A System of Systems Framework for Strategic Cargo Airlift Using Agent-Based Modelling

Nikolaos Kalliatakis [1], Tobias Dietl[1], Prajwal Shiva Prakasha [1], Thomaz Zill [1] and Björn Nagel [1]

[1] German Aerospace Center (DLR), Institute of System Architectures in Aeronautics. Hein-Saß-Weg 22, 21129 Hamburg, Germany.

E-mail: nikolaos.kalliatakis@dlr.de

Abstract.

The effective transport of cargo across the globe by aircraft, termed strategic airlift, is foundational to the success of humanitarian aid/ disaster relief (HA/DR) missions and even military operations. Due to the variable extremity of these events, it is essential for aircraft and operations to be designed with a high resilience, factoring in performance in a plethora is scenarios. This work aims to provide a framework that enables the coupling of aircraft, fleet and concepts of operations (CONOPS) design to a mission effectiveness in a strategic cargo airlift. Through agent-based modelling, the complex interaction and emergent behaviors of the different systems in the dynamic airlift environment is better captured and evaluated. Unexpected events, such as cargo requirement reformulation, aircraft servicing and changing airbase accessibility, are employed to emulate the dynamic and spontaneous nature of rapid cargo airlift missions. The impact of these events is stochastically modelled, promoting an analysis of a variety of scenarios. By creating a theoretical disaster relief mission, a trade-space exploration is conducted so that aircraft designs and operational objectives can be evaluated for their mission effect. The framework demonstrates the ability to evaluate aircraft and operational performance holistically, enabling a more robust design procedure for a variety of potential design scenarios and metrics.

1. Introduction

Rapid response to natural disasters, wartime scenarios and other crises is critical to human livelihood and protection. The first 5 days of transport are the most critical, often resulting in a strong reliance on aircraft transport and efficient operation [1]. Strategic airlift considers the bulk of the cargo movement, and features inter-continental travel using aircraft distinguished for their high payload-range capabilities. It is forecast that within the coming 2 decades, at least half of the current fleet will be structurally incapable of performing their airlift duties [2]. When paired with the highly volatile and extreme scenarios that airlifts are plagued by, it is essential that future aircraft and even operational design is evaluated with the prospective airlift performance itself. This work intends to provide a framework that facilitates the evaluation of aircraft, fleet and CONOPS performance in a strategic airlift, enabling the determination of novel technology and design variable influence on the mission effectiveness.

A key aspect of the framework is the airlift model by which the design inputs can be processed and evaluated to produce the mission outputs. Within this work, a python-based simulation is created, where spontaneous and unexpected disruptions that occur in airlift can be modelled and their resulting impact on the operation assessed. Aircraft, airbases and cargo can be modelled according to design data and user specifications to allow for scenario customization and modular variables. The ABM scheme provides an intuitive method for implementing new aircraft and responses to disruptions, offering insight to the SoS behaviors and risk management of the fleet and operation. The framework is intended to be used in conjunction with a design loop to either 1) evaluate optimal designs given a standard airlift procedure, or 2) indicate fleet/ operational resilience in lieu of low-likelihood, high impact events. Measures of effectiveness can be extrapolated from the simulation, giving users the ability to reverse engineer aircraft, fleet and operational designs to their desired outcome. The principle of this framework is illustrated in Figure 1.

