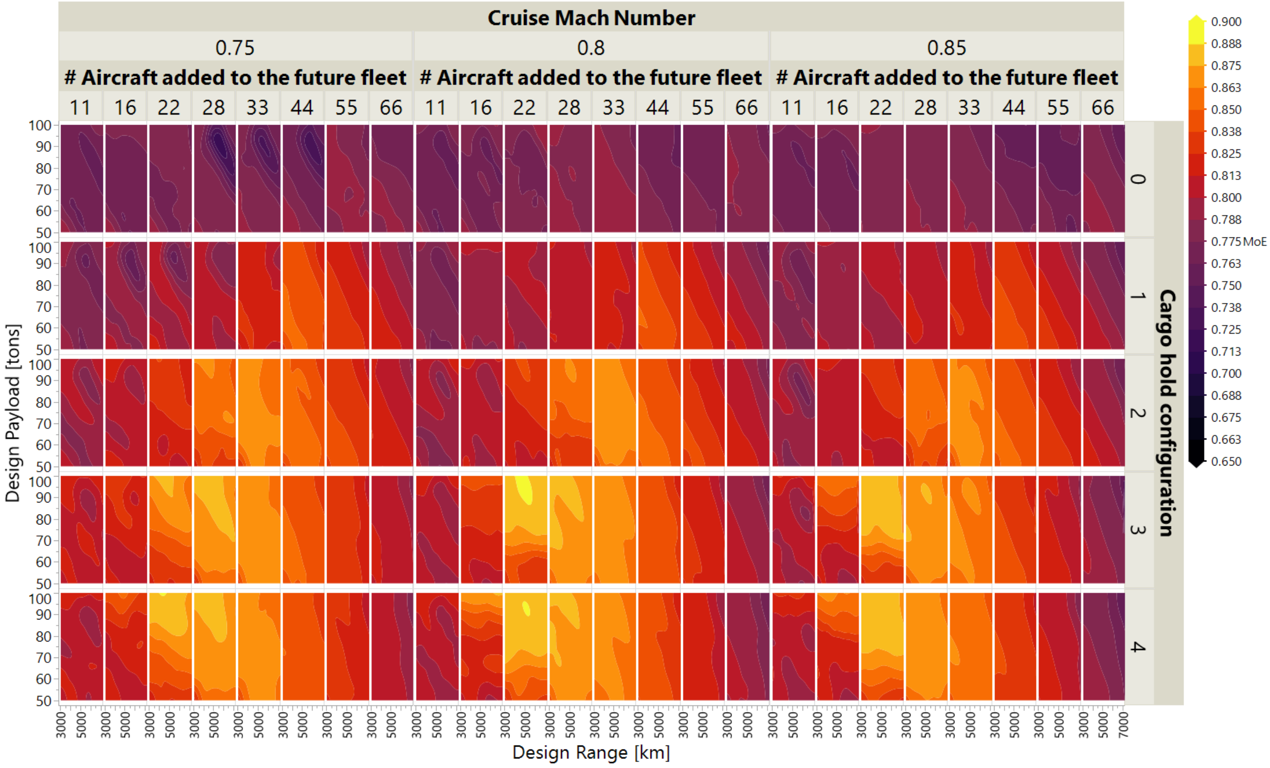
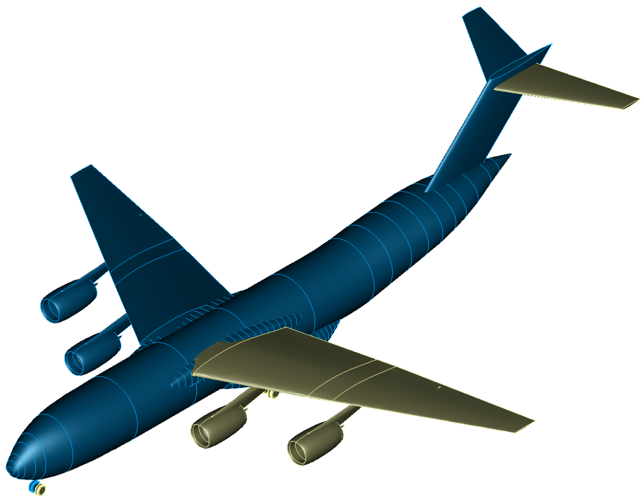
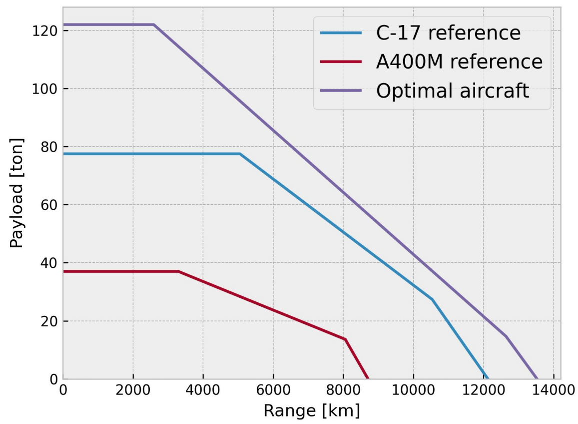


