

UNICADO – A Software for Conceptual Aircraft Design

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Abstract

Aircraft conceptual design has been used for years to develop new aircraft configurations or to evaluate new technologies in existing configurations. For this reason, competence-driven aircraft preliminary design environments have been developed worldwide, especially in universities, which are more or less at the same level. Since synergy potentials regarding the core competences of the universities remain unused, the association of the universities involved in the UNICADO research project is unique. The aim of the project is to bundle this synergy potential in the form of a common developed and used aircraft conceptual design environment. This paper describes this design environment developed based on RCE and the associated boundary conditions regarding the design of CS-25 compliant aircraft. UNICADO is implemented as a modular architecture for an easy extensibility and exchangeability of modules and disciplines. For an exact statement about the quality of the results, the developed platform is validated by means of a comparison with the existing MICADO by RWTH Aachen University. The main design mode as well as the implemented calibration modes will be validated and critically evaluated using the CeRAS CSR-01 reference aircraft. Subsequently, the results of the design of a CeRAS short- and medium-range aircraft and a CeRAS long-range configuration are presented and compared with selected reference aircraft. The comparison of the CSMR-01 and CLR designed with UNICADO to the reference aircraft on the market shows that the design environment developed for the early design phase delivers very good results. The resulting percentage deviations between the design and the reference aircraft are less than one percent for all convergence variables considered. This shows that the cooperative approach to bundle core competencies and exploit synergy potentials is effective and should be intensified in further project phases. UNICADO provides a solid foundation for the development of modern, climate-friendly aircraft. Extending the software with more advanced methods will improve the ability to model disruptive configurations and alternative propulsion concepts. Being designed as open-source software, anyone can use, understand and improve the software and contribute their own ideas for future aircraft configurations.

Article Highlights

- This paper describes the development of a university conceptual aircraft design environment.
- The validation of the design environment shows exact compliance with the reference software.
- The convergence studies performed indicate sufficient accuracy for the preliminary design process.

1 Motivation

Numerical design tools for aircraft design have been used for years to develop new aircraft configurations and to evaluate the new implemented technologies. For this reason, universities all over the world have developed their own aircraft design tools, whereby the respective design environments are strongly influenced by the university's own experience. In Germany, there are also numerous university aircraft design environments, all of which are at a comparably high level. Here, only the

accuracy of the respective tools differs due to the core competences of the developing universities. Due to the different level of detail of the individual environments, validation based on reference configurations is difficult. Therefore, six aerospace universities have joined forces in the UNICADO research project. The aim of the project is to combine the synergies of the German universities of aeronautics and astronautics in a common conceptual aircraft design code, which is to be validated against industrial reference configurations. The establishment of UNICADO enables a stronger connection of the universities to research institutions and the aerospace industry as well as its use in the education of young engineers to improve the design capabilities within Germany.

According to the study by Gradel and Geuking[1] nine different preliminary design environments exist in Germany at different universities and research institutions and are being further developed. German aerospace universities account for 7 of the 9 design environments. Of these, the tools "MICADO"[2] by RWTH Aachen University, "ADEBO"[3] by Technische Universität München, "PrADO"[4] by Technische Universität Braunschweig and "PadLab"[5] by Technische Universität Berlin cover the complete conceptual aircraft design and analysis process. However, the programs mentioned differ in the quality of the calculation methods. These vary from statistical methods, empirical and semi-empirical methods according to Howe [6], Raymer [7], Roskam [8], and Torenbeek [9], to analytical and numerical methods models such as "Lifting Line" [10] for aerodynamic analysis. Naturally, the programs usually have their strengths in the core competence disciplines of the developing university, e.g. MICADO in the field of aerodynamics, PrADO in the field of structure and lightweight design, and PadLab in the field of costs. This indicates that a cooperative collaboration of the mentioned universities enables the development of a preliminary aircraft design environment with a high level of detail.

In the following chapters, the development of the university design environment UNICADO in RCE [11] is described in more detail. The MICADO design environment not only served as a reference but was used as a starting point and will be used later to validate the developed UNICADO workflow. First, the implementation and the special features resulting from RCE are discussed. The validation itself takes place in Chap. 3 and is carried out based on a CeRAS [12] reference aircraft in comparison with the results of MICADO. Using the validated design environment, Chap. 4 presents the results of a short-medium and long-range aircraft configuration designed with UNICADO compared to an A320 and A330 aircraft configuration respectively. In conclusion, the results shown are discussed and critically evaluated regarding further work.

1. Implementation of UNICADO Architecture

The implementation of the UNICADO design environment is based on the already existing MICADO by RWTH Aachen University. It contains two design modes to allow different design processes depending on the available input data. In addition, it is possible to carry out automated calibration processes regarding the GLOBAL design variables operating empty mass (OME) and maximum take-off mass (MTOM). Each of these design processes is followed by an off-design analysis relating to a study mission, which enables an evaluation of the concept outside the design mission. The UNICADO

architecture is developed in close alignment with these MICADO features to allow for a subsequent step-by-step validation against MICADO. For this purpose, design modules, already integrated in MICADO, and their implementation are adopted, which provides a one-to-one validation of the generated designs. For the integration of further design methods and modules, the overall architecture is to be built up as modular as possible. In addition, this architecture has to ensure a conversion of the internal UNICADO data structure used to the common known external data schema CPACS. The decoupling of the off-design mission from the design enables the analysis of an already converged design for several off-design points, which improves the evaluation of the respective designs.

1. Boundary Conditions of UNICADO

The boundary conditions for the development and establishment of cross-university design software are derived from the requirements mentioned in the previous chapter. In order to guarantee a high level of detail, the synergy potentials of the participating universities are to be used in such a way that a bundling of the respective design and technical competences leads to a long-term utilization of the software. Here, the connection to the design processes of industry and non-university research must be ensured. Hereby, more efficient joint research as well as an optimized education of the next generation of engineers in the field of aircraft design is guaranteed. To fulfill this objective, the UNICADO software is to be developed open source, which ensures its use and further development outside the consortium. This leads to two important requirement criteria for the UNICADO design environment: "UNICADO can..." and "Everyone can...". The following list gives a short overview of the contents of the two mentioned requirement criteria.