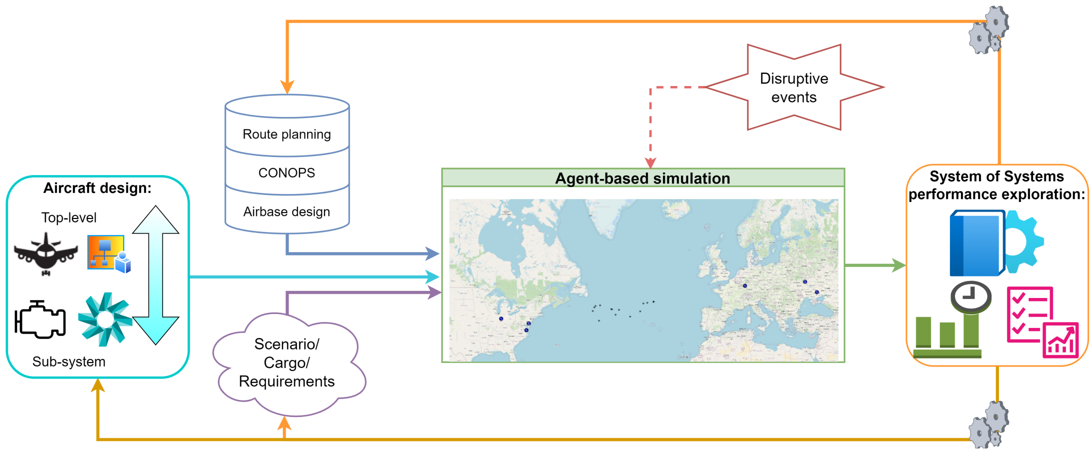


Figure 1: Design process loop overview

To create a strategic cargo airlift model that supports aircraft design and other inputs, previous works can be used as a basis and further developed. A.D. Reiman [3] created a route analysis metric, called the fuel efficiency index (FEI) which aims to improve cargo throughput whilst conserving fuel usage. While being effective for efficiency, alternative formulations for routing have been constructed to prioritize timely deliveries and minimize cost, as done by P. Mogilevsky [4]. Both techniques offer successful results, yet a model which allows the combination and tuning of these aspects and other objectives has yet been developed. Aircraft design is seldom incorporated into airlift models, with a few authors delving into the effects. C. Iwata et al. evaluated the benefits of improved engines, but on a simplified strategic airlift model [5], while C. Weit et al. [1] created a framework for aircraft design effects, but it was purposed for tactical airlift and VTOL aircraft and only performed minor sensitivity analyses. As such, there is a need for a framework that provides a greater evaluation of aircraft design to its effect within the basis of a robust and customizeable strategic airlift model.

2. Methodology

To model the varying complexities of a strategic cargo airlift, a modelling and simulation (M&S) approach was used. This section will first outline the simulation setup and then delve into model specific information.

2.1. The basics of the simulation

The simulation developed and used in this work is based on the DLR in-house System of Systems Inverse Design (SoSID) tool. SoSID is a python based simulation toolkit that employs agent-based modelling (ABM) to explore system of systems (SoS) [6][7]. ABM is not typically applied in airlift models, but its application can facilitate the testing of risk on the airlift, analyzing the emergent responses to disruptive "black swan" events like natural disaster development. To develop the SoSID tool to support strategic cargo airlift, several developments were made. The detailing of airbase, cargo and flight planning, aircraft and disruptive event models are further discussed in later sections.

SoSID functions by taking an input file that specifies certain attributes like airlift parameters (time, map location, disruptive event data, and airlift objectives), airbase parameters and aircraft parameters. If inputs are not provided, default values are assumed. The mission is then conducted by discretizing the airlift into time steps. By default, this value is 60 seconds. Each time step, an event is checked for occurrence, such as the creation of cargo or the servicing of an aircraft. These events can then trigger agent responses, such as a dispatcher processing the cargo's requirements, and aircraft creating flight paths for the cargo. Once the mission time is reached or all cargo is delivered, the simulation ends and an output file detailing mission performance (airlift time, cost, fuel consumption, etc.) and aircraft specific data (number of flights, cargo carried, load factors, fuel burn, etc.) is generated.

