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Masterarbeit

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Conceptual Aircraft Design Methodology for Disaster Relief Operations with a Variable Fidelity Interface

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Conceptual Aircraft Design Methodology for Disaster Relief Operations with a Variable Fidelity Interface

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Zusammenfassung

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Conceptual Aircraft Design Methodology for Disaster Relief Operations with a Variable Fidelity Interface

Keywords

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Abstract

Ziel der Arbeit ist der Aufbau von Vorentwurfsfähigkeiten für Cargo Flugzeuge in humanitären Einsatzgebieten. Die Arbeit basiert auf dem DLR eigenen Flugzeugentwurfstool „openAD". Die Software muss vom kommerziellen Passagier- auf Cargotransportzweck umgeändert werden. Die Abmessungen und Massen der Cargos sollen damit zum entwerfenden Faktor des parametrisierten Flugzeugentwurfs werden. Dazu wird ein Referenzflugzeug nachentworfen und auf der Geometrie-, Massen- und Leistungsebene kalibriert. Die implementierten Methoden werden durch ein geeignetes Design of Experiment validiert.

Abstract

The target of the thesis is to develop conceptual design capabilities for cargo aircraft in humanitarian areas of operation. The work is based on DLR's inhouse aircraft design tool "openAD". The software has to be modified from commercial passenger to cargo transport purposes, and make the cargo dimensions and masses driving the parametrized conceptual aircraft design. Therefore, a reference aircraft is redesigned and calibrated on the geometrical, mass and performance level. The implemented methods are validated by a suitable design of experiment.

Table of Content

List of Illustrations

List of Tables

List of Abbreviations

AMC	Aircraft Mission Calculator
CoG	Center of Gravity
CPACS	Common Parametric Aircraft Configuration Schema)
DLR	German Aerospace Center/Deutsches Zentrum für Luft- und Raumfahrt
DoE	Design of Experimet
EDA	European Defence Agency
FMTC	Future Medium-Size Tactical Cargo
HADR	Humanitarian Aid and Disaster Relief
HDR	Humanitarian Disaster Relief
HTP	Horizontal Tailplane
MLG	Main Landing Gear
MLM	Maximum Landing Mass
MTOM	Maximum Takeoff Mass
MZFM	Maximum Zero Fuel Mass
OEM	Operational Empty Mass
SATOC	Strategic Air Transport for Outsized Cargo
VTP	Vertical Tailplane
WAB	Weight and Balance Tool

1 Introduction

1.1 Motivation

Looking at the past decade of years, several major natural disasters have occurred. Due to the climate change, the severance and the number of these events is increasing. HDR (often also HADR) stands for Humanitarian Disaster Relief (respectively HADR: Humanitarian Assistance and Disaster Relief) and describes missions that are conducted to supply affected regions with the most necessary aid after a disaster case. Due to the destruction of the infrastructure, the essential supply with food, medical and technical equipment, it is often not possible to reach the affected regions over land in a short space of time. Especially the first few days immediately after a disastrous event, it is important to supply the regions with the most necessary goods or situation can become life-threatening for the people.

Besides of military forces, Humanitarian Assistance and Disaster Relief missions are carried out by various organizations at international, national, and local levels. Some prominent global organizations specializing in humanitarian aid and disaster relief include for example the Red Cross Organizations, UNICEF [1] and Doctors Without Borders [2].

Countries, military, humanitarian organizations and private organizations have stocks of relief supplies like food, medical supplies, shelters, power generators, machines, and different kinds of vehicles that can be shipped spontaneously. Every disaster has its own peculiarities and therefore the composition of the relief supplies needed can vary much from disaster to disaster [3].

In general, there is the possibility to transport relief goods over land routes, via the water way or by aircraft. Each way has its advantage or disadvantage. But more important is, which way can be used, considering the distortion of the infrastructure caused by the disaster and which way provides the fastest accessibility to the affected area.

Therefore, the fastest method to move the cargo to the places is via air. Military Transport Aircraft are used to transport these all kinds of relief supplies to the affected areas and can land on unimproved runways.

In the Military transport aircraft were often deployed for humanitarian purposes during disasters to facilitate relief efforts. For example, in 2004, when a tsunami destroyed parts of Indonesia, Sri Lanka and Thailand, in 2005, when hurricane Katrina devasted parts of the USA, In 2010, during the earthquake of Haiti. Also, in 2011 at the nuclear disaster in Fukushima.

1.2 Aircraft used for HDR Missions

Due to the requirement to transport heavy and outsized cargo directly to the scene, and easy handling of the transported cargo, civil commercial cargo aircraft cannot be used in the most cases. For load and unloading these aircraft, specific lifting vehicles would be required that cannot be assumed to be at the place of landing. Thus, military transport aircraft are typically used for HDR operations. The design requirements of these aircraft usually have a military background based on strategical or tactical tasks and requirements, that they are supposed to fulfill. Usually these aircraft shall be capable of a wide range of roles and purposes. Besides of purely transporting cargo or vehicles, they can be equipped with additional seats or can be converted into an intensive care unit. Therefore, the equipment often is modular and can be swapped with another modular furnishing in a short time.

In an HDR event huge amounts of relief supplies of different cargos like technical equipment, vehicles, food, medical supplies and rescue assistants need to be transported. But also, vehicles like large all-terrain trucks, excavators, or disassembled helicopters need to be transported. Therefore, the cargo hold dimensions must contain a wide range of vehicles and provide spaces to tie down the payload and leave gangway for the loadmaster. Besides of cargo, besides passengers like rescue teams also need to be transported.

Due to the diversity of the cargo these aircraft are different from civil aircraft. Compared to most of the civil freighter aircraft like Boeing 777F, Airbus A300F, DC-10 or Boeing 747-8F, military transport aircraft are usually equipped with at least an aft cargo door that when opened works as a ramp for loading and unloading the cargo. Some of the large military transport aircraft also have a nose that can be opened.

There are different sizes of military transport aircraft available. The sizes of the aircraft correspond to their design mission. The typical differentiation of the aircraft is their military use case: whether tactical or strategical.

Strategic use cases consist usually in moving bulky and heavy cargo, like military equipment or vehicles over a great distance. Therefore, it is favorable to move as much payload into one aircraft. The combination of long-range aircraft and high cargo capacity leads to large aircraft with wide fuselages. An example for this kind of aircraft is the Lockheed C-5M Super Galaxy. Often these aircraft also have not only a cargo ramp on the aft, some of them also have a nose cargo door. This enables fast load and unloading without shunting the cargo. Especially for large vehicles like this is an advantage.

Tactical aircraft are usually deployed from an air base relatively close to the Area of Operation. Therefore, their design range is short to medium range, and their design payload capacity is much lower than for strategic aircraft. Due to their military use case, they need to agile and robust. They are usually driven by turboprop engines which are robust and less prone to damages when operated on unimproved airstrips.

In general, the landing gear design is different from civil aircraft. Civil high wing aircraft usually carry the landing gear in fuselage or in the engine pylon. For military transport aircraft, this is not an option due to the high wing configuration and the height of aircraft. The aircraft needs to have a high stability against toppling, therefore the track of the main landing gear needs to be wide. Also, the cargo floor should be low to load and unload cargo directly with a ramp to the ground or to a truck. Therefore, the landing gear is usually placed on the lower sides in side pods outside of the fuselage. Due to landing on unpaved airstrips it is favorable to have individual axle suspension rather than a for commercial aircraft typical bogie arrangement.

The aft cargo ramp can not only be used for loading and unloading the payload on ground. In disaster cases where the aircraft cannot land, the relief supplies can be dropped from the aft ramp inflight.

1.3 Overview of military transport aircraft design landscape

Conceptual aircraft design in general is a multidisciplinary approach that consists for example of the disciplinaries like aerodynamics, structures, propulsion, systems, performance, etc. There are a some widely known standard books that are used for conceptual aircraft design, that tackle most of the disciplines, mentioned above. Most of these books can be recognized as a guideline or used as a handbook that can be followed step by step. Some examples for the overall aircraft design methodologies in the literature are composed by Raymer [4], Roskam [5], Torenbek [6] and Nicolai [7]. They lead chapter by chapter through the different design disciplines. Usually, these books give also a broad overview about different types of aircraft and show up the main characteristics and mention different design features. But most of the methodologies included in the books are concerning civil aircraft. None of the books is wholesome specified for military transport aircraft. Often, aspects for these kinds of aircraft are mentioned in an accessory sentence or as an extension of a methodology.

Besides of books or handbook methods, there are some papers and university projects and theses, that deal with military transport aircraft design. Andrade [8] designs a new heavy lift transport aircraft with the size of the Lockheed C-5 Galaxy. The paper from Bolsunovsky et al. [9] are designing a three-deck large cargo transport aircraft called “Elephant” which is similar to the large transport aircraft AN-124 from Antonov. Aditya et al. [10] are designing a military cargo aircraft based on classic handbook methods. Rabizadeh and Kasabi [11] conduct a conceptual design approach using the predominantly the methods from Raymer [4].

Besides of the overall conceptual aircraft, there are papers that tackle specific disciplines like e.g. for improving aerodynamic of a military transport aircraft aft body by Rao et al. [12]. Kalliatakis [13] develops a framework that enables the coupling of aircraft, fleet and concepts of operations in a strategic cargo airlift using agent-based modeling.

The European Defence Agency (EDA) is supporting several European nations in harmonizing their requirements for future military transport aircraft. There are two projects for a new tactical and strategic transport aircraft called "Future Medium-Size Tactical Cargo" (FMTC) and "Strategic Air Transport For Outsized Cargo" (SATOC) [14].

Among other topics, the German Aerospace Center (DLR) conducts research into aircraft design. They are using the inhouse aircraft design tool called “openAD”. This software is used for sizing and designing commercial transport aircraft. Among other top-level aircraft requirements, yet the sizing is of the aircraft is driven by the number of passengers. The capabilities of the software should be extended for cargo transport in humanitarian disaster cases. Therefore, the aircraft sizing should be driven by the cargo dimensions and masses instead of the number of passengers. New methods have to be implemented that considers the cargo and the design requirements needed for designing an aircraft for humanitarian disaster cases.

2 OpenAD Software

For the aircraft design, the software “openAD” is used, which is a python-based conceptual aircraft design software developed by DLR. It offers a “multidisciplinary and multi-fidelity design environment for aircraft design to evaluate and assess various concepts and technologies at aircraft level”. [15] The software just needs a small set of top-level aircraft requirements to calculate a valid and consistent aircraft design, but of course the more defined the requirements are, the more precise the design can become. So far, aircraft layouts conventional aircraft from the size of a Dornier D228 up to an Airbus A380 are able to be calculated. Furthermore, openAD was expanded design new layouts like Blended Wing Bodies [16], General Aviation Aircraft [17] or Supersonic Aircraft [18].

In openAD the aircraft is divided into components. Each component consists of different disciplines and every discipline contains their designated parameters with their individual calculation methods, see Figure 2-1. Due to its object-oriented structure it is very easy to extend, change or implement new parameters and new methods into the specific disciplines. Most of the implemented calculation methods are based on publicly available handbook methods, for example from Raymer [4], Torenbeek [6], Roskam [5], Luftfahrttechnisches Handbuch [19]. Open AD uses the SI unit system, therefore methods using the imperial unit system need to be converted.