UNICADO can:

- Design CS-25 compliant aircraft configurations with minimal user input.
- Guide the user through the aircraft design process.
- Prepare and visualize the results in a meaningful way for the user.
- Make decisions about a good/optimal design as well as its validity.

Everyone can:

- Use UNICADO at any time.
- Understand the relationships between all disciplines of conceptual aircraft design.
- Develop and map their own ideas for future aircraft configurations.
- Improve UNICADO and add expertise via own calculation methods.

In the following section, the implementation of the developed design environment under the above-mentioned boundary conditions is explained.

1. UNICADO Design Environment

Figure 1 shows the overall architecture of the UNICADO design environment developed in RCE [11]. The respective phases of the design process are divided into individual blocks, which ensures a modular structure. Within these blocks, the respective design process step is controlled using script, converger or directly executable tool components. All relevant back-end operations are separated into sub-functions, so that a simple replacement or modification of the respective implemented methods is possible. In addition, the TIGL Viewer [13] allows direct visualization of the respective aircraft geometry in each iteration step. A list of the functions of the script components implemented in Python 3 is given in the workflow documentation [14, p. VIII]. To understand the implemented overall methodology of the UNICADO workflow, a flowchart is shown in Fig. 2. In the following subsections, the specific features of the respective workflow sections are described in detail. First, the blocks required for workflow initialization, controlling and termination are discussed in Subsection 2.2.1. Afterward, all necessary execution blocks for the aircraft design process itself are described in Subsection 2.2.2. Subsection 2.2.3 describes the execution blocks for the off-design analysis in detail. Subsequently, Subsections 2.2.4 and 2.2.5 explain the modes integrated in the workflow for sensitivity analyses and optimization problems. Finally, Subsection 2.2.6 describes the methods implemented in the design sizing loop.

1. General Workflow Sections

- *Pre-condition*

The script implemented in the section "pre-condition" handles the data and component management of the workflow. Essential file paths as well as configuration and input parameters are set and passed on to the subsequent workflow sections. A detailed description of the implemented file management system and the modular structure of the source code is given in the developer documentation of UNICADO [14].

- *Pre-sizing*

This section contains the module "initial_sizing", which determines the initial design parameters for the thrust-to-weight ratio and the wing loading. Both parameters are kept constant in the default setting of the workflow over the entire design process and can also be defined as input parameters if necessary. UNICADO follows the philosophy of generating a consistent data set for a fixed design point. If this design is an optimum for a certain transport task in terms of an evaluation criterion, can be analysed afterwards conducting parameter studies or using the dedicated optimization loop. The design philosophy can be changed via a switch in the workflow configuration file. In this case, a new design point is according to the sizing curves updated with the current aircraft performance values of the last design loop and used for the next iteration. For this, a distinction can be **Fig. 1: Implemented overall UNICADO architecture in RCE**

made as to whether both of the above parameters or only one of them should be changed. In addition, an initial mass estimation is carried out wfor regard to the maximum take-off mass, the operating empty mass and the required fuel share. Due to the implementation as independent executable programs, no direct transfer parameters are required for subsequent modules. Communication between the modules

takes place via a project-specific external XML file developed in-house, which is based on the CPACS standard [15].

Visualization and CPACS

The results of the respective iteration steps are translated into CPACS via a module developed in-house. This enables the direct tracing of the conceptual changes of each iteration step using the implemented TIGL viewer. The translation of the data into CPACS ensures that UNICADO can be connected to other research institutes and industrial partners.

Post operations and clean up

In the "post operations" section, the final design is analyzed and evaluated in terms of its flight performance, operating costs, and emissions. For the performance analysis of the design, all top level aircraft requirements are evaluated and a detailed analysis of the flight mission is carried out in the modules "mission_analysis" and "performance_assessment" [16]. The resulting data are provided in the form of graphical outputs. Based on this, the direct operating costs (DOC) resulting from the design are calculated in the "cost_estimation" module using the Thorbeck method [17]. In addition, the DOC over the range in the form of unit costs are derived from the transportation work achieved and provided as a diagram. Finally, the design is analyzed and evaluated regarding its emissions. The "ecological_assessment" tool offers flexibility in carrying out these assessments. The user can choose to perform a complete life cycle assessment (LCA), which evaluates the environmental impact across the entire lifespan of the aircraft - from development and production through operation to end-of-life, including eventual disposal. Alternatively, by focusing on the operational phase, the user can limit the analysis to the impact of the flown mission alone. For a visualization of the design results, these are summarized by the module "report_generator" in the kind of an HTML and PDF report. In addition, CPACS and the integrated TIGLviewer can be used to generate both step files and mesh files, which can be used as the input for higher-fidelity aerodynamic (3D CFD with RANS) or structural analyses (FEM/flutter analyses). Finally, the generated data is provided in an output directory and can be extracted for further analysis.

1. Aircraft Design Cycle

- *Design sizing loop*

The scripts implemented in this workflow segment and the convergence component "design_sizing_loop" provided by RCE handle the entire aircraft design process. The scripts mentioned above initialize the design cycle and evaluate the convergence variables. The converger component itself only evaluates a given status signal. If this leads to convergence, the design loop "tool execution for design sizing" is terminated, and subsequent workflow components are started. Otherwise, the iteration process is continued. The following four convergence variables are implemented in the workflow:

- Maximum take-off mass,

- Design mission energy,
- Operating empty mass,
- Position of center of gravity in x-direction.
- *Tool execution for design sizing*

The design tools are executed using the Gauss-Seidel method [18, p. 11]. This means that all design modules are processed one after the other; a parallelization of the modules is not implemented in the current UNICADO architecture. In accordance to Zimmnau et al. [19], parallelizing the execution of the respective design modules with the Jacobi architecture within UNICADO offers no advantage in terms of calculation time and accuracy of the results. To ensure that all modules are executed at the correct time, they are also provided with trigger signals to communicate with each other. The implemented execution sequence is identical to MICADO which allows an accurate validation of the achieved design results. The data generated for the respective modules is made available via the data exchange format mentioned above. Additional required inputs are provided via a module-specific configuration file. The implemented serial execution sequence ensures that there are no conflicts regarding access rights to the aforementioned data. A description of this as well as a list of the required inputs and outputs of the respective integrated modules are described in detail in the online documentation [20]. It should be noted that reaching the target value for the MTOM calibration can be achieved via the engine efficiency as well as the aerodynamic efficiency via a drag count variation. This enables investigations to be conducted regarding changed technology states compared to a reference.