Figure 17 – Design space averaged out over both scenarios



(a) The optimal aircraft's geometry



(b) Payload-range diagram belonging to the optimal aircraft

Figure 18 – The optimal aircraft

Table 8 – Summary of optimal aircraft data

Maximum Takeoff Mass	326,910 kg
Operative Empty Mass	163,180 kg
Cruise Mach [-]	0.8
Design Payload	94.5 tons
Design Range	5,000 km
Cargo Hold WxLxH	5.44m x 39.14m x 6.0m
W/S	765.5 kg/m^2
T/W	0.30
Additional aircraft required	22
MoE	0.90

4 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?*
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?*
Regarding the first 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 the inclusion of the volume constraint 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 heavier weight of individual cargo in scenario B causing the mass constraint to be reached before the volume constraint more often, thereby limiting the effect of the volume constraint.
In response to the second 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 for 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. Moreover, design range is found to be of secondary importance compared to 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 deployment deadlines 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, 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 support double-file loading and has a cargo hold length of 39 meters. This optimal is similar to the C-5 Galaxy. A fleet of 22 aircraft with these specifications is sufficient to meet the deadlines 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.

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6 Copyright Statement

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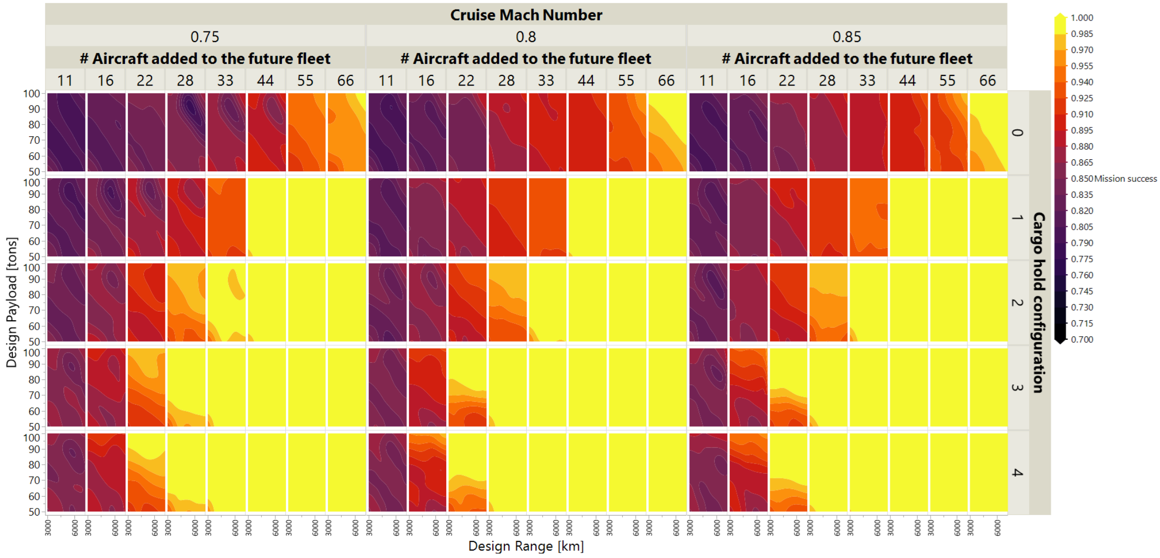
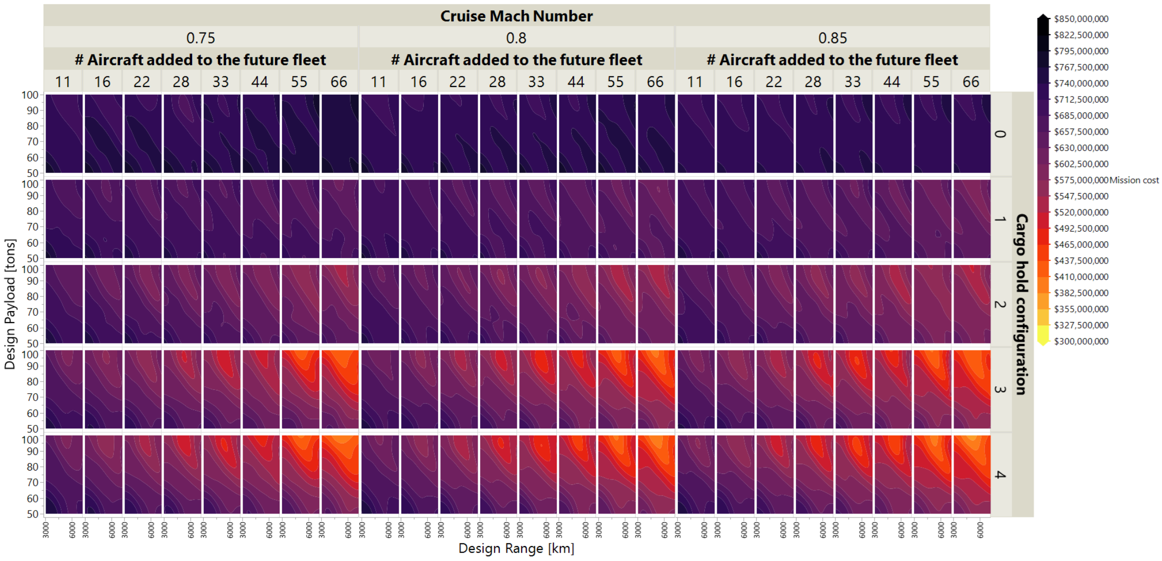
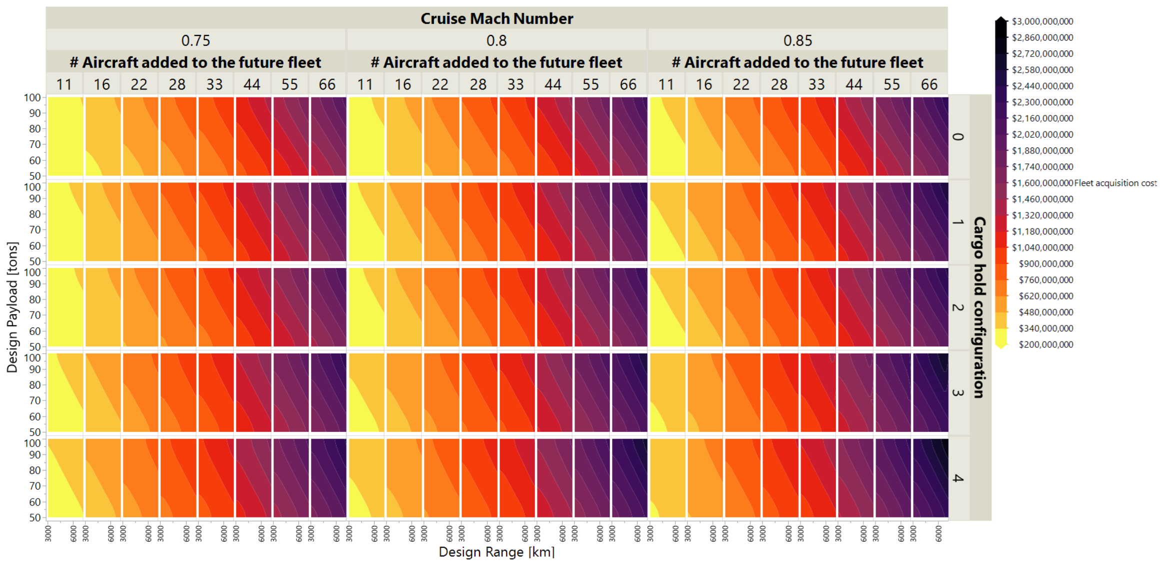
A Appendix



(a) Mission success rate



(b) Mission cost



(c) Expanded fleet acquisition cost

Figure 19 – Measures of effectiveness averaged over both scenarios