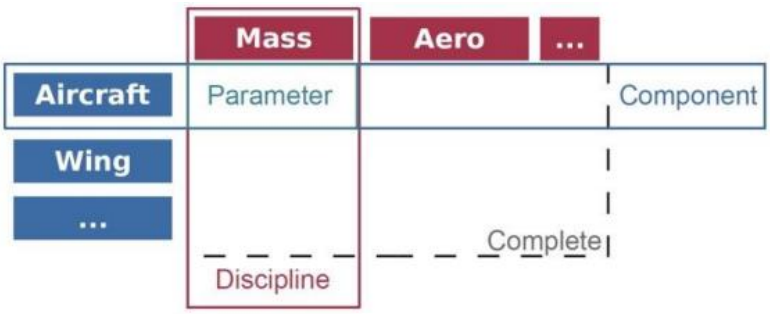


Figure 2-1: Arrangement of components, disciplines, and parameters, extracted from Ref. [15]

For exchanging data in collaborative aircraft design projects that contains various disciplines, it is beneficial to use a standardized data format. OpenAD interprets XML files using CPACS (Common Parametric Aircraft Configuration Schema) [20] as an input to define calculation settings and to manipulate calculation parameter. After openAD processed the input and calculated the aircraft design, an output file also using the CPACS schema is generated where all the relevant aircraft design parameters are exported. Each parameter holds several attributes (value, unit, factor, status, CPACS path, upper-/lower bound) that can be accessed manipulated in the CPACS tool specifics.

An input file contains the set of parameters and top-level aircraft requirements, that will drive the design. If a value of a parameter is defined, its status will be set to “fixed”, and consequently nor be calculated by the parameter’s method nor overwritten. The status can also be defined as “init”, that will use the designated value only for an estimation run but afterwards be reevaluated in the calculation run.

OpenAD is a powerful aircraft design tool, but DLR and project partners develop further tools, that are more focused or specialized in certain design disciplines. To integrate these tools for multidisciplinary and mulitfidelity collaborative aircraft design the open sourced software RCE is used [21]. The different more specialized tools will lead their results back to openAD, where the design synthesis is taking place. Besides of connecting standalone tools, RCE contains its own modules e.g. for setting up design of experiments, or conducting algorithm optimization.

3 Methodology

A new aircraft design based on a real transport aircraft is to be set up. With usage of the aircraft design software openAD, the aircraft design is processed. The setup includes extracting the publicy available performance data, defining new design methods and calibration of the software model to the performance data of the A400M.

After having obtained the baseline aircraft model, several Design of Experiments (DoEs) are conducted, to evaluate the design model and to highlight and discuss specific design parameters.

3.1 Redesgin Process of Reference Aircraft

As reference aircraft the Airbus A400M is chosen. Its aircraft design is placed between the smaller Lockheed C-130J and the bigger Boeing C-17, and is designed to conduct missions in the medium-range to lower long-range domain. Therefore, it can be deployed for strategic as well as for tactical use cases. It is driven by 4 turboprop engines and uses the typical high wing configuration combined with a T-tail. The A400M can fly up to 41.000 ft at fly at $\mathrm{Mach}\ 0{,}68$. The main landing gear consists of 6 tires and 3 axles for each side, is placed on the lower sides of the fuselage and is retracted into side pods. It has the ability to start and land on short and unpaved runways.

Due to is large fuselage diameter, a large variety of cargo can be loaded. A few loading examples are shown in Figure 3-1.

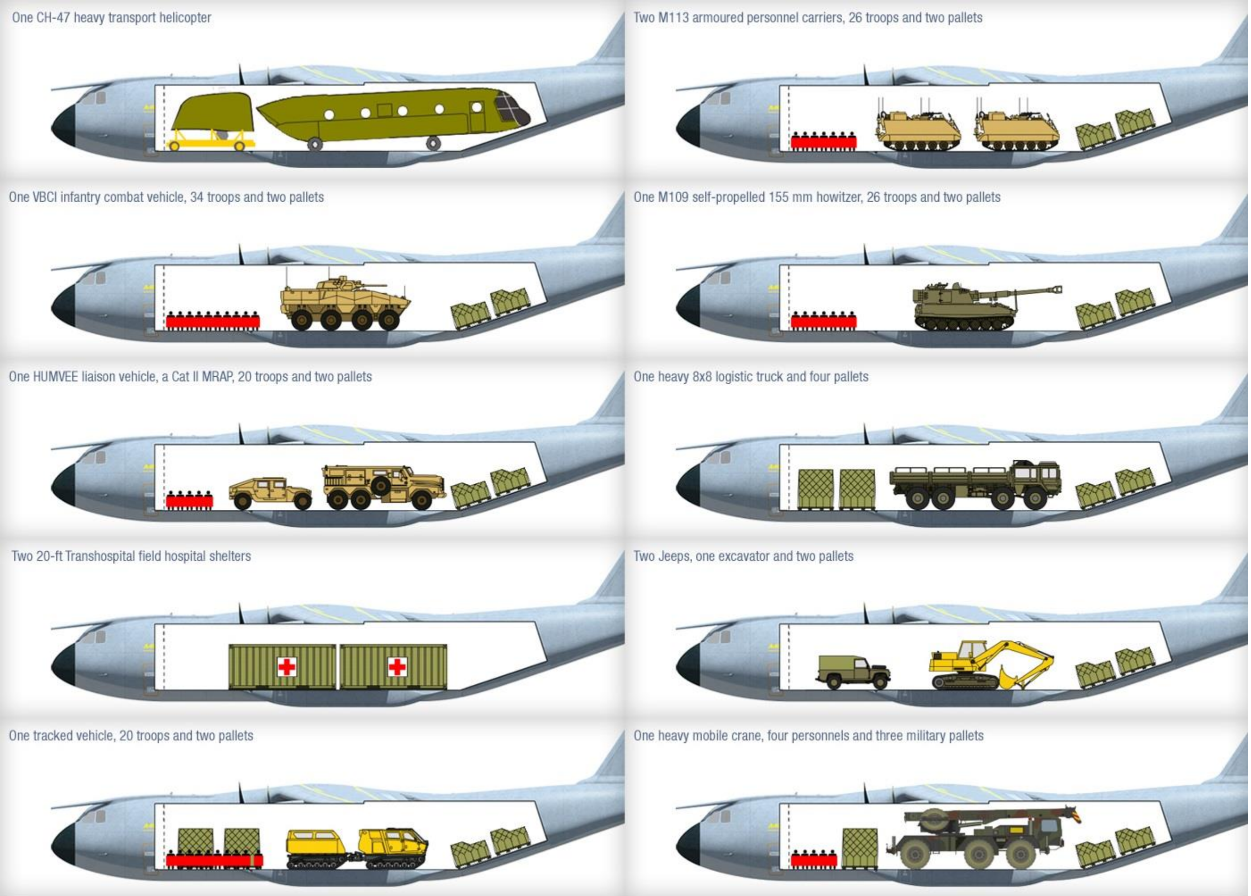


Figure 3-1: Examples of loading options, according to Ref. [22]

Aircraft manufacturer and operators keep detailed specifications and technical data about military inventory quite confidential. Therefore, there are not many information about these aircraft publicly available. Dependent on the sources of the information that can be found, they can be used as a reference values but with caution that they might not be the exact true values.

Under utilization of technical data, top level aircraft requirements, performance data and further design specifications found in the presentations from Wieland [23], López Díaz [24], Alonso [25], and in databases like Skybrary [26] a set of data could be put together that represents the reference aircraft well. A three-side view was used to measure distances and geometrical details, that cannot be found in public data, e.g. position of wing, horizontal- and vertical tailplane, engine position, fuselage diameters.

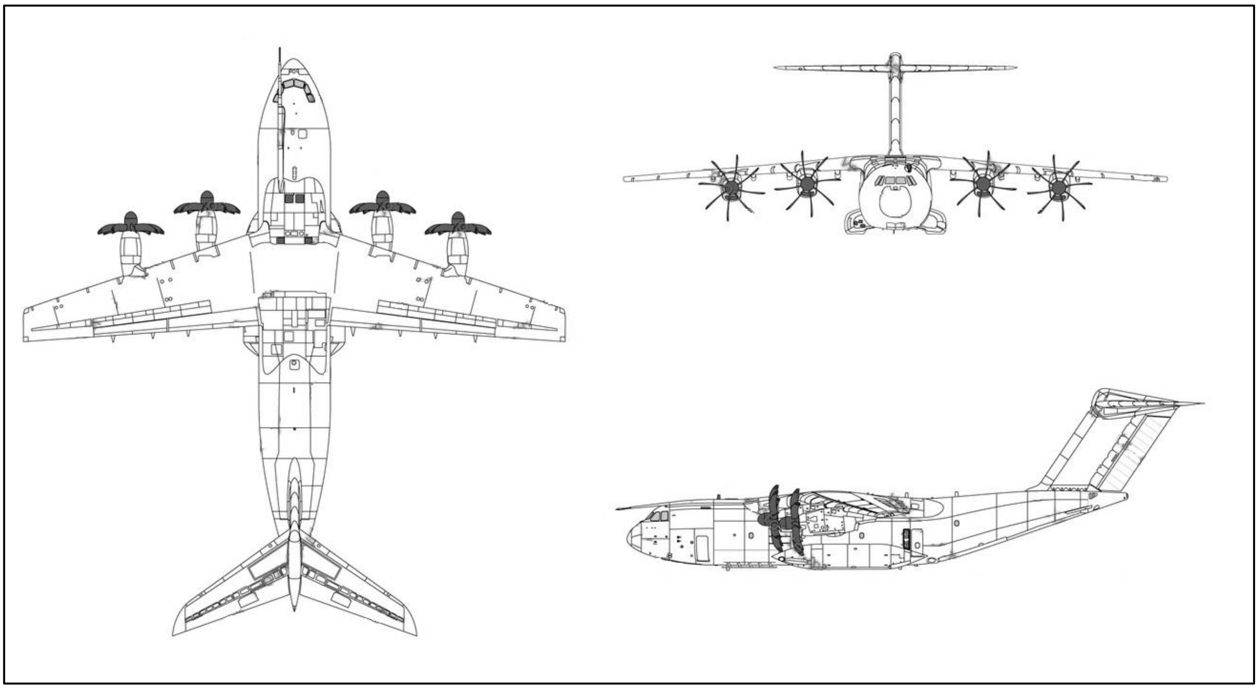


Figure 3-2: Three-side view of Airbus A400M aircraft, extracted from Ref. [26]

The fuselage was recreated using ellipses. To recreate the geometry of the fuselage width and height as well as the vertical displacement from the longitudinal centerline of several cross sections were measures from the three-side view above. Due to the geometry changes more in the area of nose and tail than for the cargo hold, more cross sections lying closer together were measured in for these areas.

Table 3-1 lists the key aircraft characteristics for that are crucial for the aircraft design.

Table 3-1: Key aircraft characteristics

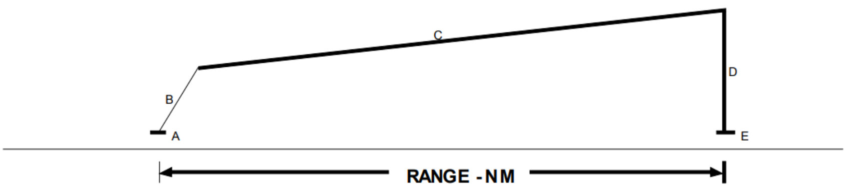
Parameter	**Unit**	**Value**
Design Payload Mass	kg	30.000
Max. Payload Mass	kg	37.000
Design Range	km	4.535
Cruise Altitude	m	7.800
Takeoff Distance	m	1.980
Approach Speed	m/s	98
Engines	-	4
Cruise mach number	-	0,68

3.2 Methods for Redesigning a Military Transport Aircraft

3.2.1 Mission Profile for Military Transport Aircraft

In the standard practice document “Glossary of Definitions, Ground Rules, and Mission Profiles to Define Air Vehicle Performance Capability” [27] of the U. S. Department of Defense, three different types for military transport missions are described, cargo air drop, cargo/transport supply – radius, and cargo/transport supply – range.