- *OME calibration*

The calibration with respect to a given operating empty mass is realized via a nested iteration loop during the first design iteration. For this purpose, the converger component of the calibration process is started after completing the "systems_design" module. For OME calibration, the MTOM is fixed and only the geometry and systems sizing as well as OME analysis components are iterated by changing the fuselage mass until the residual of OME to the target is below the user specified value. The check of convergence is done by the implemented script, which terminates the converger component after a successful test. Finally, the iteration of the design process is continued. A recalibration in a later iteration step is not carried out.

- *Plot generation of design loop*

The generation of all graphic outputs as well as the creation of the HTML and TeX reports of the respective design modules is uncoupled from the overall design process. For performance reasons, this is done only after the design process has been completed. Since a renewed execution of the design tools would result in a change of the convergence results, the project-specific aircraft exchange file is reset to the status of the penultimate iteration step before executing the loop again with plot output activated. This ensures that the generated output data matches the results of the design process.

1. Off-Design Analysis

- *Mission study loop*

For the analysis of the off-design behavior of the converged design, an iteration process for mission studies is integrated in the workflow, analogous to MICADO. This allows to analyze the behavior of the final aircraft design (fixed geometry, sized propulsion and systems) with regard to a changed transport task. The convergence variables implemented for this purpose are listed below:

- Study mission take-off mass,
- Study mission range,
- Study mission energy,
- Initial flight level of study mission.

The structure and the implemented RCE specific control elements of the mission study loop are identical to the architecture of the aircraft design process described in Subsection 2.2.2. Only the implemented modules differ. For the mission analysis just the three modules "create_mission_xml", "systems_design", and "mission_analysis" are integrated in the iteration process. A calibration of masses is also not possible since both modules, "systems_design" and "mission_analysis", are only executed in their analysis mode and not in the MTOM sizing mode. This guarantees that there are no design changes compared to the result from the design iteration. A more detailed description of the execution blocks for the study mission analysis is not given here, as their implementation is analogous to that described in Subsection 2.2.2.

1. Parameter Study Mode

A parameter study manager is implemented for the sensitivity analysis of individual parameters and their influence on user-defined target variables. Using the configuration file provided, it is possible to change each parameter of the module configuration files as well as input parameters of the aircraft exchange file (TLAR / design specification). The user can choose whether a parameter should have a percentage or absolute increment to the reference. An external CSV file can also be used to define specific values for each parameter, thus enabling a more precise analysis of aircraft designs. For the implementation in RCE, an outer loop is implemented, which on the one hand resets all workflow components after each successful or invalid design and starts a new parameter study. On the other hand, this ensures that the implemented optimization framework (Subsection 2.2.5) can independently set and change its required parameter combinations without having to start separate workflows.

1. Optimization Framework

By connecting the Efficient Global Optimization Framework (EGO) [21] developed at TU Braunschweig, it is possible to carry out optimization studies with regard to freely selectable design parameters. By specifying the target variables to be optimized and the associated boundary conditions, an optimization

process is started using the "Gaussian Process" [22] in order to train surrogates for later design tasks. For this purpose, initial sample points are generated, based on which adaptive sampling points are determined by the Gaussian process. The accuracy of the optimum achieved depends significantly on the number of calculation points specified by the user. Figure 3 shows an example of the result of an optimization study regarding the influence of different ratios of the thrust to weight ratio (T/W) and the wing loading (W/S) on the required fuel mass of a reference configuration.

1. Design methods and fidelity

The methods implemented within the respective modules vary from empirical to more sophisticated analytical methods. In the initial calculations of the individual modules, highly simplified methods according to Torenbeek [9], Roskam [8], or Howe [6] are used. In the further iteration loops and the first existing design results of the respective modules, the methods mentioned are replaced by more sophisticated methods. For this purpose, the methods according to Chiozzotto [23] and FLOPS [24] are implemented for the mass determination of the lifting surfaces whereby the analysis of the influence of fiber composite materials on the respective component masses is possible. A transport task-driven approach is implemented for the design of the fuselage. Based on the selected class layout and the associated comfort standard, the required cabin size is determined and then the outer fuselage geometry is generated [25]. In addition, the required operator item and furnishing masses are calculated with the use of scaling values, allowing a more precise analysis of the cabin layout on the total mass. An EASA-ETSO [26] tire list is implemented for the dimensioning of the nose and main landing gear, whereby a CS-25 [27] compliant design is realized. In addition, a method for calculating the Aircraft Classification Number (ACN) for flexible pavements according to FAA-COMFAA [28] has been implemented. The design process of the propulsion group is carried out via engine decks from GasTurb [29]. An implemented scaling mode is used to adapt the selected engines to the required thrust demand of the design. In addition, the nacelles and pylons are dimensioned using the sea level static thrust resulting from the scaling. The aerodynamic analysis for the lift coefficient, induced drag and moment coefficient and the resulting trim is carried out via an implemented connection to DLR's LiftingLine [10]. In addition, the viscous drag component is calculated according to Raymer [7] and the wave drag according to Korn-Mason [30]. The systems design is carried out according to ATA chapters, whereby different methods (Torenbeek, LTH, Howe) are used for the respective systems. The departure, cruise and approach steps from a self-created mission file are used as target points for the mission analysis. For this purpose, flight conditions (e.g. current climb rate, engine power, lift, etc.) are derived, which can be divided in smaller time and distance increments. For each increment, the equation of motion for a point mass is solved using the aerodynamic and engine performance as well as systems power requirement for the current atmospheric condition. This results in engine states giving the required energy demand for the current mission increment. All increments are added up.

A detailed description of all implemented modules as well as their inputs and outputs can be found in the respective module descriptions on the UNICADO website "UNICADO.io" [15].