Disruptive events, such as aircraft servicing, spontaneous cargo generation and airbase accessibility changes, are customizeable in SoSID. Spontaneous cargo generation is the method by which the simulation models potential cargo demand reformulation mid-operation. Due to natural disaster worsening or military developments, it is not uncommon that more cargo is requested and transported than initially planned for. Airbase accessibility changes and aircraft servicing model potential maintenance disruptions that can occur due to the excessive utilization of the entities in a short time. Since the impact of these events on the airlift is non-standard, they are modelled stochastically. To ensure a non-bias analysis is obtained, each simulation design point is run 15 times. This number was determined based on achieving a less than 1% error in the defined measure of effectiveness (MoE), the mean cargo delivery success. Cargo delivery success refers to the percentage of cargo that is present at its intended destination (at simulation stop) relative to the total cargo created. A 100% delivery success represents a successful mission.

2.2. Airbase implementation

The airbases are the foundations for flight path planning, acting as cargo origins, destinations, and intermediate support bases to conduct aircraft refuelling and servicing. Airbases are initialized along with the map and thus require an input GPS coordinate and name/ identifier. The identifier is used for later reference when inputting cargo requirements and aircraft initialization. Additional information such as the ramp space (aircraft capacity) and fuel pump rate can also be inputted. By default the ramp space allows for 10 aircraft and a conservative estimate on fuel pump rate of 300 gallons/ minute ($\approx 15.4kg/s$) [1] is applied. Airbase modelling also deals with spontaneous cargo generation. Each airbase can be specified as a consumer or generator for all different types of cargo. When spontaneous cargo is generated, it randomly assigns itself an origin and destination based on the airbases marked with its generation and consumption respectively. Each airbase can specify the type of aircraft that are allowed to land there, which mimics aircraft performance limitations due to potential elevation, field lengths or hazard concerns. Airbase accessibility can dynamically change throughout the simulation.

2.3. Cargo implementation

Cargo modelling revolves around its requirements. Information such as its origin, destination, mass, required pallets and required time of departure (RToD) are used as inputs and structure the cargo's interactions with aircraft and its flight path. Cargo creation is done upon initialization and throughout the operation. Planned cargo, which represents the original cargo demands of the airlift, is created at the mission start and requires direct user input, whereas spontanenous cargo, which represents new cargo demands being created mid-airlift, is generated throughout the simulation and added at specific time intervals (by default 3 days). Since cargo reformulations are unpredictable, spontaneous cargo is stochastically modelled, where a generation chance is specified for each type of stored cargo data. Spontaneous cargo's origin and destination are chosen based on the generators and consumers specified by the airbase inputs. The RToD is randomly distributed between 3 and 5 days.

Cargo can also get created when a disruptive event occurs that compromises a cargo's itinerary. When a flight is delayed, cargo's RToD may be unfilled or connecting flights may no longer be caught. In such cases, a new cargo which maintains the disrupted cargo's requirements is created, called reinstated cargo. Reinstated cargo replaces the original cargo from the point in time that the disruption affects the original cargo's schedule. In effect, the amount of reinstated cargo is a direct measure of the disruptive effects on flight scheduling and the mission's operation.

Upon creation, the cargo's travel path is determined and its assigned to flights. The procedure is segmented into 2 phases: flight path determination and aircraft allocation.

Flight paths are formed using A.D. Reiman's techniques [3] and a Dijkstra algorithm. Nodal reduction is applied to all the airbases, upon which each aircraft type computes the optimal flight path from origin to destination using an input weight function. By default, the function is flight fuel usage, meaning routes are planned to provide greatest fuel efficiency per cargo request. Details of fuel consumption computation are present in Section 2.4.