The mission that used for the aircraft design is “cargo/transport supply - range” and its mission profile (Figure 3-3) show actually a standard single way flight route departing from location A to destination B without return flight. The mission profile is divided into 5 segments (A to E) and includes warmup and takeoff, climb, cruise, and a decent segment. A reserve segment gives respect to emergencies or routing to an alternate airport. Therefore, $30\ min$ of extra fuel with and an additional $5\ \%$ of the initial fuel mass needs to be considered.



	SEGMENT	FUEL	TIME	DISTANCE	SPEED	ALTITUDE	THRUST SETTING
A	WARM-UP, TAKEOFF, AND ACCELERATE TO CLIMB SPEED	20 MIN @ GROUND IDLE + 30 SEC @ TAKEOFF/ MAXIMUM/ IRT (A/B IF REQUIRED) + FUEL TO ACCELERATE FROM OBSTACLE CLEARANCE TO CLIMB SPEED @ IRT. NO DISTANCE CREDIT.					
B	CLIMB (PARA 4.2.2)				MINIMUM TIME CLIMB SCHEDULE (1)	TAKEOFF TO OPTIMUM CRUISE	MAX CONTINUOUS
C	CRUISE (PARA 4.2.3)				LONG RANGE CRUISE	OPTIMUM CRUISE	
D	DESCENT (PARA 4.2.8)	NONE	NONE	NO CREDIT		END CRUISE TO LANDING	
E	RESERVES	30 MIN + 5% OF INITIAL FUEL		NO CREDIT	MAXIMUM ENDURANCE	SEA LEVEL	
F							
G							
H							
I							
J							
K							
L							

NOTE: (1) CLIMB SCHEDULE ENDS AT LONG RANGE CRUISE SPEED/OPTIMUM CRUISE ALTITUDE.

Figure 3-3: Cargo/transport supply – range, according to Ref. [27]

3.2.2 Landing Gear

The landing gear for military transport aircraft has a different layout than for civil aircraft, that are supposed to land on improved runways. The placement to the lower sides of the fuselage leads to the cargo floor comes closer to the ground, which enables a better cargo handling for loading and unloading. Also, the trackwidth is larger than placing the gear directly under the fuselage, which results in a better tiliting stability. There are different landing gear arrangements that can have very unique retracting mechanisms. For the model, it is assumed that there is a simple arrangement consisting of several single suspended axles on each side. On each axle two tires are mounted.

Because there are no methods for the number of axles or tires mentioned in the literature for military transport aircraft, the number of axles and tires of existing aircraft are compared. Assuming, that the number of tires and axles is dependent on the maximum takeoff mass $mTOM$, a linear regression function was created, with the special requirement of having at least 2 axles per side.

The default methodology in openAD taken for the number of main gear tires is based on statistics of Boeing, Airbus, ATR, McDonnell Douglas and Embraer aircraft. It can be assumed that these statistics only relate to civil passenger aircraft, therefore a comparative chart has been set up, which is presented in Table 3-2. This chart gives an overview about maximum takeoff mass, payload, number of main landing gear tires, number of engines and the engine type of military transport aircraft in a range between Lockheed C-130J and Antonov AN-225.

Table 3-2: Comparable medium to long range military transport aircraft

Aircraft Model	Manufacturer	MTOM [kg]	Payload [kg]	# MLG Tires	# Engines	Engine Type
An-225	Antonov	640.000	190.000	28	6	Turbofan
An-124	Antonov	402.000	150.000	20	4	Turbofan
C-5	Lockheed	381.000	129.000	24	4	Turbofan
C-17	Boeing	265.350	78.000	12	4	Turbofan
An-22	Antonov	250.000	80.000	12	4	Turboprop
Y-20	Xi'an	220.000	66.000	12	4	Turbofan
A400M	Airbus	141.000	37.000	12	4	Turboprop
C-2	Kawasaki	141.000	36.000	12	2	Turbofan
C-390	Embraer	87.000	26.000	8	2	Turbofan
C-130J	Lockheed	70.370	20.000	4	4	Turboprop

The relation of number of MLG tires per side plotted over maximum takeoff mass is illustrated in Figure 3-4. The dashed line represents the linear regression of these data and the formula for the regression line is given in equation (1). It is assumed that an aircraft below a MTOM of $69.100\ \mathrm{kg}$ has four tires.

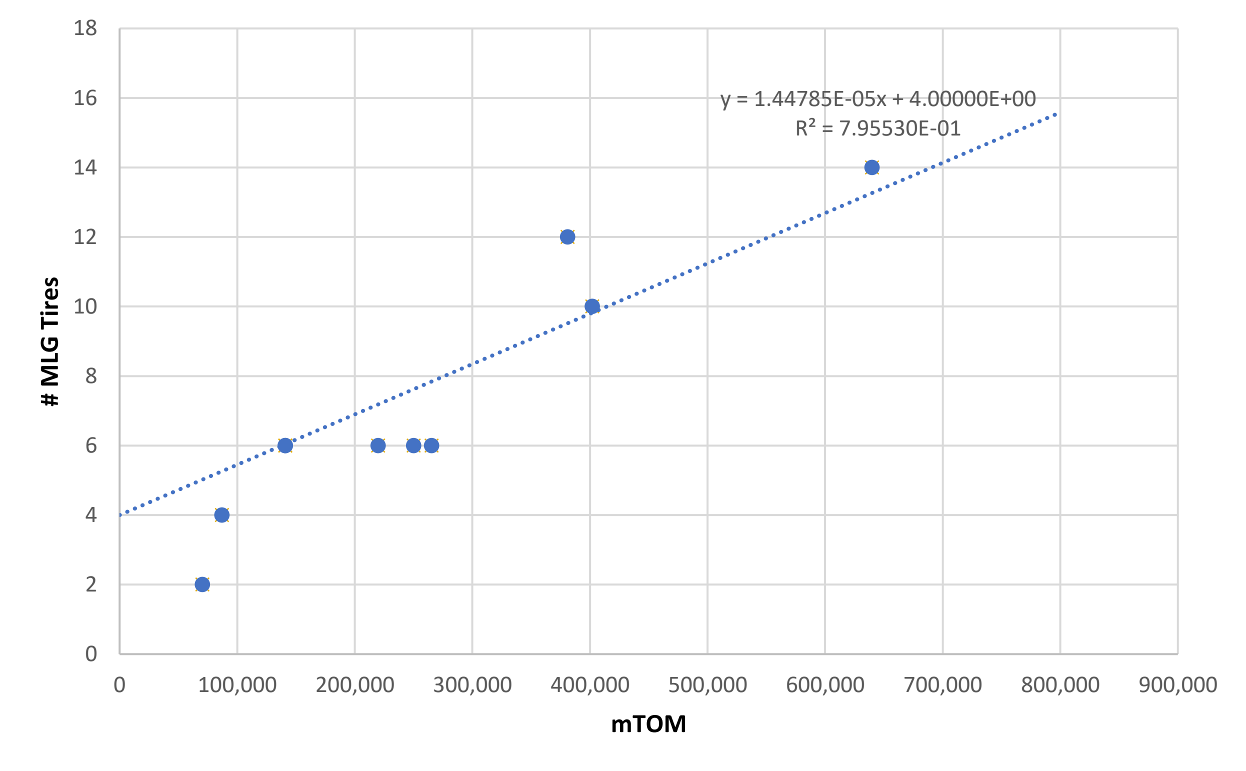


Figure 3-4: Number of main landing gear tires over maximum takeoff mass

$$\# \, MLG \, Tires = 1.44785 \times 10^{-5} \times mTOM + 4.0 \tag{1}$$

Dissolving equation (1) for MTOM considering the landing gear has even numbers in steps of two tires, the domains of MTOM for the number of tires can be calculated.

Table 3-3: Resulting number of MLG tires

$\boldsymbol{mTOM\ domain}\ [\boldsymbol{kg}]$	$\boldsymbol{\#\ MLG\ Tires}$
$mTOM < 69.100$	*4*
$69.100 \leq mTOM < 207.200$	*6*
$207.200 \leq mTOM < 345.300$	*8*
$345.300 \leq mTOM < 483.500$	*10*
$483.500 \leq mTOM < 621.600$	*12*
$mTOM \geq 621.600$	*14*

The openAD default arrangement for the MLG is using a boogie or a tripe boogie layout, where two or three axles are suspended by one shock absorber. This is the most typical arrangement that commercial aircraft are using. In difference military transport aircraft, are using individual suspended axles. The new geometrical approach considers each axle as an individual landing gear, e. g. for 6 tires, 3 axles are necessary and in turn 3 individual landing gears with the same geometry were created.

Dependent on MTOM domains of Table 3-3, the number of tires is selected. The number of tires defines the number of axles and the number of axles again define the number of landing gear units.

3.2.3 Payload and Aircraft Sizing

The default fuselage geometry definition is based on an inside out approach where the cockpit, passenger number and cabin definition is sizing fuselage length and height. The idea of this methodology is driving the aircraft sizing and design according to the size and mass of the payload.

Therefore, number of passengers and three types of cargo can be individually defined in its dimensions (length, width, height, mass) and the numbers of the individual types. A minimum clearance space of $0{,}15\mathrm{m}$ $(6\ \mathrm{inch})$ for each cargo units to all sides is considered. The aft cargo ramp is not defined for cargo placements.

The cargo dimensions drive the diameter and length of the fuselage. The sum of all cargo lengths including clearance spacings is directly defining the cargo hold length. The widest cargo and spacing to the sides define the cargo hold width. Equally the tallest cargo and a top spacing defines the cargo hold height. For simplification cargo units cannot be stacked on top of each other nor are two lines of cargo along the center line of the aircraft possible. The cargo holds' width and height are coupled with the fuselage diameter using a scaling coefficient.

The passengers are assumed to have a mass of $110\ \mathrm{kg}$ each, that includes the body weight of $80\ \mathrm{kg}$ plus $30\ \mathrm{kg}$ of personal equipment or luggage.

In difference to commercial aircraft, the seats are assumed foldable and placed along the fuselage sides and are equally distributed over the cargo holds' length. Thus, passengers sit with their backs to the fuselage side walls. The passengers seating depth (w_{Seat}) is assumed to require $0{,}6\ \mathrm{m}$.

$$w_{cabin} = w_{Cargo} + 2 \times w_{Seat} + 2 \times t_{Spacing} \tag{2}$$

$$\mathrm{h_{cabin}} = \mathrm{h_{Cargo}} + \mathrm{t_{Spacing}} \tag{3}$$

The center of gravity for each cargo unit is assumed to be in its geometrical center. With masses and positions of each cargo, the Center of Gravity (COG) for all cargos can be calculated, according to (4).

$$\mathrm{x_{CoG,Cargo}} = \frac{\sum \mathrm{m_i} \times \mathrm{x_i}}{\sum \mathrm{m_i}} \tag{4}$$

The baseline cargo layout is depicted in Figure 3-5 and has a total of $30.000\ \mathrm{kg}$. The cargo types loaded are two cargo pallets, one box truck, two light pallets and 58 passengers. Masses and dimensions of the baseline cargo types are listed in Table 3-4.