1. Workflow Validation

In the following chapter, the results of the validation of the developed design environment are presented. For this purpose, comparative studies between MICADO and the developed UNICADO design environment were carried out using the CeRAS-Short-Range (CSR-01) aircraft of the CeRAS database [12]. First, the results concerning the mode of creating aircraft designs based on given Top Level Aircraft Requirements (TLARs) are discussed. Then, the results for the validation of the calibration modes are presented.

1. Validation of Clean Sheet Design Mode

Using the TLARs of the CSR-01 aircraft, the "clean sheet design" mode of the UNICADO design environment is validated against the results of MICADO. The CSR configuration is a 150-passenger single-aisle aircraft in two-class seating with a design range of 2,500 nautical miles by a given standard alternate range of 200 nautical miles and a holding flight time of 45 minutes. A detailed listing of the TLARs is given in Table 1. In addition, the validation of the implemented iteration loop for the off-design analysis is performed based on the data for the modified flight mission of CSR-01. The resulting modified mission parameters are listed in Table 2. Values which are not listed are identical to those in Table 1.

Table 1
Top Level Aircraft Requirements of the
CeRAS CSR-01 reference aircraft

RequirEment	Value
Design RaNge	2,500 NM
Design CruisE MAch Number	0.78
Number of PassengerS	150
Payload Mass	17,000 kg
TAKE-OFF Field Length	2,200 m
Design LAnding Field Length	1,850 m
Initial Cruise ALTitude	33,000 ft

The analysis of the results shows that both MICADO and the developed UNICADO design environment, with a relative convergence criterion of 0.0025, require 11 iteration steps. The percentage deviation of the individual convergence values is less than 0.0001 percent. Table 3 compares the results of the convergence variables for both design tools.

Table 2
Modified mission parameters of the
CSR-01 reference aircraft for off-
design validation

RequirEment	Value
Mission RaNge	500 nm
Payload Mass	13,608 kg
Initial Cruise Altitude	35,000 ft

Table 3
Comparison of the resulting convergence parameters of both
design tools

ConvergEnce Criteria	MICADO	UNICADO Workflow
maximum Take-Off Mass	77,065 kg	77,065 kg
Operating Empty mass	42,012 kg	42,012 kg
Design Energy	6,168 GJ	6,168 GJ
AFT X-Positlon OF CoG	16.66 m	16.66 m
CM at optimal Cruise CL	2.59e-05	2.59e-05

The results of the off-design analysis of both design tools are exactly identical due to the rounding implemented here. The corresponding results regarding the convergence variables implemented in the off-design loop are summarized in Table 4. The results concerning the required initial cruise altitude and the mission range are fulfilled.

Table 4
Results of the off-design analysis of both design
tools MICADO and UNICADO

ConvergEnce Criteria	Result of both Tools
Mission RaNge	500 NM
Mission Take-Off Mass	61,521 kg
Mission Energy	2,661 GJ
Initial Cruise Altitude	35,000 ft

The comparison of results shown between MICADO and the UNICADO workflow indicates that the developed design environment delivers identical results in the implemented level of detail. For a more in-depth evaluation of the design accuracy, the results of the convergence studies of a CeRAS short- and medium-range aircraft as well as a long-range configuration are given in Chap. 4.

1. Validation of Calibration Mode

The validation of the implemented calibrations with respect to the target parameters OME and MTOM is performed analogously to the procedure described in Chap. 3.1. The respective target values to be achieved are 42,100 kg for the operating empty mass and 77,000 kg for the maximum take-off mass. A comparison of the results of the different calibration modes is summarized in Table 5.

OME calibration

The comparison of the results of both design tools in terms of the implemented OME calibration mode indicates that both MICADO and the UNICADO design environment achieve very good results. In both cases, a target value of 42,092 kg was reached after 4 iteration steps using a predefined relative convergence limit of 0.0025. The absolute deviation from the specified target value is less than 0.0002 percent.

MTOM calibration via fuel flow modification

The analysis of the comparative results with regard to the MTOM calibration by changing the fuel flow does not show any significant deviation in the results of the two design environments. The resulting deviation of 77,018 kg to 77,017 kg is also explained in this case by the implemented rounding of the output values. Regarding the specified target value of 77,000 kg, a percentage deviation of approx. 0.0002 percent results in both cases with an identical number of required iteration steps by 16.

MTOM calibration via drag count reduction

For the calibration of the maximum take-off mass, using the drag count reduction mode, both design tools require 19 iterations. The achieved target values are identical and with 76,975 kg slightly below the specified target value. The resulting percentage deviation is approx. 0.0003 percent and is also acceptable for the conceptual aircraft design.

Table 5
Comparison of the results of the individual calibration modes of both aircraft design environments

Calibration Parameter	MICADO	UNICADO Workflow
OME calibration	42,092 kg	42,092 kg
Fuel flow MTOM calibration	77,018 kg	77,017 kg
MTOM calibration via drag count reduction	76,975 kg	76,975 kg
4 Evaluation of a CSMR and CLR aircraft		

The following chapter presents the results of a short- and medium-range aircraft as well as a long-range aircraft designed with UNICADO. To validate and evaluate the design quality, the A320neo is used as a short and medium-haul reference and the A330-900 as a long-haul reference. The resulting TLARs of the

designs are taken from the respective manufacturer's manual "*Aircraft Characteristics - Airport and Maintenance Planning*" (ACAP) [31] [32]. For a comparison of the range profile and the resulting flight performance, the aircraft version number WV055 of the A320neo and the WV920 of the A330-900 are used. The data required for this are given in the aforementioned document in the form of a payload-range-diagram. The TLARs and results for the CeRAS short-medium range are given in Chap. 4.1 and for the CeRAS long-range design in Chap. 4.2.

1. Design of a CSMR aircraft

Figure 4

Percentage deviation of convergence variables compared to the reference aircraft

Using the UNICADO workflow validated in Chap. 3 and a given relative convergence limit of 1×10^{-6} , a CeRAS short- and medium-range aircraft (CSMR-01) was designed. The higher convergence limit used in this case, compared to that of Chap. 3, is used to analyze the convergence behavior and the resulting percentage changes per iteration step. The resulting percentage deviations regarding the four convergence variables per iteration step are shown in **Fig. 4**. 18 iterations are necessary for the design process with the specified convergence boundary. From the shown percentage deviations compared to the reference it can be seen that convergence is achieved for three of the implemented convergence variables from an iteration number of 13. This corresponds to a convergence criterion of 1×10^{-4} and is regarded as sufficiently accurate due to the minimal change in the results for the conceptual aircraft design. Only the foremost position of the center of gravity still shows minor fluctuations concerning the convergence. The resulting percentage deviations after completion of the iteration are below 0.5 percent for all variables compared to the data of the reference. All studies performed are based on the TLARs of the A320neo, which are listed in the table below.

