

# A Toolbox for Rotorcraft Preliminary Design

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## ABSTRACT

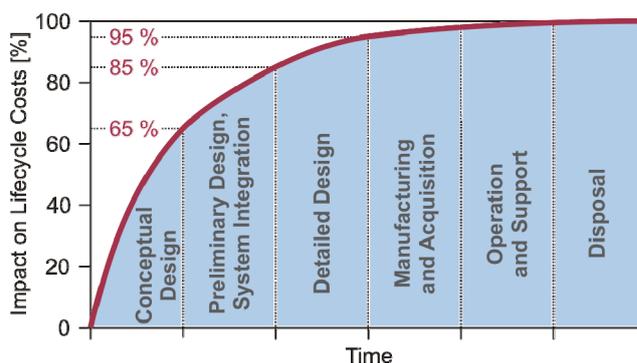
The German Aerospace Center (DLR) developed a toolbox, which is able to reflect the conceptual and preliminary design process of rotorcraft configuration. Such a toolbox is a valuable aid for the design engineer and can be used for the assessment of new technologies with regard to the overall configuration. This toolbox is currently extended to model novel rotorcraft configurations. Automated optimization procedures will be added in the future as well. This paper describes the toolbox layout and data management as well as the various individual tools developed at DLR in detail. Exemplary results of design tasks are given.

## INTRODUCTION

The design of aeronautical vehicles is usually divided into three stages: conceptual design, preliminary design and detailed design (Refs. 1, 2). The conceptual design stage defines the basic layout of the vehicle with respect to the specifications given. Based on this concept the preliminary design phase adds more details to the layout and further optimizes the configuration. The goal of the detailed design phase is to generate a description of the vehicle, which can be used for the subsequent manufacturing process. This paper describes a toolbox developed at DLR, which can be used to support the design engineer during the conceptual and preliminary design phases. These early design phases have a huge impact on the lifecycle cost for a product. Figure 1 shows that about 85% of the lifecycle cost are locked after these phases. Therefore the availability of computational aids is an extremely valuable tool for any design engineer.

The design of rotorcraft is a highly complex process. Compared to fixed-wing aircraft the design space is wider and more heterogeneous. Preliminary design tools are frequently used by the rotorcraft manufacturing companies. In general, they are based on detailed knowledge of existing helicopters and heavily use empirical methods. Despite this being an efficient means for the preliminary design of helicopters, the exploration of new unconventional designs is very limited due to a lack of data of existing

configurations. In recent years there has been a renewed interest especially in the design of unconventional concepts differing from the classical main and tail rotor configuration.



**Figure 1. Impact of the design phases on lifecycle cost (Ref. 3)**

Hence, the subject of rotorcraft design has been addressed by a variety of aerospace research organizations in recent years, for example by NASA (Ref. 4), NLR (Ref. 5) or Georgia Tech (Ref. 6). The French aerospace lab ONERA conducted a similar project from 2011 to 2014 (Ref. 7), active collaboration with the German Aerospace Center (DLR) on some topics was agreed upon and performed.

DLR started to work on the development of an integrated design software toolbox in 2009. As a collaboration of the Institute of Flight Systems, the Institute of Aerodynamics and Flow Technology and the Institute of Structures and Design the DLR internal project RIDE (Rotorcraft Integrated Design and Evaluation) started in 2010 and has successfully been completed in 2012. The objective of the project was to provide a basis for a multidisciplinary, integrated and automated tool for preliminary rotorcraft design with a

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strong focus on the analysis and assessment of selected configurations. The DLR project EDEN (Evaluation and Design of Novel Rotorcraft Configurations) started in 2014 and is based on the toolbox developed in the RIDE project. The main objectives of this project are the assessment of novel rotorcraft configurations and the assessment of the effect of new technologies with respect to the overall configuration. The development of suitable models for the interaction of different components of the rotorcraft is another main task of the project.

The developed design toolbox provides a profound basis for future activities, as the basic methodology can be adopted for any rotorcraft design as long as the underlying physical models are augmented to correctly represent such configurations. The toolbox pursues a blank sheet approach, thus only using the customer specification as a driver for the whole design process. Therefore it covers a wide design space and can provide high flexibility for various design solutions.

The DLR activities in the area of helicopter design are not primarily focused on the ability to design new concepts, but rather on the application of the gathered knowledge to the assessment of existing configurations and the estimation of the overall effect of technological advantages of individual subsystems.

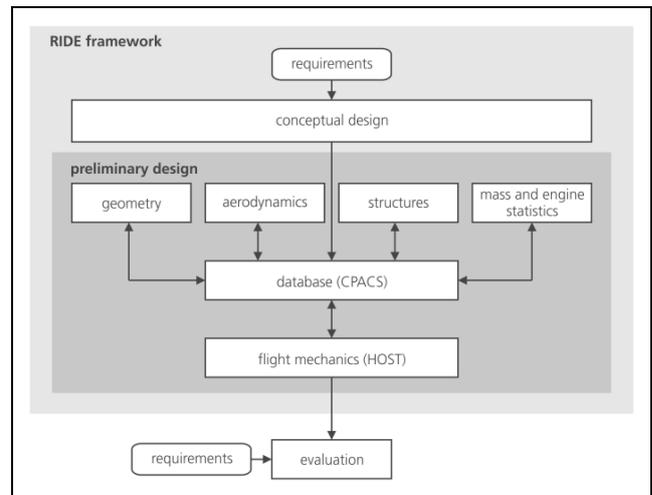
This paper describes in detail the structure of the design toolbox. A first preliminary design study carried out using the developed toolbox is presented. Finally the current status of the DLR activities on the subject of rotorcraft preliminary design as well as an outlook of planned activities are given.