Once the flight path is determined, scheduled flights which already match portions of the route, and are capable of fitting the cargo, are found. In the absence of viable scheduled flights, the aircraft then bid for the cargo by creating a prospective flight scheme. Prospective flights aims to fulfill the cargo's requirements, whilst ensuring that new flight does not compromise other cargo deliveries within the aircraft's schedule. This procedure can be quite complex as it has to incorporate preceding and succeeding flights. Thus prospective flight scheduling includes aspects such as refueling between flights, cargo unloading and loading (assumed to be 15 minutes each), and even deadhead (flights without any cargo) flight creation or removal. When either all viable scheduled flights are collected, or prospective flights are proposed, flights must be compared to determine which is "best." This is done by discretizing the flight's information into a value function, which incorporates aspects of value and an associated weight. The value function is shown in Equation 1, where B represents the user inputted weight. To bound the function, the different value aspects are normalized, indicated by the ˆ, with the largest magnitude of that aspect amongst all bids.

$$Bid = B_{time} * \hat{Time} + B_{utilization} * \hat{Utilization} + B_{fuel} * \hat{Fuel} + B_{cost} * \hat{Cost} \tag{1}$$

$$AC_{best} = Min(Bid_{AC}) \tag{2}$$

$Time$ refers to the difference in time (seconds) between the flight's departure time and the current simulation time. $Utilization$ refers to the change in flight hours the new flight incurs. $Fuel$ and $Cost$ refers to the fuel and cost changes due to the new flight plan.

The value function considers all flight path changes, including the removal and addition of deadheads. The "best" flight is then the one which produces the minimum Bid, as all value aspects are in fact non-desireable. For example, a large $Time$ value refers to a long time before the flight's departure, which can impede mission completion time and thus is valued against.

2.4. Aircraft modelling

Aircraft modelling captures the aircraft's ability to transport cargo, adhering to its performance limits and constraints. Volume (measured through pallet capacity) and payload mass constraints are easily verified with the cargo loading. Fuel constraints are based on the flight distance and loaded mass. Within this study, flight fuel determination is based on assuming the entire flight is in cruise condition, which is feasible given the long distances. This enables the use of the Breguet range equation (3), which uses cruise velocity (V), the thrust specific fuel consumption ($TSFC$), the lift-over-drag ratio ($\frac{L}{D}$) and the ratio ($\frac{W_{i-1}}{W_i}$), representing the change in weight across the flight. For a given distance and assuming flight end mass is simply payload and operational empty weight, solving the weight ratio gives the fuel required for the flight.

$$R = \frac{V}{g_0 \cdot TSFC} \frac{L}{D} \ln \frac{W_{i-1}}{W_i} \tag{3}$$

This assumption has underlying assumptions; notably, the aircraft flies at a 1) constant bulk velocity and 2) a constant L/D and $TSFC$, taken to be the mean value across the flight.

For a fixed route distance, each new cargo addition increases the post-flight mass, increasing initial fuel mass. Given a known flight time and fuel estimation, the cost can be estimated as a summation of the fuel costs and the operational costs [4]. The fuel cost is the product of flight fuel usage and the fuel cost per kg. The operational cost is the product of flight time (hrs) and the cost per flight hour ($CPFH$) of the specific aircraft, which is based on a 2012 Air Force dataset [8].

Throughout the operation, aircraft may required servicing. This event is unpredictable, but can be approximated by a stochastic servicing model which applies a specified value of servicing hours to an aircraft, which is probabilistically checked for servicing upon landing [5]. Aircraft servicing prevents the aircraft from bidding for cargo and delays all current flights for the aircraft by the servicing time. This can impact the cargo delivery times and sometimes prevent it from catching connecting flights. In such instances, the cargo is reinstated so that other aircraft can take the cargo before the delayed flight departs.

3. Analysis

This section intends to demonstrate the framework's abilities. An theoretical disaster relief mission is constructed and a trade-space exploration on aircraft design and operational objectives is evaluated.

3.1. Mission setup

Airlift missions can greatly vary in nature, thus this section seeks to capture some of the some notable airlift complexities and demonstrate the framework's capabilities. In this goal, the mission was defined to be a disaster relief mission with the goal of providing 20'000 people within Subang Malaysia with food, water and other necessities that would be typically be required. A fleet of 4 x C-5M and 6 x C-17 conduct the airlift, and are initialized along with cargo at Travis airbase. The airbase and map setup is shown in Figure2.