Table 6
Top Level Aircraft Requirements and
reference values of the A320neo according to
ACAP

Requirement	Value
Design RaNge	2,947 NM
Design CruisE MACH Number	0.78
Number of PassengerS	180
MAXIMUM Payload Mass	19,300 kg
TAKE-OFF Field Length	1,900 m
Design LAnding Field Length	1,850 m
Initial Cruise Altitude	33,000 ft
Maximum certified altitude	40,000 ft

A comparison of the absolute values of the design masses and the center of gravity position of the reference and the final design is given in Table 7. A comparison of the payload-range-diagram derived from the design and the reference diagram is shown in Fig. 5. It should be noted that both diagrams are almost exactly on top of each other and are therefore difficult to differentiate. For a more detailed analysis of the maximum deviation, the corner points B and C of both diagrams are given separately in Fig. 6.

Table 7
Comparison of the position of the center of gravity and the design
masses between design and reference according to ACAP [31]

ConvergEnce Criteria	Reference Aircraft	UNICADO Workflow
maximum Take-Off Mass	79,000 kg	79,006 kg
Operating Empty mass	45,000 kg	44,996 kg
Design Fuel Mass	16,900 kg	16,898 kg
Front X-Positlon OF CoG	16.45 m	16.38 m

The percentage difference in range at the point of maximum take-off mass and maximum payload (*Point B*, Fig. 6, *top*) between the design and the reference aircraft is 1.2 percent. The resulting absolute range difference is 30 nautical miles, whereby the design of the CSMR-01 has a lower range than the reference aircraft. The lower part of Fig. 6 shows that the design of the CSMR-01 achieves a slightly greater range at the point of maximum fuel mass at maximum take-off mass (*Point C*) compared to the reference. The percentage difference is 0.6 percent and corresponds to an absolute change in range of 15 nautical miles. The resulting change in the remaining payload mass at this point is 1.34 percent.

The geometric dimensions of the design and those of the reference aircraft as well as the resulting geometric deviations are shown in Fig. 7 and Fig. 8 in the form of a top and side view. In both figures, the design of the CSMR-01 is shown as a wireframe model. The geometric conditions of the reference are shown as an aircraft surface model. Figure 7 illustrates that the fuselage geometry as well as the wing position between the two models are approximately the same, but that the maximum wingspan of the CSMR-01 design exceeds the reference. The depicted comparison of the tailplane geometry shows that the surfaces and spans are almost identical as well. Only the tailplane position is shifted in the design, which results from an enlarged tailplane lever arm compared to the reference. The significant discrepancy in the engine size shown in Fig. 7 and Fig. 8 is due to the missing model of the engine used in the reference data. However, the actual engine position is identical for both aircraft. Figure 8 also illustrates that the vertical tail geometry shows the greatest deviation of all geometric components. The increased stabilizer area of the CSMR-01 is due to different stability criteria between the design and the reference aircraft. The offset of the rudder position is also a result of an increased lever arm compared to the reference.

1. Design of a CLR aircraft

As a second validation case, an A330-like long-range aircraft configuration is designed with UNICADO as CLR. All required design parameters are taken from the ACAP [32]. The resulting TLARs are summarized in Table 8. The required reference value for the OME can be determined from the point specified in the payload-range-diagram for reaching the maximum tank capacity and the payload associated with the point. Using the design range given in Table 8 and the masses given in the ACAP, the required fuel share of the reference configuration can be calculated. A comparison of the resulting design parameters is given in Table 9.

Table 8
Top Level Aircraft Requirements and
reference values of the A330-900 according
to ACAP

Requirement	Value
Design RaNge	6,700 NM
Design CruisE MAch Number	0.82
Number of PassengerS	300
DEsign Payload Mass	31,500 kg
TAKE-OFF Field Length	3,100 m
Design LAnding Field Length	1,950 m
Initial Cruise Altitude	35,000 ft
Maximum certified altitude	43,000 ft

Table 9
Comparison of the position of the center of gravity and the design masses between design and reference according to ACAP [32]

Convergence Criteria	Reference Aircraft	UNICADO Workflow
maximum Take-Off Mass	251,000 kg	251,050 kg
Operating Empty mass	136,915 kg	136,687 kg
Design Fuel Mass	82,585 kg	82,863 kg
Front X-Position OF CoG	N/A	29.56 m

The comparison of the main mass fractions shows that the deviation between the reference and the design is less than one percent for all mass fractions. A comparison of the x-position of the center of gravity is not possible, as this is not given for the reference.

4.3 Discussion

Based on the results of the design of a CeRAS short- and medium-haul aircraft (CSMR-01) and those of the long-haul configuration (CLR) presented in Chaps. 4.1 and 4.2, it can be concluded that the developed UNICADO aircraft design environment generates extremely good designs for comparable operational aircraft. Table 7 illustrates that the percentage deviations of the final design, based on the TLARs of the A320neo [31], are far below one percent. The deviation shown there with regard to the design mission fuel can be explained by the engine model created using GasTurb [29]. The implemented model does not exactly reproduce the performance data of the original Pratt & Whitney PW1127G-JM [33] engine, which results in a slightly lower fuel consumption. With regard to the conceptual aircraft design, however, the resulting deviation is not to be regarded as critical, since it has no significant influence on the result of the overall aircraft design. The discrepancy shown in Table 7 regarding the center of gravity (CoG) position, on the other hand, must be considered in a differentiated manner. On the one hand, the mass estimation module implemented in UNICADO is based on conceptual design methods, which means that an exactly identical mass distribution compared to the A320neo cannot be realized. On the other hand, the specified reference value regarding the center of gravity position is taken from the manufacturer's ACAP [31], which also does not contain the exact position for data privacy reasons, making an exact assessment regarding the center of gravity position of the design difficult. However, from the absolute deviation of 7 cm to each other, it can be deduced that this difference also has no significant influence on the overall result of the design. This can be proven by the payload-range-diagrams depicted in Fig. 5 and Fig. 6. If the shown deviation regarding the center of gravity position had a significant influence, this would be evident in Fig. 5. As this position has an influence on the trim angle of the tailplane and an increased trim results in an increased drag, an influence on the fuel consumption would be visible. Since both payload-range-diagrams are almost exactly on top of each other and the fuel quantity is almost identical, there is no influence of the changed CoG position on the overall design. The minimal percentage deviation of points B and C between the reference aircraft and the designed CSMR-