## SOFTWARE TOOLBOX

The toolbox divides the design process into two stages (see figure 2). A separate conceptual design tool generates an estimation of a suitable configuration based on the requirements and provides a starting point for the subsequent computations. In this stage a statistics-based approximation is combined with simple physics-based methods and a genetic algorithm to obtain a favorable solution.

In the following stage (preliminary design) the design is refined by bringing in the perspectives of different disciplines. The geometry module uses parametric representations of helicopter fuselage geometries in a modular assembly to generate a three-dimensional Computer-Aided Design (CAD) model (CATIA) (Ref. 8). The aerodynamic properties of the fuselage are calculated using a linearized potential code with coupled viscous boundary layer calculations (VSAERO) (Ref. 9). Afterwards a generic structure of the fuselage is determined on the basis of static analyses of suitable load cases (ANSYS) (Ref. 10) using an automatically generated finite element method (FEM) grid. The engine parameters are obtained by means

of an exhaustive database of existing turbine engines. A statistical mass estimation completes the refined design. The resulting final configuration is at last evaluated using the flight mechanics code HOST (Helicopter Overall Simulation Tool) (Ref. 11). The output data of the various modules can finally be compared to the customer requirements and thus the design can be evaluated. This evaluation is done manually at the moment, although it is planned to be integrated into the automated process chain and means for incorporating certification criteria have been developed. The range covered by the conceptual and preliminary design modules is geared towards performance-centric rotorcraft design, as factors including costs or noise are not considered in the tool chain yet.



**Figure 2. Process chain of the toolbox and interactions between individual modules**

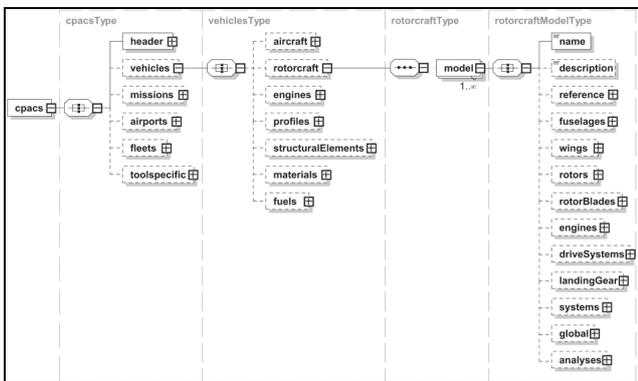
The Common Parametric Aircraft Configuration Scheme (CPACS), a data exchange file format based on the Extensible Markup Language (XML) serves as a common interface for all the software modules.

The various tools are described in detail in the following.

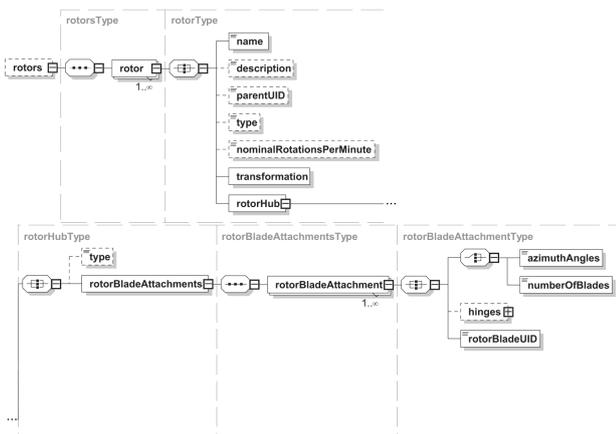
### Data Management and Framework

The CPACS data exchange format is the key component of the DLR rotorcraft design environment. It is used as a common interface for communication and data exchange between the user and between all integrated software modules. The development of CPACS started in 2005 within the context of the internal DLR project TIVA with the objective to create a common parametric description of the system “aircraft” suitable for all disciplines involved in the conceptual design and analysis process. Since 2012 CPACS is released to the public under an open source license (Ref. 12). In the early RIDE project phase the CPACS format has been extended by definitions for rotorcraft and rotorcraft-specific data. Figure 3 shows the structure of the XML definition of a rotorcraft configuration. The extensions were included in the official CPACS version 2.2 released in 2014.

The newly created `<rotorcrafft>` definition is derived from the existing `<aircraft>` definition. Figure 4 shows the structure of `<rotor>` nodes. It contains information about the type of the rotor (main rotor, tail rotor, fenestron, propeller), its nominal rotation speed and, most importantly, the `<rotorHub>` element. This element includes information about the rotor hub type and about all attached rotor blades together with the hinges used to attach them to the rotor head. In order to avoid the replication of rotor blade geometry definitions, the `<rotorBlade>` elements have been moved to a catalogue node `<rotorBlades>` of the model definition and are referenced using their unique ID inside the `<bladeAttachment>` elements. The blade geometry itself is defined using the existing data structure for the definition of wings.



**Figure 3. Root structure of the CPACS data exchange format.**



**Figure 4. Structure of the CPACS rotor definition.**

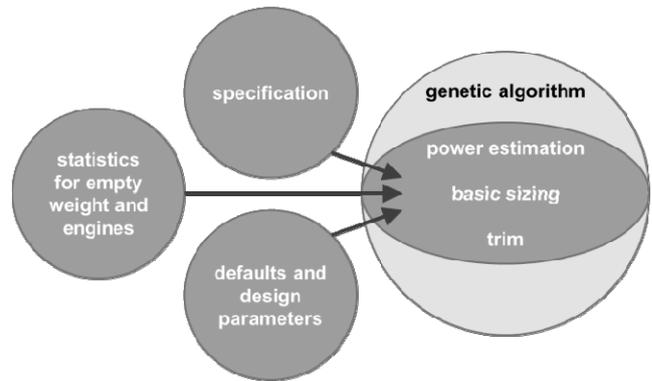
Furthermore, the subnodes `<global>`, holding basic design parameters (e.g. design range and design gross weight) and `<analyses>`, storing analysis results to be shared between modules, have been adapted for rotorcraft and the tools used in the RIDE tool chain. Finally, a new child node definition

has been added to the `<toolspecific>` node for each new analysis module.