Figure 3-5: Baseline cargo layout. Ramp area for simplification not considered for cargo placement. Cargo dimensions are not fitting to absolute scale of cargo. Graphic from Ref. [22], edited

Table 3-4: Baseline cargo types

Cargo type	Number of units	Weight per unit	Length	Width	Height
Cargo pallet	2	3.310 kg	1,5 m	3,2 m	1,5 m
Box Truck	1	15.000 kg	8,5 m	3,2 m	4,25 m
Light Pallet	2	1000 kg	1,5 m	1,0 m	2,65 m
Passengers	58	110 kg	-	-	-

3.3 Calibration of openAD Model

Usually aircraft manufacturers have their own knowledge bases and use their own nonpublic design methodologies. Therefore, the aircraft design performed with openAD, which uses mostly public methods, will not directly match the masses, as well as geometrical, technical and performance data of the reference aircraft. Therefore, a calibration is conducted. The calibration aims for matching structural component masses, as well as geometricals and performance parameters.

The calibration conducted via the input file for openAD, by setting the attribute “status” to “fix” or “init”. That means, if a value is fixed, the value is directly taken from the input file without calculating its methodology. At the beginning, every known parameter is fixed, because the entirety of all describes the reference aircraft best. After that, the fixed parameters one by one are unfixed and multiplicated with a factor to match the targeted values.

The calibration process is depicted in Figure 3-6 and is described the following paragraphs.

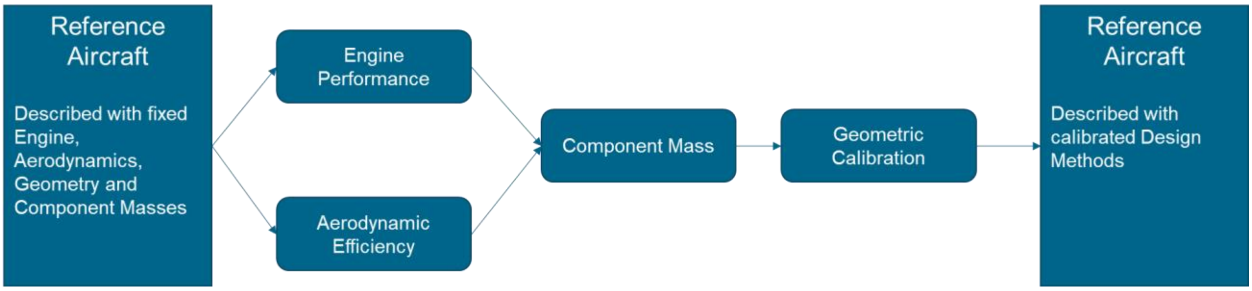


Figure 3-6: Calibration process

The calibration starts with the aerodynamic and engine performance calibration. In cause of a lack of reference values about propulsive and aerodynamic performance for the reference aircraft, these are an uncertainty factor for the aircraft design. Therefore, the calibration of these two disciplines are handled simultaneously. The adjusting screws for these disciplines consist of the engine efficiency $\eta_{\text{Gasturbine}}$ and the $\text{factor\_}c_D$ that is put on top of the overall drag coefficient calculation of the aircraft. Both values are manually adjusted until both are within a reasonable range. This becomes evident, when the lift over drag ratio and the specific fuel consumption are within the range of comparable aircraft and engines.

After the performance is calibrated, the component masses of the aircraft are calibrated. Within the presentation of Wieland [23], a chart of structural component masses and the operational empty mass (OEM) is given, see Table 3-5. Besides of OEM, also values for maximum takeoff mass (MTOM), maximum zero fuel mass (MZFM) and maximum landing mass (MLM) are extracted from the data sources. All of these values are first set to fixed values. With the known MTOM value of 141.000kg and the MLM of 114.000 kg, a ratio of MLM to MTOM can be set up.

The structural component masses are calibrated by unfixing and scaling each component to its targeted value one by one. The result of the openAD calculation and its targeted value from the technical data is compared. Usually, the calculation method does not match the target value. Thus, a scaling factor has to be figured out. After the scaled method value is fitting roughly, the parameter is calibrated.

Table 3-5: Structural component masses, extracted from [23]

Component	Mass
Wing	13.000 kg
Fuselage	19.000 kg
Horizontal Tail	2.200 kg
Vertical Tail	1.800 kg
Operational Empty Mass	66.500 kg

In the next step the geometricals are calibrated. The planforms are fixed for wing, VTP and HTP to the reference aircraft. Therefore, most relevant geometrical parameters are reference wing area and span of wing, VTP and HTP as well as fuselage with, height and length. After the calibration, a fixed aspect ratio extracted from the reference aircraft data is used instead of the absolute dimensions. This enables the scaling of the size wing according to the aircraft's needs, e.g. the aircrafts MTOM increases. The sizing factors of the reference wing area are approach speed, maximum landing mass and $c_{L,max,Landing}$. Except of $c_{L,max,Landing}$, all parameters are given in the data sources and are fixed, thus $c_{L,max,Landing}$ can be determined. After this, the value of $c_{L,max,Landing}$ and the approach speed is kept fix and the status of the other values are set to "init".

The sizing of the vertical tailplane (VTP) is dependent on the "one engine out during takeoff" event. The volume coefficient-like parameter $\mathrm{coeffoei}$, is the driving factor for the sizing. To obtain the value of the parameter from the reference aircraft as a guess, the geometrical dimension of the tailplane is fixed. In the next step, this value is set to "fix" and the geometrical dimensions are unfixed.

To free the sizing for the reference area of the horizontal tailplane (HTP) from absolute dimensional values. Similar to the VTP, at first all the known geometrical values of the reference aircraft are fixed and the volume coefficient of the HTP is calculated by openAD. Then this value is set fix and the geometrical dimensions can be unfixed.

3.4 Design of Experiments

After the calibration process is concluded, three different Designs of Experiments (DoE) are conducted. With these experiments different design parameters are varied to examine how the aircraft design model behaves

For the DoEs an RCE workflow is setup, visualized in Figure 3-7. It consists of several components and works as followed:

1. Load calibrated baseline Input File
2. Create a DoE-Matrix containing factors for the investigated design parameters
3. Create new Input File by merging Baseline Input File and factors of the Design of Experiment
4. Save new Input File
5. Conduct the aircraft design process based on the updated factors of the new Input File. provided by the Take the new Input File and conduct the aircraft design process performed by OpenAD
6. Save OpenAD outputs
7. Extract selected parameters from OpenAD outputs
8. Write selected parameters of each run into a Data Sheet

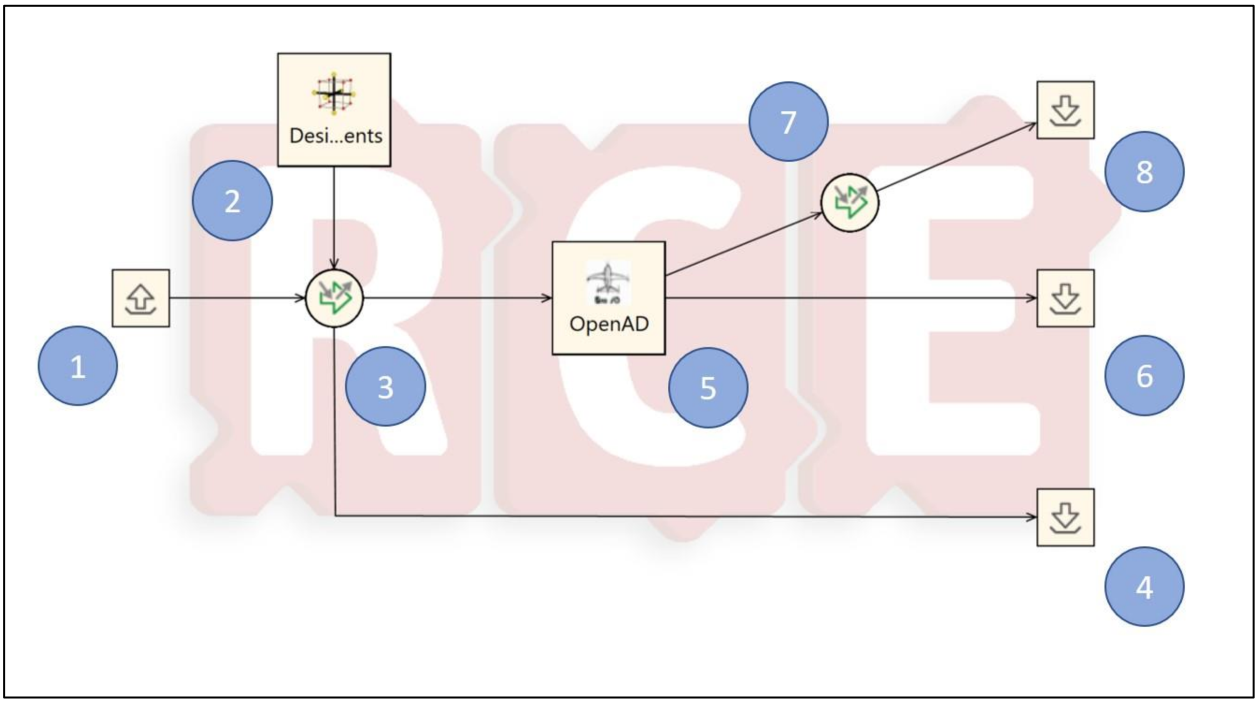


Figure 3-7: RCE Workflow

The first DoE investigates the influence of the dimension and masses of the different cargo units on the aircraft design (baseline dimensions in Table 3-4, layout in Figure 3-5). The cargo length and mass are changed up to $\pm 30\%$ and the height by up to $\pm 20\%$. For each cargo unit a full factorial data exploration with 5 levels is conducted. That results in 125 different scenarios for each cargo unit. In total three cargo types, 375 runs have to be calculated.

Table 3-6: Design parameters for DoE 1

Height	Length	Mass
$\pm 20\%$	$\pm 30\%$	$\pm 30\%$

The second DoE consists in the variation of the design range and the takeoff field length, three types of cargo layouts and investigates their influence on the aircraft design. The baseline values are $4535\ \mathrm{km}$ for the design range, $30.000\ \mathrm{kg}$ of payload and $1981\ \mathrm{m}$ and an for the takeoff field length. The total payload mass increases for a heavy and compact cargo to $33.500\ \mathrm{kg}$ and decreases for a voluminous and light cargo transport to $8.200\ \mathrm{kg}$. The cargo information for the 2 additional layouts are listed in Table 3-8 and Table 3-9. Range and takeoff length are varied for $\pm 40\%$ over 9 levels for three different cargo layouts resulting in 243 possible combinations. The heavy and compact layout includes a heavy all-terrain truck like the MAN 15t mil gl MULTI, assuming a gross weight of $29.500\ \mathrm{kg}$ that can be used to transport relief supplies over difficult terrain. An example for the cargo of the voluminous and light layout can be a disassembled mid-size helicopter, that is reassembled on site and can be used for aerial reconnaissance of the HDR situation and to supply remote locations with relief supplies.

Table 3-7: Design parameters for DoE 2

Design Range	Takeoff field length	Cargo type
$\pm 40\%$	$\pm 40\%$	Baseline, heavy & compact, voluminous and light

Table 3-8: Cargo masses and dimensions for heavy and compact cargo layout. No passengers transported.

	m	n	h	l	w
Cargo 1	29.500 kg	1	4,25 m	8,3 m	4,0 m
Cargo 2	1.000 kg	4	4,25 m	8,3 m	4,0 m

Table 3-9: Cargo masses and dimensions for voluminous and light cargo layout. No passengers transported.

	m	n	h	l	w
Cargo 1	1.000 kg	1	1,02 m	1,02 m	1,02 m
Cargo 2	7.200 kg	1	4,25 m	16,23 m	4,0 m

The third DoE addresses the characteristics that are related to the fuel. The design range is changed by $\pm 40\%$, the Loitering Time and additional reserve fuel percentage are changed by $\pm 50\%$. It should be noted for the additional reserve fuel percentage, that $\pm 50\%$ is the change of the percentage and not the percentage value itself. A combination of 125 different scenarios is obtained by using 5 values for each design parameter.