01 (*shown in the upper and lower part of Fig. 6*) can also be attributed to the already described problem of the propulsion system model used. Due to the slightly larger trim angle of the tailplane and the resulting larger drag, the design undercuts the reference range at Point B by 1.2 percent (Fig. 6, *top*), but is acceptable considering the early aircraft conceptual design phase. At point C (Fig. 6, *below*) the described effect is reversed. The slightly lower fuel consumption with the same total mass leads to a slower center of gravity migration with increasing range, which inverts the described discrepancy in the trim angle. This explains the slightly larger range of the CSMR-01 design compared to the reference. The same applies to the associated lower substitution of the payload mass of 1.34 percent in the aforementioned Point C.

The comparison of geometric dimensions between the reference aircraft and the CSMR-01 design, presented in Fig. 7 and Fig. 8, shows few differences in terms of absolute dimensions. The discrepancy shown in Fig. 7 regarding the different wingspans between CSMR-01 and the reference aircraft results from the specified increased wing aspect ratio to enhance efficiency concerning fuel consumption. For this, the boundary condition for the maximum possible wingspan is derived from the ICAO Aerodrome Reference Code [34, p. 34] of the A320neo (*ARC: 3C III C* [35, p. 2]). Since the CSMR-01 falls below the resulting limit of 36 meters, this requirement is considered to be fulfilled, which means that no significant deviation in terms of operational costs is to be expected.

The discrepancy in both figures regarding the resulting tail positions between design and reference aircraft is a consequence of the more restrictive stability criterion implemented in UNICADO and the associated larger lever arms between the neutral points of the tail and the wing. This ensures a sufficient stability reserve for further design stages. The same applies to the enlarged vertical stabilizer of the CSMR-01 shown in Fig. 8.

The deviation in the results of the CeRAS long-range configuration compared to the reference configuration shown in Table 9 can be attributed to the engine model used, as well as to the furnishing masses and the operator items chosen. The engine deck created with GasTurb [29] for the engine model of the long-range configuration does not correspond exactly to the original (RR Trent 7000 [36]) in terms of fuel consumption and net thrust. This results in a slightly increased fuel requirement of approx. 300 kg for the given design mission, however, this is within an acceptable range for conceptual aircraft design. The specified deviation with regard to the operating empty mass is due to the comfort standard used and the associated masses for furnishing and seating classes. As the ACAP of the A330 [32] only specifies the seat class distribution used, but no information about the seats and galleys themselves, it is not possible to make an exact statement regarding the operator items and the furnishing masses. A comparison of the manufacturer empty mass would be more useful for an evaluation between reference and design, as only structural and component masses are used here. Due to the lack of manufacturer information regarding the manufacturer empty mass, a comparison of the operating empty mass is unavoidable, but leads to a certain degree of uncertainty in the design. Due to the lack of manufacturer information regarding the x-position of the center of gravity, it is not possible to analyze the deviation between the reference and the design for the long-distance configuration. For reasons of completeness

in respect of the convergence variables implemented in UNICADO, this is also given for the design in Table 9.

5 Conclusion

Based on the results of the validation shown in Chap. 3 and the design of a short- and medium-as well as a long-range aircraft presented in Chap. 4, it can be concluded that the UNICADO workflow developed in the research project produces highly accurate aircraft design concepts for conventional aircraft configurations, certifiable with respect to the CS-25 regulations. Through the study shown in **Fig. 4** regarding the convergence behavior of the design environment, it can be deduced that a convergence limit of 1×10^{-4} can be considered sufficient to achieve accurate results in the preliminary aircraft design. The deviations of the respective convergence variables are significantly below one percent from this limit, which means that no significant changes in the results are to be expected with smaller convergence criteria. The achieved results demonstrate that the developed design environment generates aircraft designs with a very high level of detail, enabling both a direct comparison with and an evaluation against already operating aircraft on the market. In the context of the boundary conditions stated in Chap. 2.1, it can be concluded that the developed design environment fulfils these. In particular, the large number of visualization and logging options during the design process enables direct monitoring of the process. This guides the user intuitively through the aircraft design process and allows to check its validity and meaningfulness already during the iteration. In addition, the modular implementation allows existing design modules to be extended and new ones to be added, enabling continuous development and the introduction of new functionalities and expertise. The required condition of designing aircraft to comply with certification in accordance with CS-25 [27] must be considered to have limited capability. Since the paragraphs listed in this regulation are aimed at the final certification process and the actual aircraft has already completed the development phase, it is not feasible for an aircraft conceptual design tool to fulfill all this paragraphs. From the draft of the CSMR-01 given in Chap. 4.1 as well as the demonstrated validation against the CSR-01 from Chap. 3.1 it can be deduced that all paragraphs necessary for the conceptual design are complied with, whereby the boundary condition from Chap. 2.1 can be regarded as fulfilled. The presented results of the CSMR-01 and CLR designs and their comparison with the reference data of the A320neo [30] and A330-900 [32] show that the developed workflow also meaningfully represents the use of new technologies and is therefore also suitable for the design of modern, more climate-friendly aircraft. For an even more detailed design of these innovative aircraft, the UNICADO design environment must be expanded in future development phases to include more sophisticated design methods for modeling disruptive configurations and more climate-friendly propulsion concepts. This will make it possible to represent alternative aircraft and propulsion concepts. As a consequence, the design and overall assessment capability of UNICADO regarding the formulated goals for climate-friendly aviation of “Fly the Green Deal” [37] will be significantly increased.