The various tools are embedded into an integration framework, which manages the sequence of execution and the data transfer using the CPACS dataset. The integration framework is used as a user interface for the assembly, execution and control of process chains. There are two compatible integration frameworks available at DLR: The commercial software ModelCenter by Phoenix Integration (Ref. 13), and Remote Component Environment (RCE), an open-source framework developed in-house (Ref. 14). The former has been selected for use in the RIDE project, whereas the process chain is transferred to RCE during the current project.

### Conceptual Design

The process chain of the design toolbox starts with a basic sizing of the configuration (conceptual design). The COMRADE (COMputer-aided Rotorcraft Assessment and DDesign) tool gives estimations of the main parameters based on the customer specification. The structure of the tool can be seen in figure 5. The tool combines statistics and flight mechanics to create a configuration, which can be used as a starting point for the design task. The only mandatory input is the specification or a typical mission of the rotorcraft to be designed. Various design parameters (e.g. aerodynamic coefficients or parametric fuselage dimensions) as well as the underlying databases for mass and engine statistics are set by default, nevertheless they can be changed manually by the user to drive the solution into a desired direction.



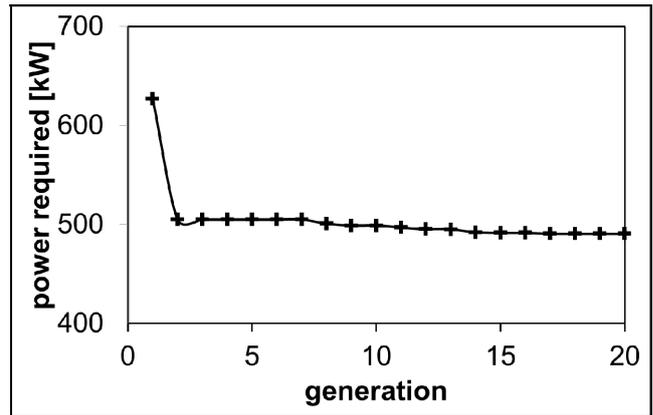
**Figure 5. Basic inputs and structure of the COMRADE module.**

The tool estimates the main dimensions of the helicopter fuselage, which are derived from the payload and cabin volume specification. The empty mass of the helicopter is estimated using a statistical approach based on a database of more than 140 existing helicopters. The approach consists of a multivariable regression combined with an estimation of a minimum degree of complexity of the regression function by use of hypothesis testing. Details of the statistical method used here have been published previously (Ref. 15). Additionally the main and tail rotor parameters are estimated

using momentum theory augmented with estimations of tip loss and global separation on the rotor blades. The fuselage drag is taken into account by applying a fixed drag coefficient to the calculated fuselage drag area. After calculating the power required for the given flight condition, the engine characteristics are estimated by regression using a database of 144 existing engines. The performance estimations are completed by calculating the required fuel weight and trimming the helicopter.

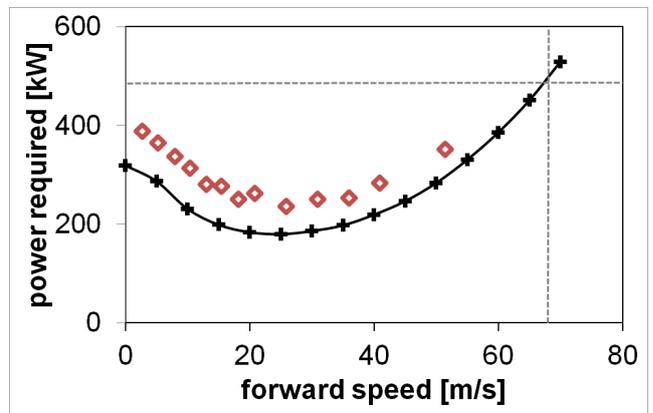
In order to determine a near-optimal solution, the whole sizing and performance estimation code is embedded inside a genetic algorithm. The algorithm performs a heuristic search for design variables specified by the user considering constraints (i.e. minimum and maximum values), which can also be set manually along with the desired resolution of the variable. Therefore the different design variables are converted to a binary value taking into account the range and resolution of the desired design space for that particular variable. For example, if the number of rotor blades is modelled with a minimum value of 2 and a maximum value of 5 and a resolution of 2 bits, the corresponding two bit string would be 00 for 2 blades, 01 for 3 blades, 10 for 4 blades and 11 for five blades. All design variables to be determined by the algorithm are combined into a string variable (resembling a bit array with a length depending on the number and resolution of design variables) which forms the genetic representation of the design space. This leads to maximum flexibility for the user to tailor the optimization process. Afterwards a random initial population is generated. The subsequent reproduction facilitates random crossover and mutation operations and is evaluated by a fitness function which can comprise any output variables of the embedded calculation module described above.

Applied to a design specification based on the MBB Bo-105 helicopter, the algorithm provides satisfactory results in terms of convergence behaviour and accuracy of the performance data as shown in the following. In this example, the genetic algorithm was initialised with a population of 100 solution candidates with the design variables to be determined being main and tail rotor diameter, the number of main rotor blades as well as main rotor solidity and tip speed. The solutions are evaluated for minimum required power (fitness function). The algorithm converges rapidly over the course of the first few generations (figure 6). The whole calculation is performed in less than five seconds on a standard PC.