Figure 2: Simulation airbase locations for mission setup

Only the C-17 aircraft can land at Subang, emulating its improved landing versatility over the C-5M. The mission was analyzed for a maximum of 6 days, as these are the most critical to human livelihood [1]. Food and water requirements were based on humanitarian standards to treat the citizens for 6 days. Additional to food and water, tactical airlift vehicles, in the form of 3 HH-60 VTOLs, were added to the requirements to assist with the theoretical last mile delivery. Other relief material (blankets,

tents, etc.) was treated as 50 x "generic
pallets", each representing a single, fully loaded pallet. Overall, the mission's planned cargo demands are shown in Table 1.

Table 1: Use case cargo plan

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

To test the framework in modelling extreme scenarios, several disruptive events will be emplaced on the mission. Aircraft servicing will be present, with each aircraft having a 5% chance of incurring a maintenance upon each landing. The servicing can randomly last from 4-16 hours. Spontaneous cargo generation will also take place, with its introduction on day 3 of the mission, symbolizing new cargo demands in lieu of the potential growing natural disaster. Each of the planned cargo in will have a chance of generation. Finally, the idea of an airbase runway being damaged or serviced (due to over-utilization) will be tested in the form of aircraft losing access to Kadena airbase 2.5 days into the mission.

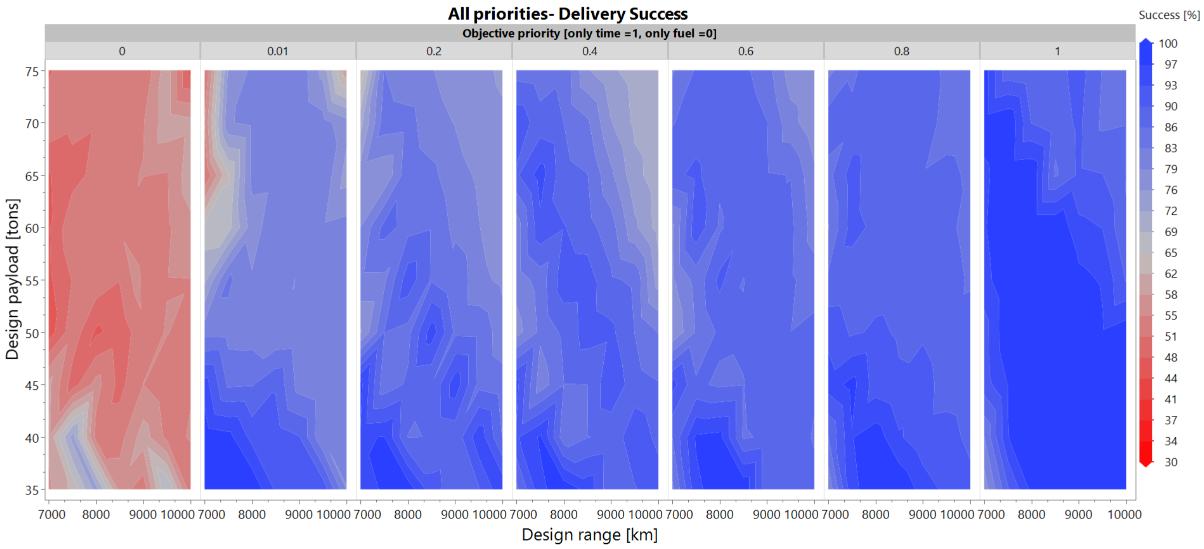
With the scenario defined, result analysis in the form of a trade-space exploration can occur. The design of experiments (DoE) for the trade-space is conducted where the C-5M is varied in its design payload, design range and its pallet capacity, representing a variety of aircraft designs. New aircraft designs are computed using Raymer's conceptual sizing equations [9] and a standard design mission for cargo aircraft [10]. This method was also used to determine the required $TSFC$ and $\frac{L}{D}$ that correspond to the standard values for the C-5M and C-17. With the variety of aircraft designs, the DoE features different operational objectives, varying the bidding weight of time and fuel (other weights are ignored in this analysis).