Table 3-10: Design parameters for DoE 3

Loitering Time	Additional reserve fuel percentrage	Design Range
$\pm 50\%$	$\pm 50\%$	$\pm 40\%$

4 Analysis and Discussion

In the following chapters, the aircraft design is evaluated and discussed. Firstly, the baseline aircraft design is examined. After that the design variations and the influences of the design parameters of the different DoEs on the aircraft design is inspected.

4.1 Calibrated baseline Aircraft

4.1.1 Three-side view

Figure 4-1 shows up the three-side view of the redesigned A400M model laid over the the A400M three-side view of Figure 3-2. It becomes visible that the overall geometrical redesign is matching well for most of the dimensions. In the side view the vertical diameter of the fuselage, seem to be slightly too large. This can be explained by using not a flattened kind of cross section geometry on the belly side of the fuselage. Instead the fuselage diameter geometry is simplified by using normal elliptical geometry. The length of the aircraft and the positioning of the wing, as well as the VTP and the HTP fits quite well. In the side view, the HTP could be placed slightly upward. In the top view, it is visible that the horizontal diameter of the fuselage as well as the span and geometry of the wing planform and HTP are matching close to perfect. The engines on the other hand could have been placed slightly outward. In the front view it becomes visible, that the engines are positioned too high and the nacelles are too small. But the sizing of the propeller diameter is matching good.

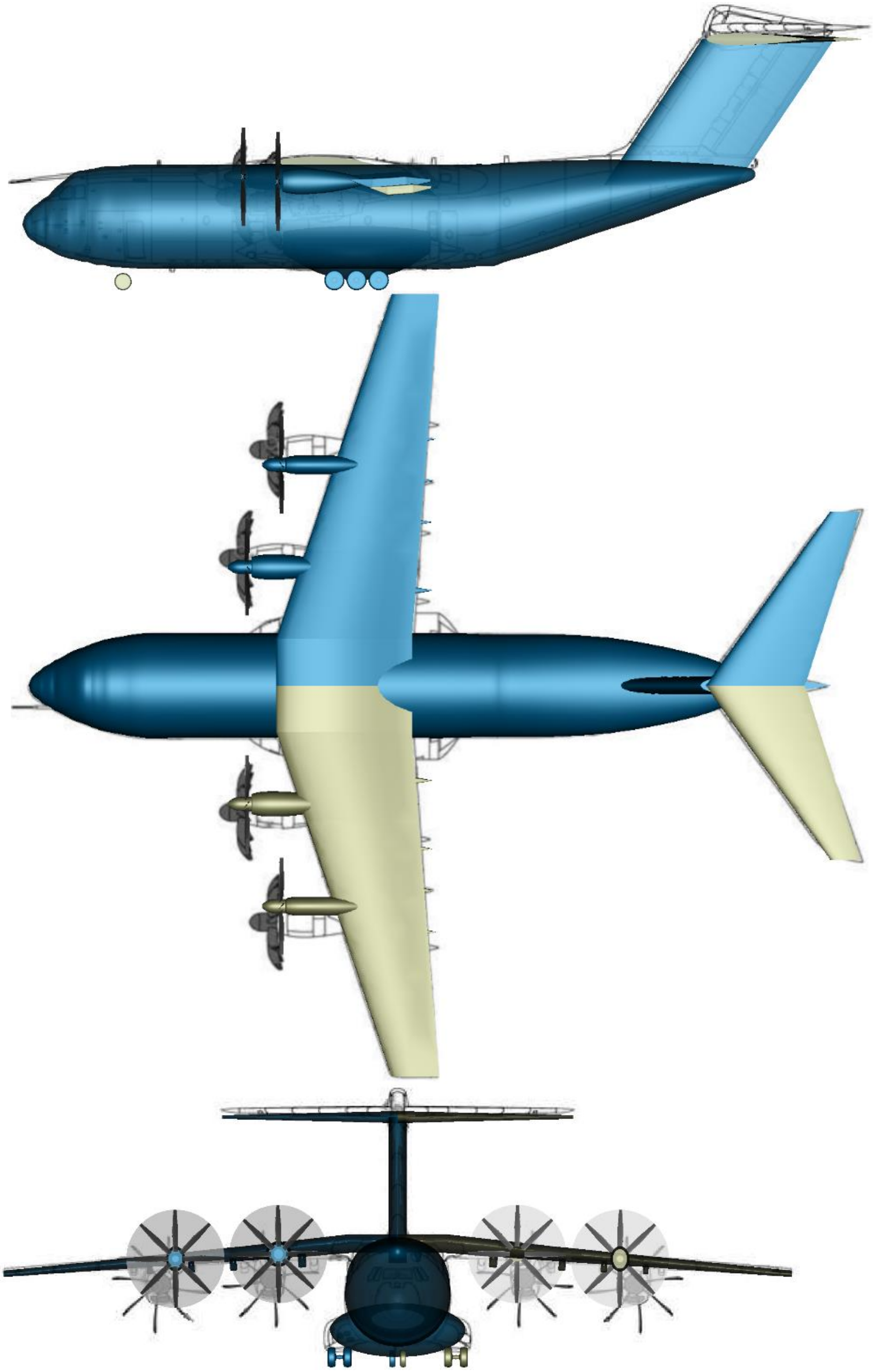


Figure 4-1: Three-side view of remodeled A400M aircraft

4.1.2 Aerodynamics

The lift over drag polar of the clean aircraft configuration is shown in Figure 4-2. Its maximum lift over drag ratio of approx. $14{,}25$ is reached at a lift coefficient value of $0{,}55$. During the mid-cruise phase, the lift over drag ratio is approx. $13{,}75$ at a lift coefficient of $0{,}45$. In Figure 4-3 the drag polar of the clean aircraft configuration is visualized. The value of the drag coefficient c_{D0} at zero lift is approx. $0{,}02$ or 200 when expressed in drag counts. For the lift coefficient of the mid-cruise phase, the drag coefficient increases to $0{,}035$.

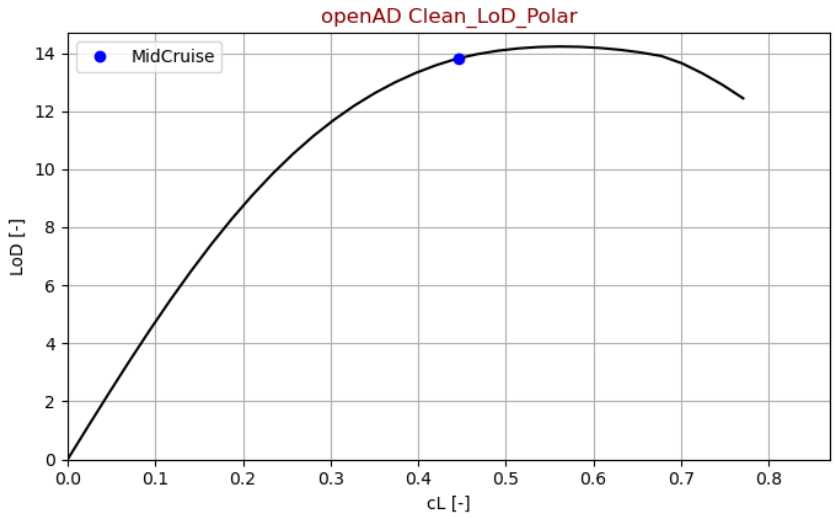


Figure 4-2: Clean lift over drag polar

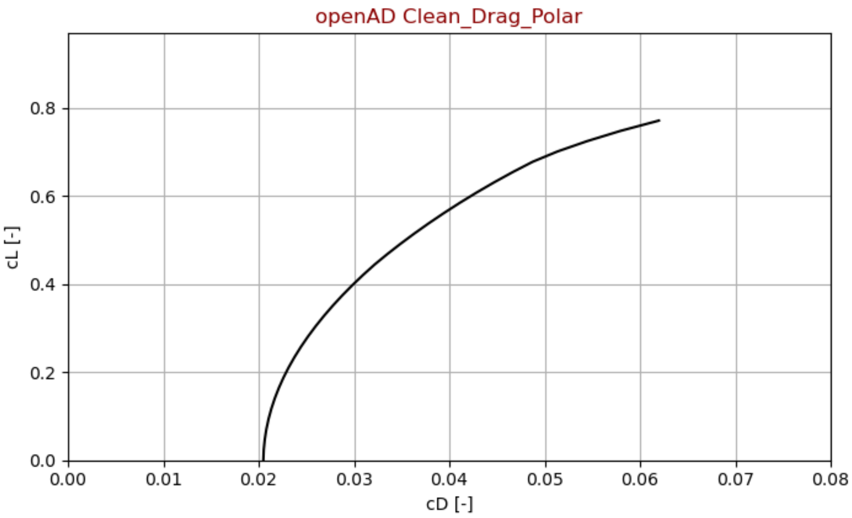


Figure 4-3: Clean drag polar

4.1.3 Drag Breakdown

In Figure 4-4 the drag breakdown of the remodeled aircraft is depicted. The entirety of the aircraft structure, consisting of the wing, HTP, VTP, fuselage and engines, accounts for approx. $62\ \%$ of the overall drag which is in total about $200\ \text{drag counts}$. The induced drag contributes with $35{,}3\ \%$ to the overall drag and has about $113\ \text{counts}$. Due to a low mach number in cruise condition of $0{,}68$ the wave drag is relatively small having only $9\ \text{drag counts}$.