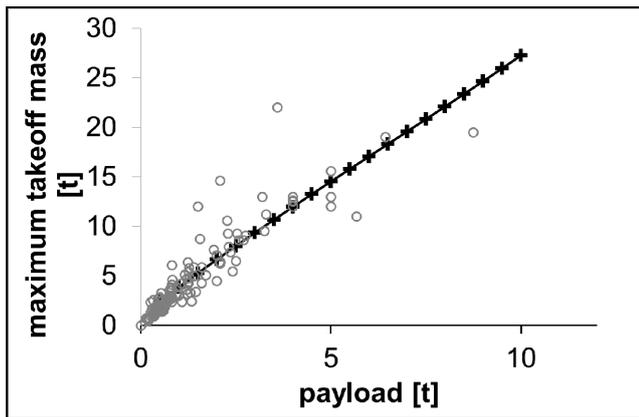
**Figure 6. Convergence behaviour of the genetic algorithm for a MBB-Bo-105-like design with a population size of 100 individuals.**

The algorithm was tested by varying the specifications for forward speed and payload. The results are shown in figures 7 and 8. For the forward speed variation the design solutions found by the algorithm resemble the well-known relationship between forward speed and power with the characteristic minimum required power found at medium forward speeds. Compared to the reference Bo-105 helicopter the results show a good agreement with the cruise speed and engine parameters.



**Figure 7. Design solutions for different forward speed specifications in comparison with flight test data (red diamonds, Ref. 16) and the reference values of cruise speed and maximum continuous power of the MBB Bo-105 (dotted lines).**

The payload variation leads to a significant increase in rotor radius, power required and takeoff mass for increasing payload. The results compare favourably with data of existing helicopters.



**Figure 8. Design solutions for different payload specifications compared with the data of existing helicopters (grey circles).**

### Geometry Design

The geometry generation module (GEOGEN) (Ref. 17) is based on automation of the commercial CAD/CAE system CATIA V5 via its VBA (Visual Basic for Applications) programming interface. It automatically instantiates components from a catalog of predefined templates, adapts their parameter values, assembles them and finally exports the generated geometries to CPACS. Like all analysis modules of the RIDE design environment, it reads all input parameters from a CPACS dataset and writes the generated geometry back to this dataset. The component catalog is an XML database containing interface definitions and filenames of available geometry components. The generated assembly is also returned as a CATIA part document in native CATIA format (CATPart). The definition of component types and components in the component catalog resembles techniques known from object-oriented programming languages:

- *Component type definitions.*

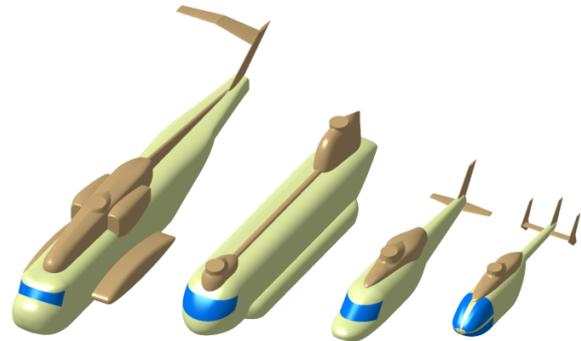
Component types are used to define standardized interfaces for components and hence allow any component in an assembly to be exchanged by components of the same type. They correspond to abstract base classes in object-oriented programming.

- *Parametric geometric components.*

Components serve as a framework for the interface definition and the creation or instantiation of CAD geometries from component templates. Each component is assigned to a component type, thus inheriting all parameter and subcomponent definitions from this component type, corresponding to classes derived from abstract base classes in object-oriented programming.

A component catalog containing component type definitions and a set of basic components intended for the creation of rotorcraft geometries suited for preliminary design analyses has been created in the project RIDE. The generated components focus on the generation of helicopter fuselage

geometries, but also contain simple templates for the creation of empennages, rotor blades and wings. Figure 9 shows example geometries generated using components from the RIDE component catalog.

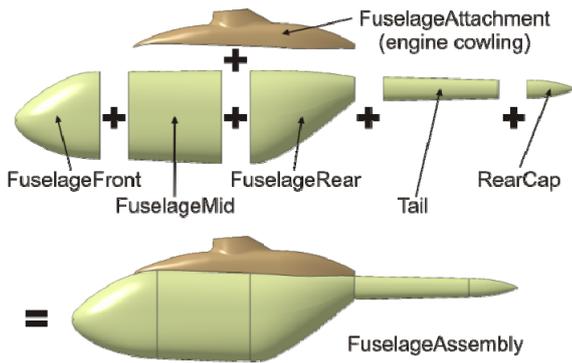


**Figure 9. Example geometries generated using GEOGEN and the RIDE component catalog.**

The RIDE component catalog contains definitions for the following component types:

- *Fuselage*
- *FuselageFront*
- *FuselageMid*
- *FuselageRear*
- *Tail*
- *RearCap*
- *FuselageAttachment*  
(e.g. engine cowlings, sponsons)
- *RotorBlade*
- *Wing*
- *Profile2D*
- *Point*

Figure 10 depicts an example fuselage assembly generated using components from the RIDE component catalog and its subcomponents.