3.2. Trade-space exploration

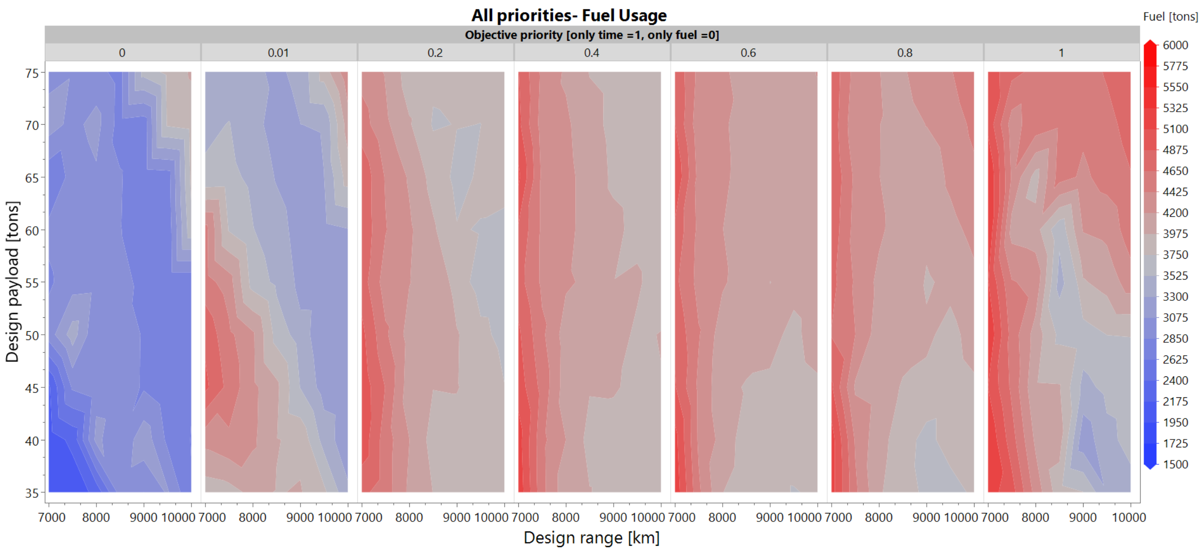
The trade-space results can be evaluated by analyzing the metrics of delivery success and mission fuel usage, as shown in Figure 3, where contours are intended for qualitative comparison, highlighting key trends, and should not be regarded as definitive. The objective priority brackets include the range of weights from that indicated up to the graph right of it ($0.8 \geq$ "Objective priority 0.8" < 1.00).

When aircraft are designed smaller (with a reduced payload/ range), fuel consumption for the same route is reduced. Despite this simultaneously reducing the cargo carrying ability, smaller aircraft tend to result in a higher mission delivery success due to their competitive fuel consumption with the C-17. Reducing C-17 reliance is beneficial as it allows the C-17's to prioritize the final leg delivery. When fuel considerations are reduced (objective priority increases to time), larger aircraft designs are favored, as their ability to travel faster with more cargo increases mission delivery success. Interestingly, the largest designs are not optimal as they require larger refuelling times, impacting timely delivery. Ordinarily the aircraft on-ground time is constrained by the loading/ unloading time, but in such instances refuelling times become constraining and these effects compound. The framework highlights the high performing designs, indicating the potential design space for optimization to occur.