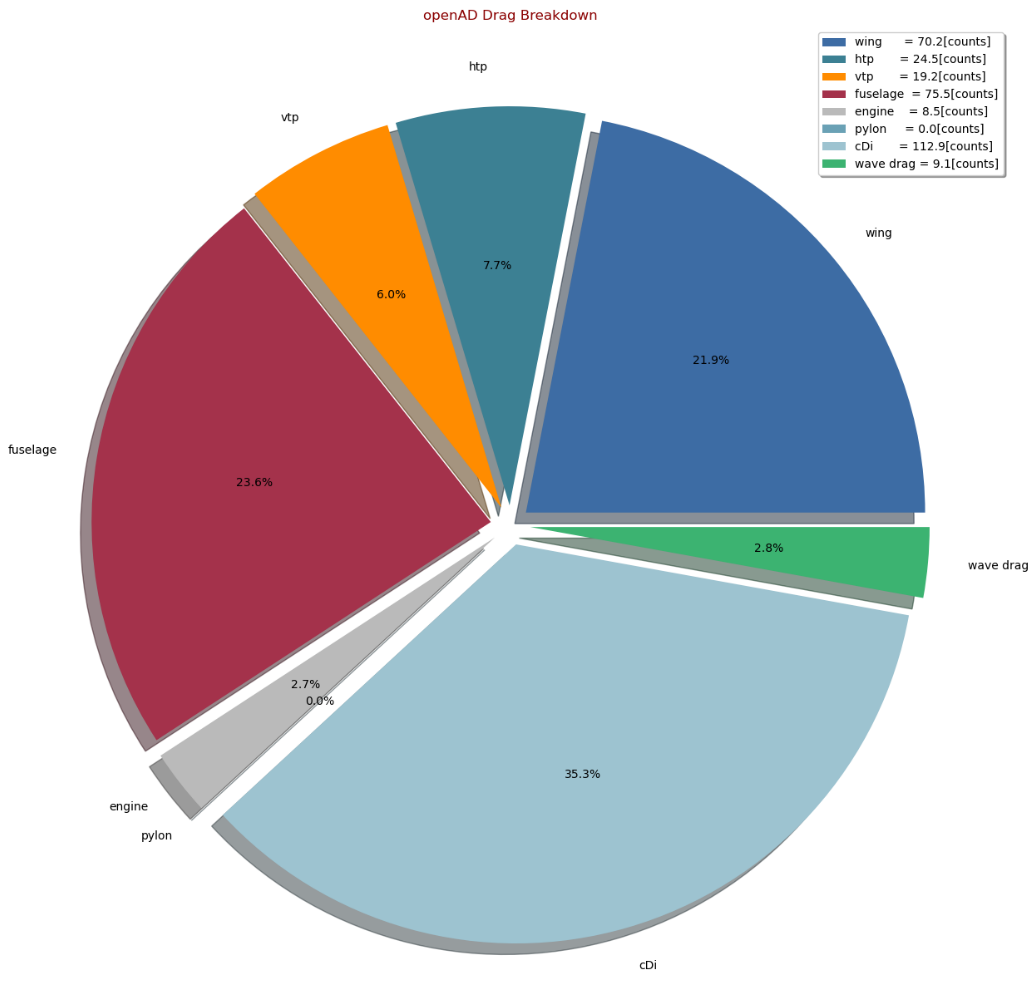


Figure 4-4: Drag breakdwon

4.1.4 Mass Breakdown

The MTOM breakdown visualized in Figure 4-5 represents the mass distribution of the aircraft components. If one compares the values for the wing, VTP, HTP and fuselage with the reference values of Table 3-5, only small deviations to the targeted values can be observed.

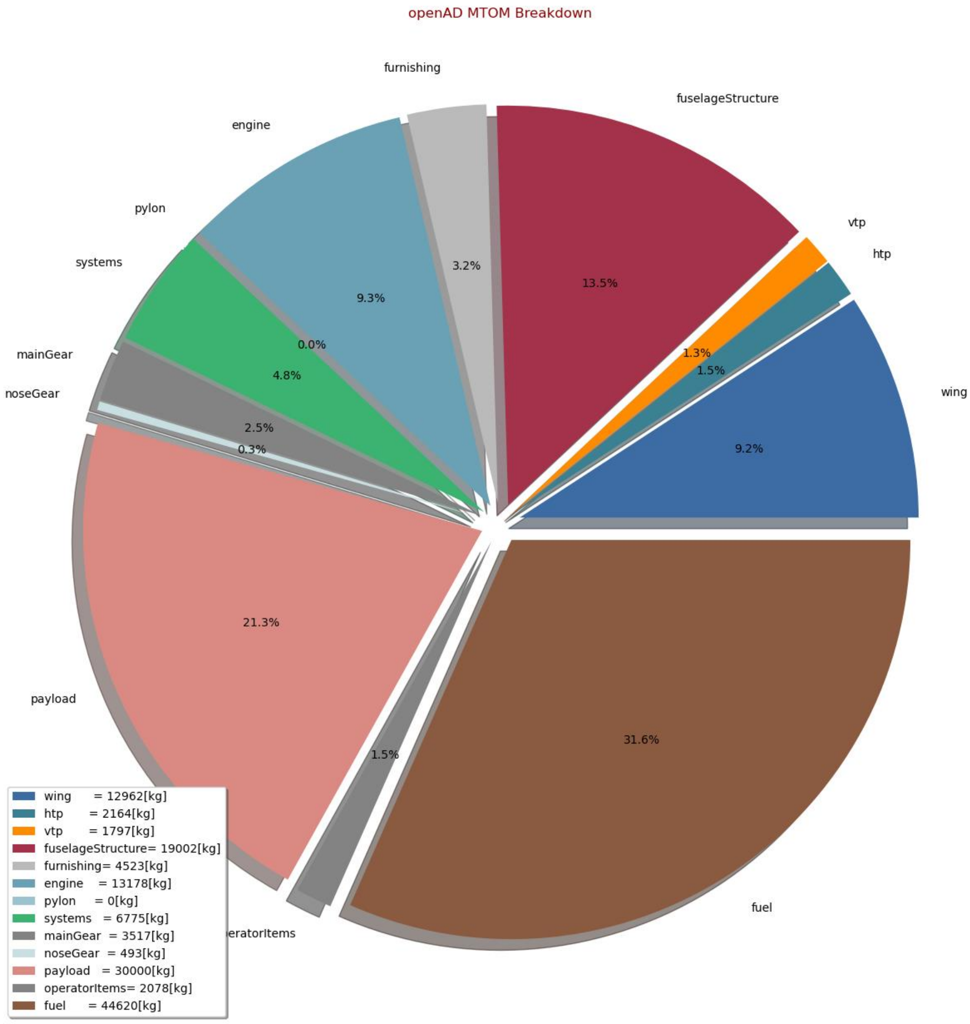


Figure 4-5: MTOM Mass breakdown

4.1.5 Payload Range Diagram

The Payload Range diagram is shown in Figure 4-6. The maximum payload of $37.000\ \mathrm{kg}$ can be carried up to a range of approx. $3.500\ \mathrm{km}$. The design point of the aircraft was defined at carrying $30.000\ \mathrm{kg}$ of Payload over a range of $4535\ \mathrm{km}$.

Comparing the payload range diagram from openAD calculations with a payload range diagram from Ref. [23], the maximum payload of the openAD model can be carried about $700\ \mathrm{km}$ further. The point of the maximum fuel carried is located quite high for a payload of $25.000\ \mathrm{kg}$ and $5.300\ \mathrm{km}$ of range, whereas the value from the literature is at $10.000\ \mathrm{kg}$ and $8.000\ \mathrm{km}$ of range. However, the diagram from literature assumes an aircraft with an MTOM of only $130.000\ \mathrm{kg}$ instead of the $141.000\ \mathrm{kg}$ at the openAD version. Eventually, the diagram refers to an early stage from the design process, but still the difference is quite big. A further try of explanation is the uncertainty in the assumption of the efficiency of the engines and the performance of the aerodynamics. As a result, the fuel consumption might be too high, which can lead to a shortened range.

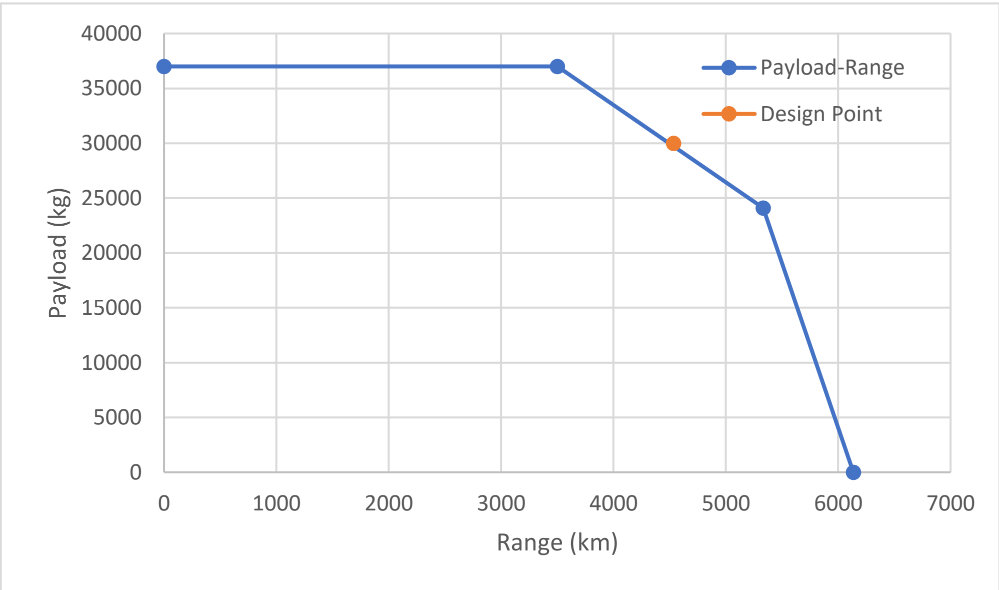


Figure 4-6: Payload-Range Diagram from openAD calculations

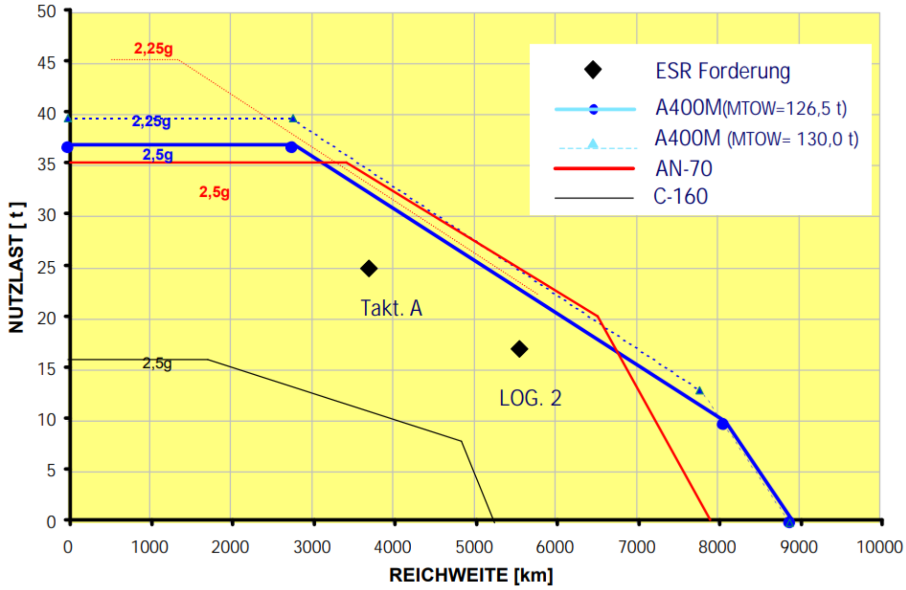


Figure 4-7: Payload Range Diagrams, extracted from Ref. [23]

4.1.6 Comparison of selected aircraft characteristics

Table 4-1 shows up a comparison of the MTOM, OEM, wing reference area, span, wing loading and the deviation of the values for the calibrated baseline aircraft design from openAD and the A400M technical data.

Table 4-1: Comparison of selected design characteristics and their deviation between openAD model and the A400M reference aircraft

MTOM [kg]		OEM [kg]		Wing ref. area [m^2]		Wing Span [m]		Wing Loading [kg/m^2]	
openAD	A400M	openAD	A400M	openAD	A400M	openAD	A400M	openAD	A400M
140.572	141.000	66.489	65.000	221,2	221,5	42,32	42,36	635,6	636,6
-0,30 %		+2,29 %		±0,00 %		±0,00 %		0,16%	

Table 4-2 provides an overview about the most central design characteristics.

Table 4-2: Design geometry, masses and propulsion characteristics

Parameter	Unit	Value
Geometry		
Wing Ref. Area	m^2	221,2
Wing Span	m	42,32
Wing Aspect Ratio	-	8,1
Wing MAC	m	5,66
Wing Taper Ratio	-	0,349
HTP Ref. Area	m^2	66,0
HTP Volume Coefficient	-	1,230
VTP Ref. Area	m^2	55,0
VTP Volume Coefficient	-	1,863
Fuselage Length	m	39,12
Fuselage Width	m	5,65
Fuselage Height	m	5,55
Masses		
Max. Takeoff Mass	kg	140.570
Max. Landing Mass	kg	113.820
Max. Zero Fuel Mass	kg	103.490
Operating Empty Mass	kg	66.490
Max. Fuel Mass	kg	44.620
Max. Payload	kg	37.000
Propulsion		
Takeoff Shaft Power	kW	7.656
Propeller Diameter	m	5,27
Wing Loading	kg/m^2	635,6
Power-to-Mass Ratio	-	0,239

4.2 Results of DoEs

In the following subchapters, the results for the different DoEs are presented.