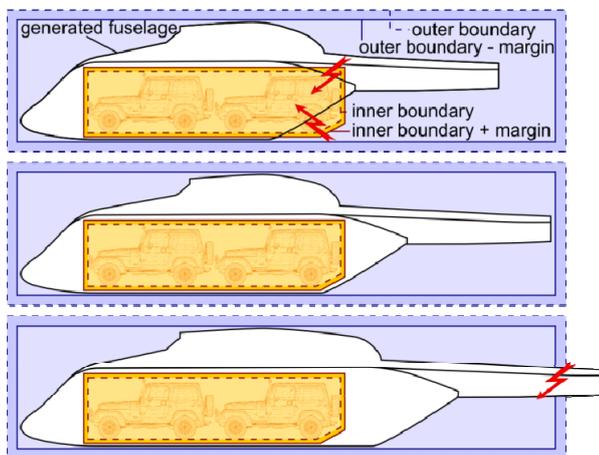


**Figure 10. Example of a fuselage assembly using components from the RIDE component catalog.**

GEOGEN includes an option to check whether the generated assembly satisfies geometric boundary conditions usually coming from the requirements definition. The boundaries are specified by CPACS fuselage definitions in the input dataset. Two boundaries can currently be specified (Figure 11):

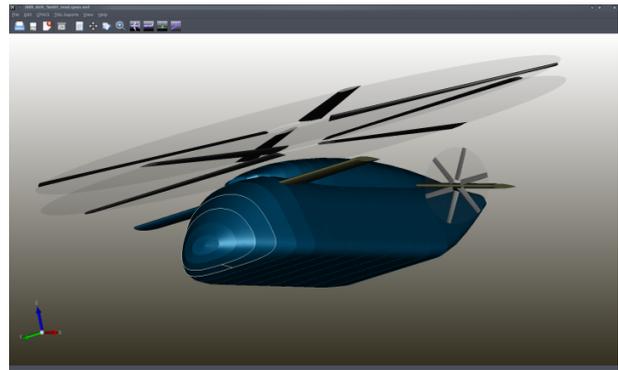
- An *inner volume* along with a minimum margin, used for specification of the required cabin volume.
- An *outer volume* along with a maximum margin, used for specification of the maximal outer dimensions.

If a boundary check fails, GEOGEN returns a predefined exit code without exporting the geometry to the CPACS dataset.



**Figure 11. Boundary checks. Top: Inner boundary fails; Middle: OK; Bottom: Outer boundary check fails.**

Figure 12 shows an example of a more complex fuselage structure, which has been assembled using the GEOGEN tool.



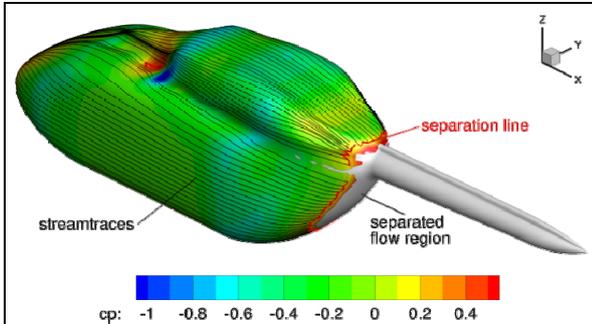
**Figure 12. Representation of a CPACS dataset of an advanced compound coaxial helicopter created by GEOGEN.**

### Aerodynamics

The overall flight performance prediction of helicopters using the flight mechanics code HOST (see below at section Flight Mechanics Evaluation) relies on aerodynamic performance maps for isolated components (fuselages, tail surfaces, wings). There are several modules of multiple fidelity levels available in the RIDE toolbox for the determination of these performance maps.

The module AEROFUSE generates aerodynamic performance maps of isolated fuselages. AEROFUSE is based on VSAERO (Ref. 9), a commercial linearized 3D panel code with coupled viscous boundary layer calculations, and a subsequent simple procedure for estimation of the pressure drag caused by separated flow. This additional procedure plays a significant role in the aerodynamic design of the helicopter. Helicopter fuselage design is often driven by operational and functional considerations, while the aerodynamic efficiency only plays a secondary role. This leads to bluff fuselage shapes, whose flow field is typically dominated by a region with separated flow at the aft of the fuselage, even in the cruise design point. Hence the drag component caused by separated flow cannot be neglected when considering helicopter fuselage drag. Potential codes do not account for the viscous pressure drag caused by separation when only using body surface panels. Using VSAERO, the effects of flow separation are usually modeled by manual definition of wake panels shedding at the separation line. But tests showed that this procedure cannot be easily automated and lacks robustness. Thus a simpler, more robust method for the estimation of viscous drag has been implemented in the postprocessing tool PLTCONVERT using the surface pressure and boundary layer data output by VSAERO. This method is based on the assumption of constant pressure in areas of separated flow. The assumed value for the pressure coefficient in these areas can either be set by the user or determined automatically. In the latter case it is derived by calculating the mean pressure coefficient on the separation line predicted by VSAERO's boundary layer code. The effect of the viscous pressure drag on the global force

coefficients is then calculated by summing the pressure force differences due to the corrected pressure coefficient on all panels where separated flow is predicted by VSAERO. Exemplary results for a BK117-like fuselage are shown in figure 13.



**Figure 13. Surface pressure distribution, streamlines and area with separated flow predicted using VSAERO on a simplified BK117-like fuselage geometry at zero incidence and sideslip.**

The polars of empennage surfaces are calculated using existing fixed-wing analysis tools based on LIFTINGLINE or VSAERO.

Additional drag components, e.g. parasite drag due to the rotor hub and landing gears is estimated using handbook methods. The module HANDBOOKAERO enables the user to easily select predefined methods for the estimation of additional drag components using approaches found in well-known aircraft and rotorcraft design literature or based on experimental results for basic shapes (e.g. Ref. 18).

Furthermore a database containing geometry and aerodynamic characteristics of common rotor blade airfoils has been set up. The database can be accessed in the process chain using the analysis module AEROPOLE. It adds the data for selected airfoils into the CPACS dataset.