Total mission fuel usage incorporates the C-17 fuel consumption, which justifies the potential higher usage despite designing smaller aircraft. When time is considered with fuel, deadhead flights (with no cargo) become more prevalent to promote earlier departures. This improves delivery success, but increases fuel usage. Conversely, when time priorities are increased in combination with larger aircraft designs, fuel usage can actually decrease as fewer flights are



((a)) Delivery success comparison



((b)) Fuel usage comparison

Figure 3: Trade-space MoE evaluation for all designs and bidding weights

required to complete the mission, leveraging the improved cargo carrying capabilities despite the higher flight fuel requirements. In essence, optimizing fuel usage requires a balance between designing aircraft that are small enough to be fuel efficient and designing large aircraft that exploit their payload-range capabilities, resulting in a reduced number of flights required.

The exploration has exemplified the impact of aircraft design and operational objective choices on the airlift's performance. It serves to demonstrate part of the framework's current capabilities and can be further expanded to explore different objective combinations or fleet designs. The results are not definitive but show promise for future resilience testing of different designs or identifying optimal design spaces.

4. Conclusion and Recommendations

The purpose of this research was to create a framework to help evaluate different aircraft designs in a strategic cargo airlift. To this end, an airlift model that allows for scenario customization and the implementation of disruptive event was constructed so that aircraft performance, fleet design and CONOPS can be tested in several extreme mission variants. Aircraft design and operational objectives were varied in a trade-space based on a theoretical disaster relief mission to demonstrate these capabilities. Results displayed the high dependency of aircraft design and operational objective on the resulting airlift, with significant deviations in fuel usage and mission completion time. For example, certain operational objectives, when paired with larger aircraft that consumed more fuel per flight, were shown to produce a reduced total mission fuel usage compared to smaller aircraft. This was a consequence of leveraging the larger aircraft's payload capabilities, where fewer flights were required to transport the cargo, reducing the total fuel usage. The results illustrate the framework's utility for resilience testing and design optimization processes, but can be expanded to include tactical airlift and a higher fidelity aircraft design tool, which together would yield a more holistic and developed evaluation framework. Additional analysis, such as evaluating refueling methods, cargo types, mission locations and ranges, are natural progressions to this preliminary research soon to be assessed.

References

[1] Colby Weit, Steven Chetcuti, Lansing Wei, Marc Muehlberg, Cherlyn Chan, Hassan Gilani, Cameron Clanchy, Katherine N. Schwartz, Alicia Sudol, Jimmy C. Tai, Cees Bill, and Dimitri N. Mavris. Modeling airlift operations for humanitarian aid and disaster relief to support acquisition decision-making. Atlanta, 2018.

[2] RAND Corporation. Reducing long-term costs while preserving a robust strategic airlift. Technical report, Santa Monica, 2013.

[3] Adam D. Reiman. Enterprise analysis of strategic airlift to obtain competitive advantage through fuel efficiency. Technical report, Dayton, 2014.

[4] Philip Mogilevsky. Optimizing transportation of disaster relief material to support u.s. pacific command foreign humanitarian assistance operations. Technical report, Monterey, 2013.

[5] Curtis Iwata, Philip A. Fahringer, John Salmon, Dimitri N. Mavris, and Neil Weston. Comparative assessment and decision support system for strategic military airlift capability. 2011.

[6] San Kilkis, Nabih Naeem, Prajwal Shiva Prakasha, and Nagel Bjorn. A python modelling andsimulation toolkit for rapid development of system of systems inverse design (sosid) case studies. In *AIAA*, 2021.

[7] Prajwal Shiva Prakasha, Nabih Naeem, Patrick Ratei, and Björn Nagel. Aircraft architecture and fleet assessment framework for urban air mobility using a system of systems approach. *Aerospace Science and Technology*, 125:107072, 2022. SI: DICUAM 2021.

[8] Mark Thompson. Costly flight hours, 4 2013.

[9] Daniel P. Raymer. *Aircraft design: A conceptual approach.* Air Force Institute of Technology, 1992.

[10] *GLOSSARY OF DEFINITIONS, GROUND RULES, AND MISSION PROFILES TO DEFINE AIR VEHICLE PERFORMANCE CAPABILITY*, volume MIL-STD of *A*. Department of Defense, 3013 edition, 2008.