4.2.1 DoE 1: Influence of dimension and mass of different cargo units

The first DoE investigates the influence of the dimension and masses of the different cargo units on the MTOM. The effect is visualized as a colorplot in Figure 4-8. The plots are grouped for the scaling factors of the cargo mass $(\pm 30\%)$ on the x-axis and for different cargo units on the y-axis. Each subplot shows the scaling factor for the cargo units length $(\pm 30\%)$ on the x-axis and for the height $(\pm 20\%)$.

It becomes evident, that the variation of cargo 1 (cargo pallets) and cargo 3 (light pallets) hardly have an impact on the MTOM of the aircraft design. Since the height and length of cargo 2 (box truck) do not fall under the dimensions of cargo 1 and 3, even at the smallest sizing factor for the dimensions, cargo 2 stays decisive for the size of the fuselage cross-section. On top of the geometrical sizing, cargo 2 is also much heavier and therefore the effect on the MTOM is amplified. Focusing on cargo 2, the MTOMs course of increase from $120.000\ \mathrm{kg}$ in the bottom left corner up to $170.000\ \mathrm{kg}$ in the top right corner meets the logical expectation of becoming heavier, due to the increased fuselage size, the increased payload mass. The truncated data field at cargo 2 with a mass factor of 1 is due to convergence problems in the openAD calculation. Thus, no data can be obtained from openAD calculations. In Figure 4-9 the effect of scaling cargo unit 2 becomes directly visible for the aircraft design. Using the smallest scaling factors of the DoE $(\mathrm{m} = 0{,}7;\ \mathrm{h} = 0{,}8;\ \mathrm{l} = 0{,}7)$ the blue aircraft is obtained. The green aircraft is the result of the baseline aircraft with no scaling. The pink aircraft is obtained by using the maximum scaling factors $(\mathrm{m} = 1{,}3;\ \mathrm{h} = 1{,}2;\ \mathrm{l} = 1{,}3)$ for cargo unit 2.

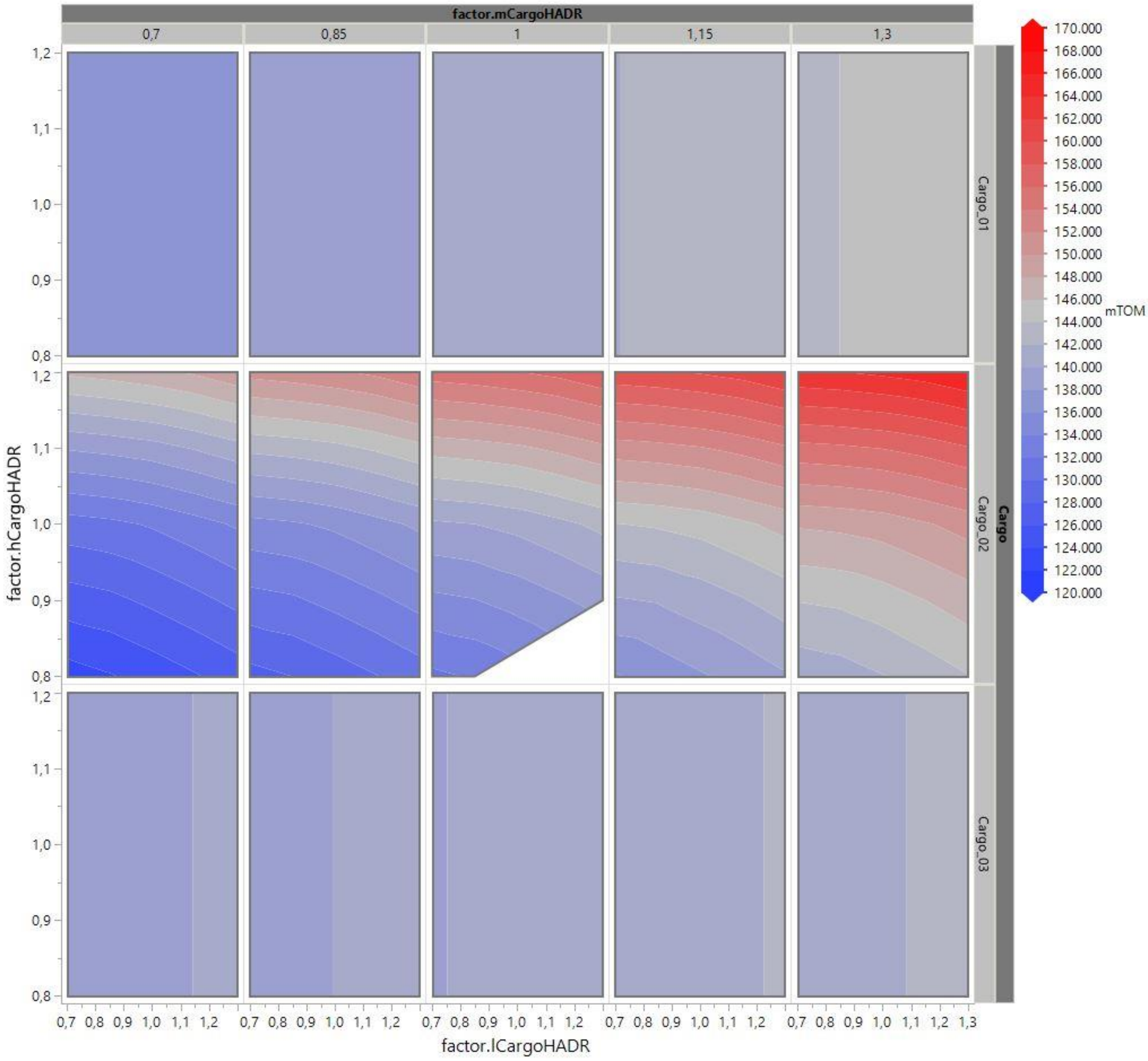


Figure 4-8: Influence of cargo unit dimensions and masses on the MTOM

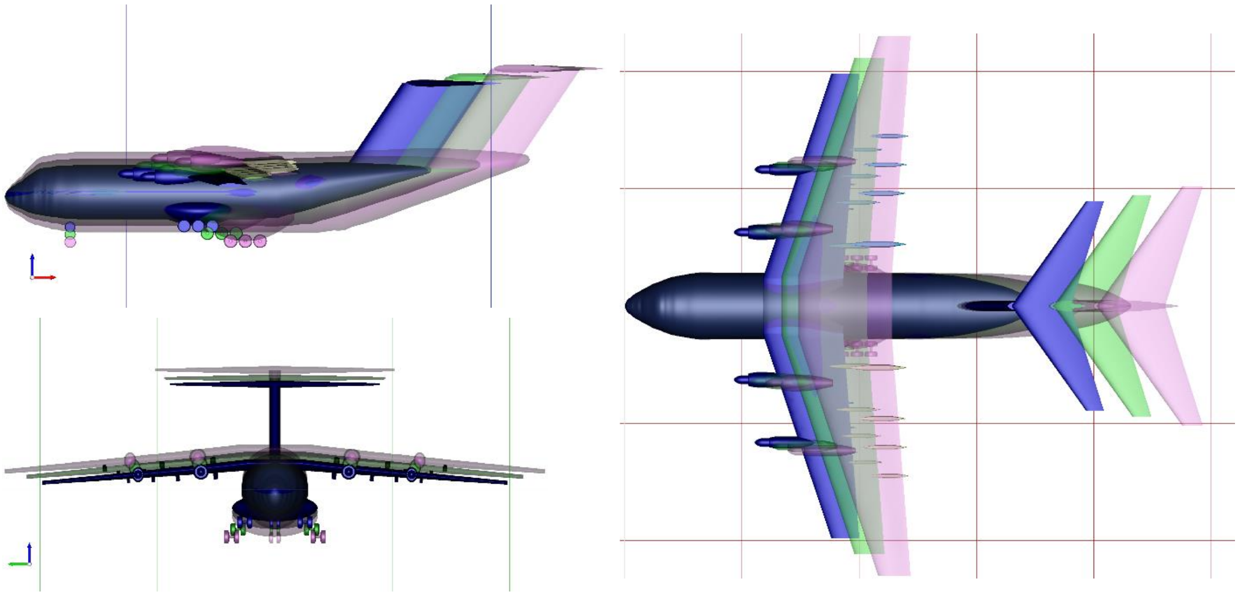


Figure 4-9: Effect of cargo scaling parameters of cargo unit 2 on aircraft size. Blue: Minimum scaling factors; Green: Baseline (no scaling); Pink: Maximal scaling factors

4.2.2 DoE 2: Influence of different cargo types, takeoff length and range

The second DoE consists in the variation of the design range and the takeoff field length, three types of cargo layouts and investigates their influence on the aircraft design. The results for MTOM are visualized in the colorplot of Figure 4-10 and within are grouped for the different cargo types alongside of the y-axis. The design range is applied on the x-axis while for each cargotype the required takeoff field length is applied on the y-axis. Besides the baseline payload configuration, a payload with cargo configuration containing one very heavy single cargo mass and a payload of a voluminous but light cargo mass are assumed in contrast, the payload dimension and masses for the additional cargo layouts are listed in Table 3-8 and Table 3-9. The initial value of $4.535\ \mathrm{km}$ for design range is varied for $\pm 40\%$ resulting in values between $2.720\ \mathrm{km}$ and $6.350\ \mathrm{km}$. The initial required takeoff field length is $1980\ \mathrm{m}$ and also varied for $\pm 40\%$ resulting in a variation range between $1190\ \mathrm{m}$ and $2770\ \mathrm{m}$. The curvature of the graph up to the kink point, from where it changes into an almost vertical line, is due to the dependency of the available takeoff field length and the thrust required to accelerate the aircraft. The shorter the runway the more thrust is necessary to takeoff. And the more thrust is required, the heavier engines, the heavier the structure and the more fuel is necessary. Therefore, the highest values for the MTOM can be found at the highest design range, the shortest takeoff field length and the heaviest cargo layout. After the kink point, other the sizing methods for the mission become relevant, and therefore impact of the runway distance to the MTOM vanishes. Overall the range has the most impact on MTOM.