### Improved Mass Statistics

The RIDE module MASERATI (Mass Estimation of Rotorcraft based on Statistics) calculates the rotorcraft masses based on equations which were developed by the evaluation of existing aircraft. Here the level of detail is low and currently limited to the weight of the complete respective group (e.g. body group, landing gear group or drive system).

Presently, four different methods for the calculation of the weights are implemented in MASERATI: Prouty (Ref. 19), Layton (Ref. 20), Beltramo (Ref. 21) and Palasis (Ref. 22). The respective statistical equations were taken from the literature mentioned and are based on historical trends. In some cases, single equations had to be corrected since there were obvious mistakes in the printed source which was on hand. In order to avoid potential new mistakes, all equations

were implemented in the original imperial units. The user can select which units are used for the input and output data. MASERATI requires up to 56 different input variables. If all these variables are accessible, the program can calculate the weights with all the currently implemented methods and compare the different results. In many cases, not the complete set of variables will be defined. Then, MASERATI selects the calculation method which fits the best with the available variables. In MASERATI, only the weights of the single systems/groups are currently calculated; the respective mass positions as well as their moments of inertia cannot be calculated. The mass positions are defined within the RIDE module GEOGEN and transferred to MASERATI where the overall moments of inertia for the complete rotorcraft are calculated by use of the Steiner theorem. The structure of the MASERATI output data is based on SAWE RP No. 8A (Ref. 23).

For the future, it is planned to introduce some factors into the calculation process which take into account the technological progress achieved with new materials and design methods. Due to limited resources and the lack of complete datasets for newer aircraft this could not yet be realized. Up to now MASERATI has only been validated by use of the data of “historical” rotorcraft. New configurations have not yet been tested.

For the estimation of the rotor blade mass and moment of inertia a generic rotor blade structure (C-spar or D-spar design) is scaled with respect to the airfoil definition and blade dimensions. By integration along the blade length the blade mass and center of gravity as well as the first and second moment of area are determined.

### Structural Analysis

The structural analysis of rotorcraft fuselages within EDEN is conducted in two subsequent steps. In a first step the primary structure (e.g. frames, stringers) to carry global bending and torsion is provided to the fuselage loft by the tool F-DESIGN (Fuselage-Design). Structural components are distributed due to knowledge based design criteria and geometric requirements (e.g. door cut-outs).

So-called design sets have to be defined by the user in the tool-specific node in the CPACS file. A design set comprises the definition of so-called master frames, master stringers and various regions in longitudinal and circumferential direction where structural reinforcements can be distributed with arbitrary spacing.

Design sets can be defined (inside the XML interface) using the elements described below:

- *Master frames.*  
In this XML-node frames are defined that have to be located at certain x-positions of the fuselage.
- *Master stringers.*  
Master stringers are – analogue to the master frames –

longitudinal reinforcements that have to be placed exactly according to their definition in this node. A master stringer is defined by regions between master frames and a corresponding z-position. This node is also used for the definition of the cabin floor.

- *Additional frame regions.*

A frame region is embedded by two master frames (which are defined in the master frame node). For each additional frame region a maximum frame pitch is defined. Fdesign\_rc distributes the frames equally in the corresponding zone making sure that the maximum pitch is not exceeded.

- *Additional stringer regions.*

Between two master stringers a unique stringer distribution can be defined by entering a maximum stringer pitch.

- *Additional stringers.*

This node is used to place stringers that do not start at the first frame and end at the last one. It is possible to define a stringer in this node that runs – in contrast to the surrounding stringer pattern – between two frames. This node is particularly important for the definition of cut-outs.

- *Default frames.*

All regions of the fuselage that are not located inside an additional frame region are provided with frames according to this default frame definition. A maximum pitch for the frames is defined in this node.

- *Default stringers.*

Analogue to the default frame definition, all regions of the fuselage where no stringers are placed due to the definitions given above, are filled by stringers which are given a maximum pitch in this node.

For instance, master frames can be positioned at the edges of door cut-outs to reinforce the structure to redistribute load. Close to the main rotor, where very high loads are introduced into the airframe, a region may be defined where frame spacing is closer compared to the rest of the fuselage.

Analogue, master stringers may be positioned according to certain design rules. For instance may the stringer pitch be reduced close to the main rotor, thus, generating more stringers. Moreover, a master stringer may be used to define the cabin floor position. Also, fuselage skin panels are generated by F-DESIGN.

By this means the structure may be stiffened only where it needs to take higher loads.

Based on a generic heavy transport helicopter five generic frame distributions and two different stringer distributions between the two upper main stringers are shown in Figur 14. The main stringers that were used as outer limits for the stringer distribution are denoted in figure 15. An overview of the different configurations for figure 15 is given in tables 1 and 2. The frame region that was modified was defined

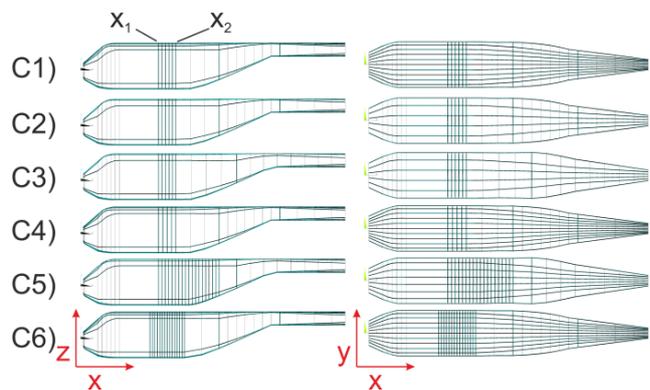
between  $x_1$  and  $x_2$  close to the main rotor, where master frames were automatically placed, too. Note that – to highlight the versatility – the tail boom was provided with alternative frame spacing in configurations C3, C5 and C6. Thus, frame configurations F1 and F2 are different though having the same values for  $x_1$ ,  $x_2$  and the maximum frame spacing between  $x_1$  and  $x_2$ .