Declarations

Availability of data and material:

UNICADO and a short-medium as well as long-range design are published at unicado.io or the dedicated repositories.

Conflicts of interest:

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Abbreviations

Acronyms	
ACAP	Aircraft Characteristics - Airport and Maintenance Planning
ADEBO	Aircraft Design Box
ARC	Aerodrome Reference Code
ATA	Air Transport Association
CeRAS	Central Reference Aircraft Data System
CL	Lift Coefficient
CLR	CeRAS Long-Range
CM	Moment coefficient
CoG	Centre of Gravity
CPACS	Common Parametric Aircraft Configuration Schema
CS	Certification Specifications
CSMR	CeRAS Short- and Medium-Range
CSR	CeRAS Short Range
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
EASA	European Union Aviation Safety Agency
ETSO	European Technical Standard Order
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
LTH	Luftfahrttechnisches Handbuch
MICADO	Multidisciplinary Integrated Conceptual Aircraft Design and Optimization Environment
RCE	Remote Component Environment
PadLab	Preliminary Aircraft Design Lab
PrADO	Preliminary Aircraft Design and Optimization
TLAR	Top Level Aircraft Requirement
UNICADO	UNiversity Conceptual Aircraft Design and Optimization

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Figures

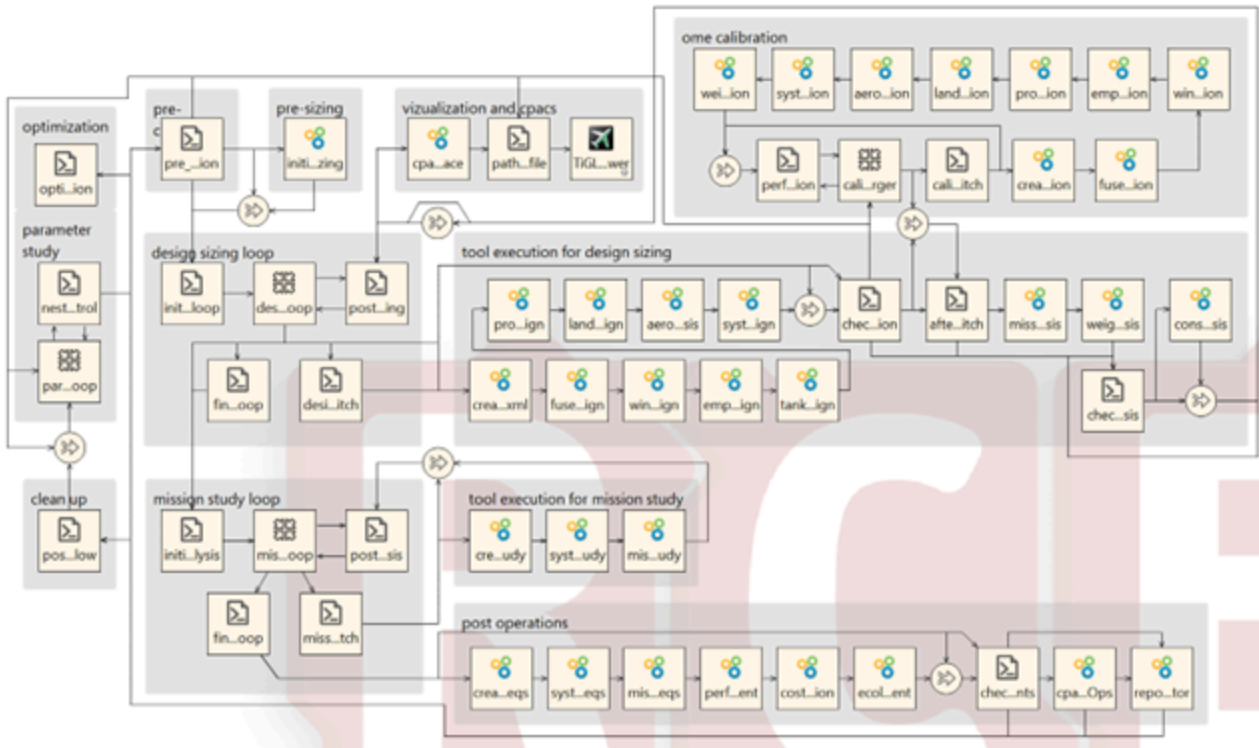


Figure 1

Implemented overall UNICADO architecture in RCE

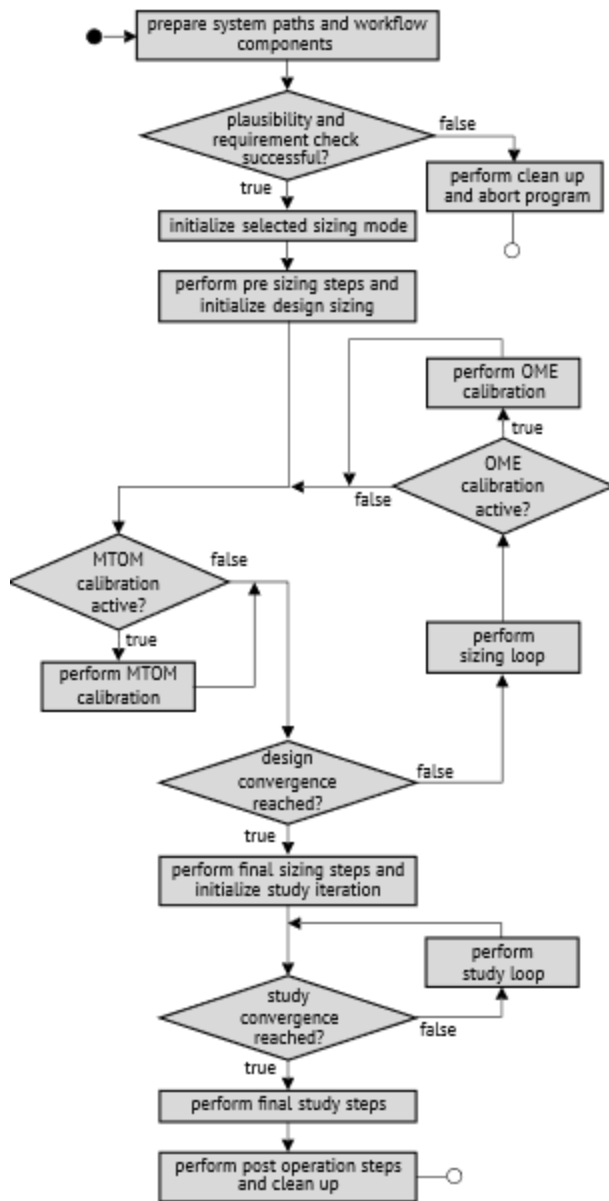


Figure 2

Flowchart of the design process of the implemented UNICADO workflow

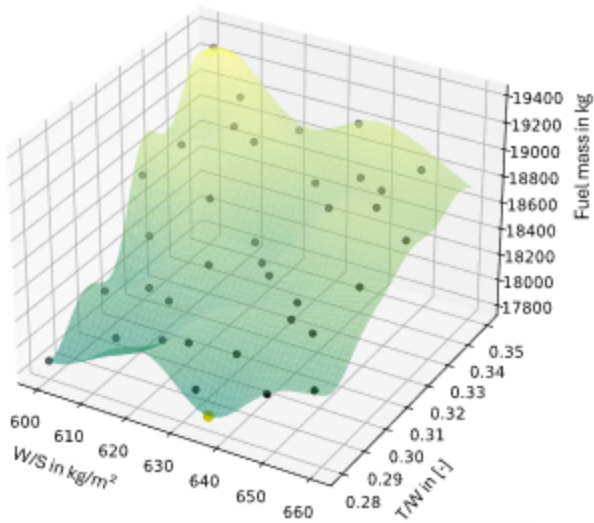


Figure 3
 Result of the optimization regarding the required fuel mass as a function of the selected T/W and W/S

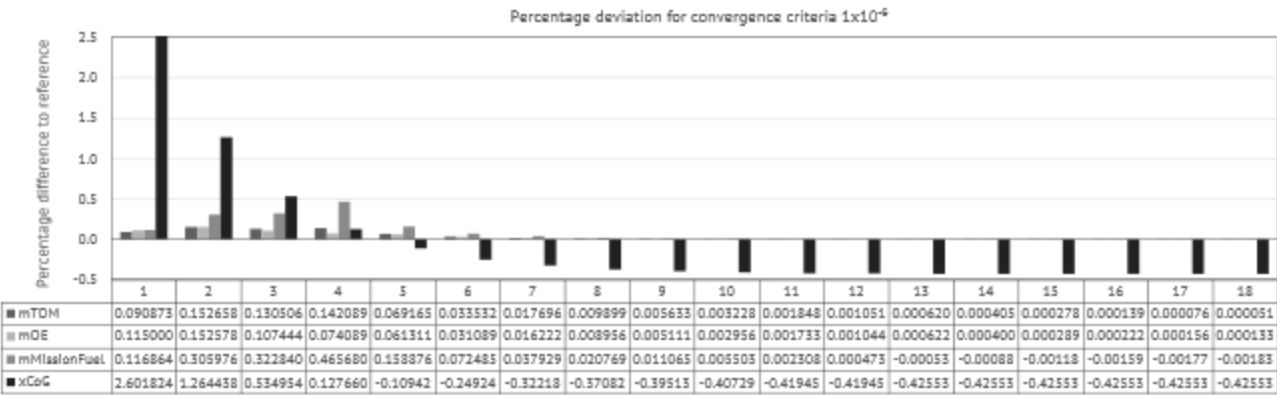


Figure 4
 Percentage deviation of convergence variables compared to the reference aircraft

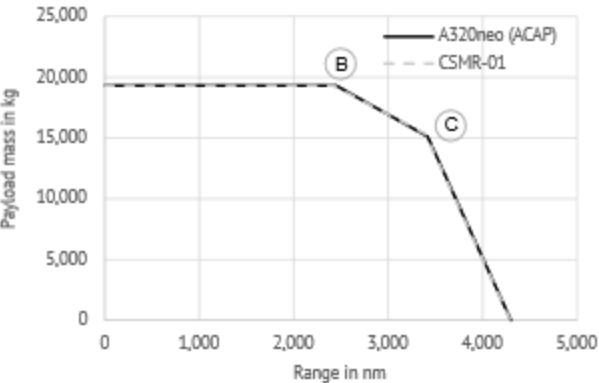


Figure 5
 Comparison of the payload-range-diagrams of design (CSMR-01) and reference aircraft (A320neo)

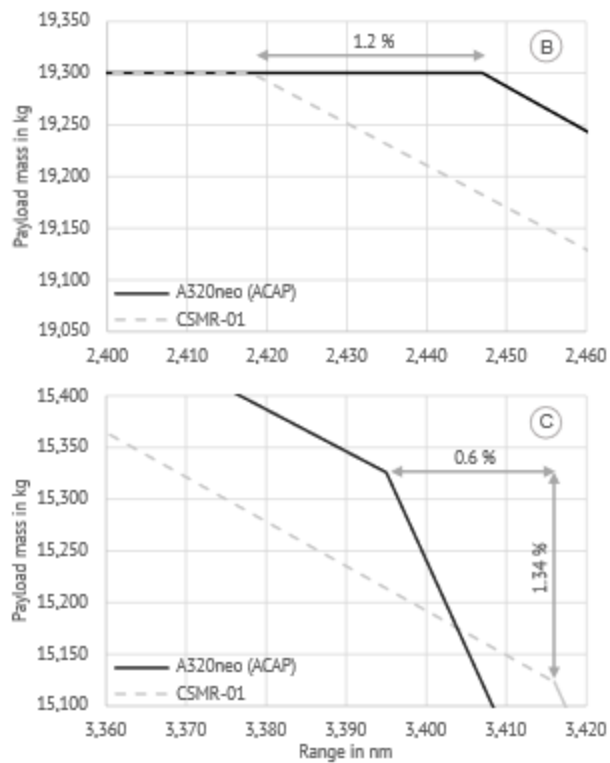


Figure 6

Percentage deviation of points B and C of the payload-range-diagram between design (CSMR-01) and reference aircraft (A320neo)



Figure 7

Top view of the comparison between design and reference aircraft



Figure 8

Side view of the comparison between design and reference aircraft