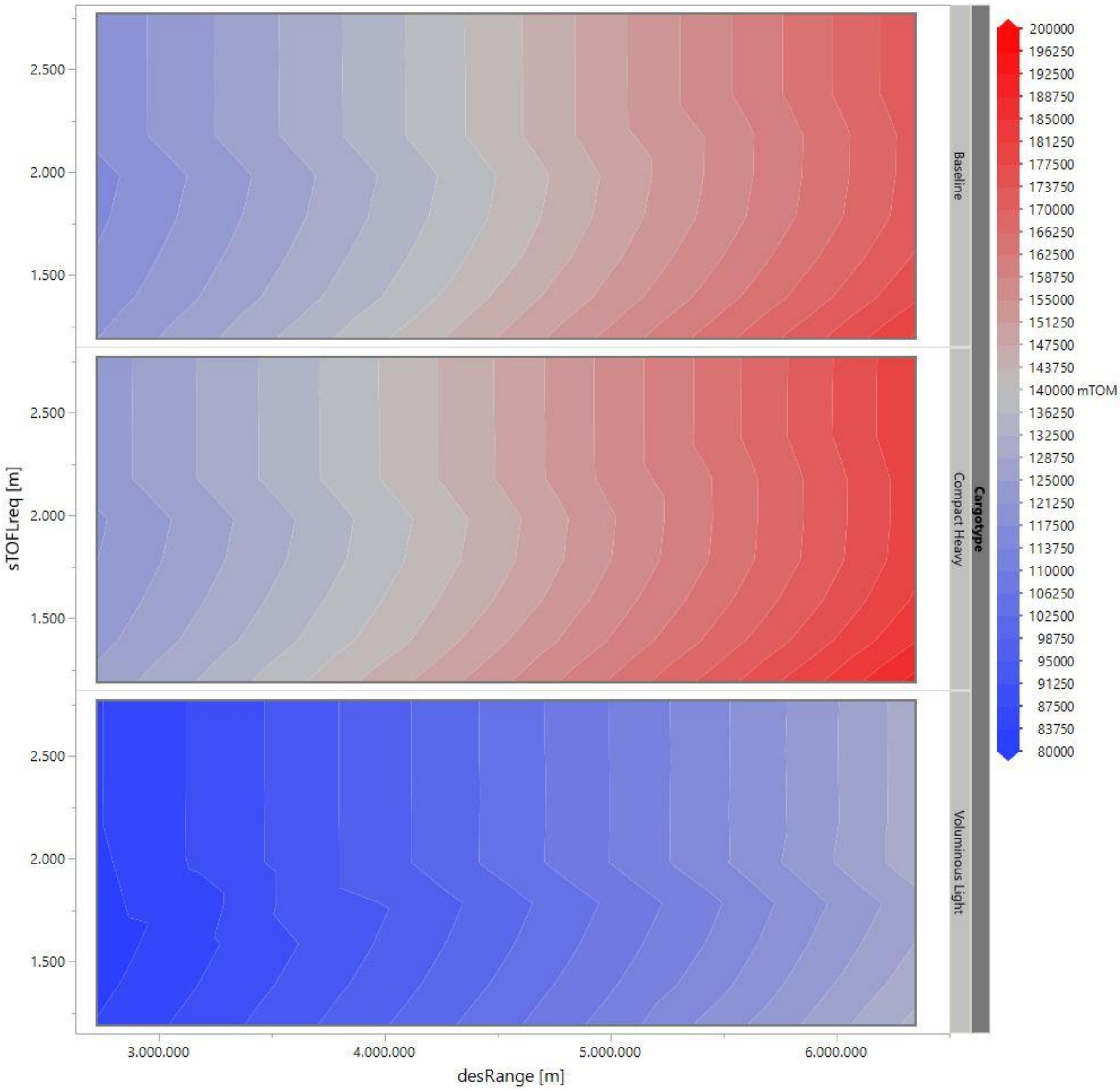


Figure 4-10: Influence of different cargo types, takeoff length and range on the MTOM

4.2.3 DoE 3: Influence of mission design parameters

The impact of the mission design parameters consisting of missions loitering time, reserve fuel factor and design range on the MTOM is illustrated in Figure 4-11. The x-axis is grouped for five design ranges. The loitering time is applied to the x-axis, the reserve fuel factor is applied to the y-axis. The initial values for the design range are $4535\ \mathrm{km}$, for reserve fuel factor 5 % and for loitering time 1800 s which equals to 30 min. In the DoE each value is varied for $\pm 50\%$ resulting in a design range between 2721 km and 6349 km, a reserve fuel factor between 2,5 % and 7,5 % and a loitering time in a range of 15 min (900 s) to 45 min (2700 s). The behavior of the MTOM increasing from the bottom left corner to the top right corner is logical. In the bottom left corner, the design range, the reserve fuel factor and the loitering time have the overall lowest values, therefore the least amount of fuel needs to be carried (approx. 24.000 kg) and the MTOM is only 113.100 kg. In contrast on the top right corner of the diagram, the mission design parameters have their highest values leading to an MTOM of 178.100 kg containing 72.400 kg of fuel. The fuel mass of the baseline aircraft is 44.600 kg.

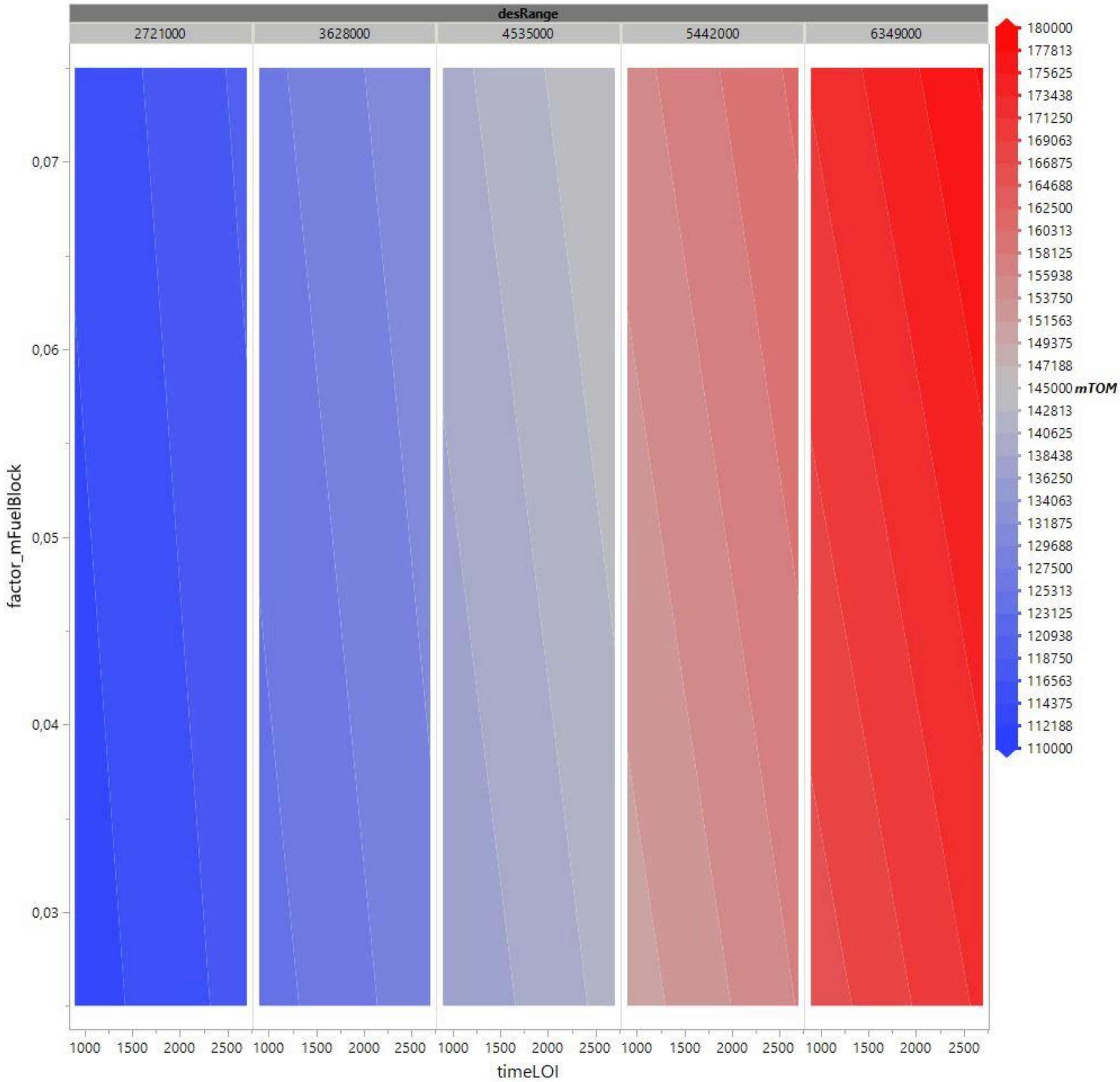


Figure 4-11: Influence of loitering time, reserve fuel factor and design range on MTOM

5 Conclusion and Outlook

The purpose of the thesis is to extend the capabilities of the DLR-inhouse aircraft design tool “openAD” to cargo transportation by designing a military transport aircraft for humanitarian disaster relief missions. DLR uses openAD as their primary conceptual aircraft design tool for commercial aircraft, so the design methodology is based on a knowledge base of civil passenger transport aircraft. For cargo transport purposes, the cargo dimensions and masses should be the driving parameters for the aircraft design instead of the passengers. Design features of military transport aircraft are elaborated from existing aircraft and implemented into the calculation methodology. A redesign of the Airbus A400M transport aircraft in openAD was set up. Therefore, technical data of the aircraft was collected. A reference aircraft is redesigned and calibrated on geometrical, mass, and performance level. Modifications of existing methods for the mission profile, fuel mass and landing gear as well as new method for the cargo driven aircraft sizing were implemented. Due to deviating values of the methods of the redesigned aircraft from the reference aircraft, a calibration process was performed. After the completion of the calibration, the sizing methods are tested with the calibrated aircraft model. Therefore, three different designs of experiments are performed. In these, the influences of cargo sizing, design range, required takeoff field length, fuel reserve factor and loitering time on the aircraft sizing are tested. Deviations in the payload range diagram can be an indicator that the calibration of the aerodynamic and engine performance was not accurate enough. Another reason for the deviation can be traced back to uncertainties in the top of climb and cruise altitude.

The width of the cargo was not varied during the DoEs, therefore, the fuselage width stayed the same. But the sizing of the width according to the cargo was already implemented, which can be easily tested out in further DoEs.

Due to the aircraft sizing is dependent on the payloads CoG, it might be advantageous to only define the CoG of the cargo, and their total masses as well as the cargo holds volume instead of defining the cargo units themselves. Then, the user can choose depending on the application which sizing methodology he wants to use.

The aircraft geometry of the baseline aircraft compared to the reference aircraft looked well for the most parts. But it can be refined for the sizing and positioning of the engines, the positioning of the HTP and the fuselage diameter.

The aircraft configuration itself can also be modified, for example using turbofan instead of turboprop engines. Also, the geometry for the sides pods that contain the MLG when retracted and the fuselage-wing fairing can be programmed in a future step.

The military cargo aircraft design model can be utilized in many different ways for future applications. It can be used for conducting conceptual aircraft design studies by integrating openAD into an RCE framework and linking it with more discipline specific tools to obtain a more refined aircraft design. Another application for the tool is the integration into an agent-based simulation process, where the parameterized aircraft design is part of a holistic approach in which the operative and logistical influences are simulated.

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7 Statement of Authorship

Erklärung zur selbstständigen Bearbeitung einer Abschlussarbeit

Gemäß der Allgemeinen Prüfungs- und Studienordnung ist zusammen mit der Abschlussarbeit eine schriftliche Erklärung abzugeben, in der der Studierende bestätigt, dass die Abschlussarbeit „— bei einer Gruppenarbeit die entsprechend gekennzeichneten Teile der Arbeit [(§ 18 Abs. 1 APSO-TI-BM bzw. § 21 Abs. 1 APSO-INGI)] — ohne fremde Hilfe selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel benutzt wurden. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich zu machen.“

Quelle: § 16 Abs. 5 APSO-TI-BM bzw. § 15 Abs. 6 APSO-INGI

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Hiermit versichere ich,

Name: Schmitz
Vorname: Matthias

dass ich die vorliegende Projektarbeit mit dem Thema:

Conceptual Aircraft Design Methodology for Disaster Relief Operations with a Variable Fidelity Interface

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