**Table 1. Frame / stringer configurations.**

| configuration | frame region | stringer region |
|---------------|--------------|-----------------|
| C1            | F1           | S1              |
| C2            | F1           | S2              |
| C3            | F2           | S2              |
| C4            | F3           | S1              |
| C5            | F4           | S2              |
| C6            | F5           | S1              |

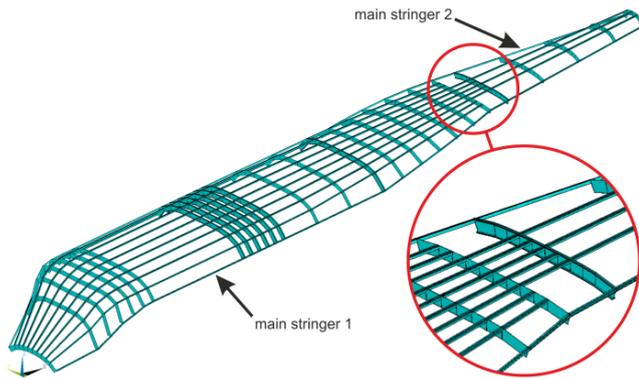
**Table 2. Definitions of frame / stringer regions (units in meters)**

| region | $x_1$ | $x_2$ | frame pitch | stringer pitch |
|--------|-------|-------|-------------|----------------|
| F1     | 4.5   | 5.5   | 0.2         | N/A            |
| F2     | 4.5   | 5.5   | 0.2         | N/A            |
| F3     | 4.5   | 5.5   | 0.3         | N/A            |
| F4     | 4.5   | 8     | 0.2         | N/A            |
| F5     | 4.0   | 6.0   | 0.15        | N/A            |
| S1     | N/A   | N/A   | N/A         | 0.3            |
| S2     | N/A   | N/A   | N/A         | 0.4            |



**Figure 14. Generic frame / stringer distributions.**

One important feature recently implemented in the process chain was the so-called *stage modeling* feature. It allows the generation of virtual stringers without any reinforcing structural elements. Stage modeling can thus be used to interrupt stringers (for the generation of cut-outs) or to end them (for tapered lofts). As an example for tapered lofts the reduction of stringers in the tail boom of a generic rotorcraft is shown in figure 15.

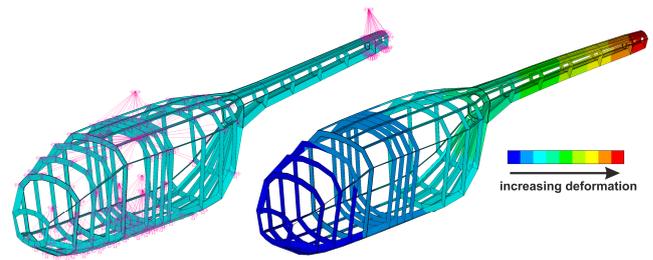


**Figure 15. Reduction of stringers for a generic tail boom.**

As result of the F-DESIGN run an updated CPACS file with a full set of data to describe the fuselage structure is written which will subsequently be processed by ROFUMA (Rotorcraft Fuselage Mass Assessment). ROFUMA is an ANSYS based tool to generate and analyze the structural behavior of rotorcraft FE (Finite Element) models. Loads respectively load cases are generated by the tool COMRADE before and stored into the CPACS file. Gravity is taken into account.

An exemplary static computation of a steady flight load case for a light utility helicopter is shown in figure 16. Non-structural masses (systems, payload, occupants, etc.) and external loads (e.g. main rotor lift) are applied to single nodes and distributed to an individually defined region of the airframe by the use of constraint equations (e.g. rigid body elements (RBE)) to avoid high stress concentrations. The extent of the constrained regions has to be defined by the user within the CPACS file. Exemplary the corresponding elements are highlighted in figure 16 (left).

Figure 16 shows an exemplary calculation of a light utility helicopter during constant flight (fuselage skin panels are not shown for visibility reasons). The magnitude of deformation is shown in the right plot in an amplified way. Due to a fixation of the model at the first frame the deformation nearby is zero. As all secondary masses (except occupants and rotor gear boxes) are in this example concentrated in the center of gravity, the region where the lift is introduced into the fuselage shows only little deformation. Tail rotor load leads to bending and torsion of the tail boom.



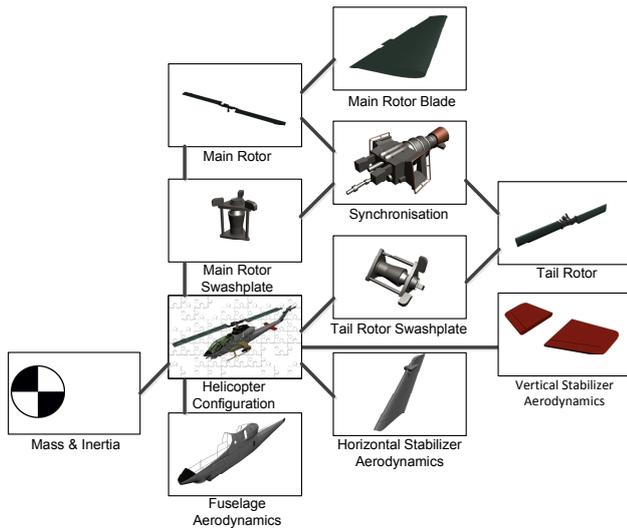
**Figure 16. ROFUMA FE model and nodal displacements (magnitude).**

Concluding the structural analysis a static sizing run will be conducted using the optimization tool S-BOT+ (Sizing robot+) which will be extended for use with rotorcraft structures within EDEN. S-BOT+ will conduct static sizing of the airframe using fully stressed design principles as well as basic stability criteria for shells and reinforcement beams. More information on the sizing process and S-BOT+ is given in Ref. 24. Future work in the field of structural analysis of rotorcraft will focus on detailed and extended geometrical modeling (e.g. short wings) and on the extension of the tool AC-CRASH (Ref. 25) to rotorcraft fuselages to investigate survivable crash load scenarios.

### Flight Mechanics Evaluation

The flight-dynamic modelling and simulation forms the core of the preliminary design process as all data generated by the preceding tools are eventually processed into the simulation of the rotorcraft. The simulation therefore serves as the central analysis tool for the design process. HOST (Helicopter Overall Simulation Tool) is a FORTRAN-77-based software developed in 1994 by the aerodynamic department of Eurocopter France. HOST is an integration structure for all the existing and future helicopter simulation tools modelling the mechanics of the flight of the helicopter and its dynamic behavior in flight or on the ground (Ref. 11). Since its introduction HOST was continuously extended with new models and new functionalities (flight control systems, dynamic engine models, additional rotor-induced velocity models, etc.).

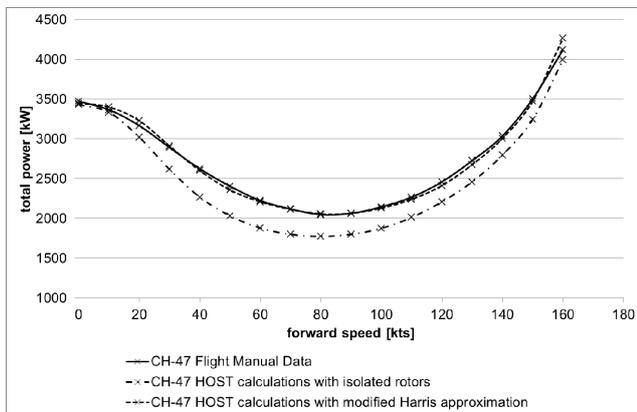
The dataset structure of HOST is modular with the main configuration file to link all the functionalities and dependencies among the mostly physics-based helicopter modules (figure 17).



**Figure 17. Setup of HOST input files for a dataset representing a conventional helicopter configuration**

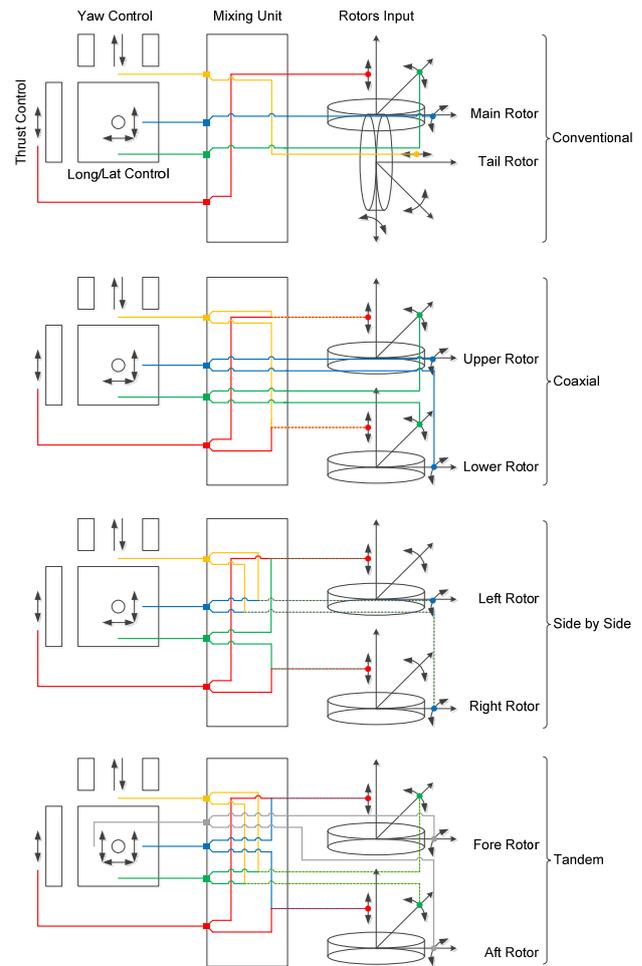
The depth of the modelling of the rotor system is variable (actuator disc, blade element method, rigid or soft blades). It is necessary for the complete integration to transfer the data from CPACS into HOST input files, to enable an automated HOST execution and to process the obtained data inside the design framework. The automated generation of a complete HOST input dataset based on the CPACS input is performed by supplementary routines written in the Python programming language.

In order to be able to design tandem rotor configurations, an estimation of the rotor-rotor-interaction based on the approximation given by Harris (Ref. 26) was included into the HOST simulations. Figure 18 shows that the approximation gives satisfactory results in comparison with CH-47 flight manual data.



**Figure 18. Total power dependent on forward speed for HOST-calculations with and without rotor-rotor-interaction compared to flight manual data.**

For any helicopter with two main rotors the rotor controls have to be reduced to four or five pilot inputs in order to model them in HOST and apply the same equilibrium law as in the conventional case. Therefore the rotor controls are determined from the pilot inputs using a mixing unit inside the HOST simulation. An overview of the implemented control laws is given in figure 19.



**Figure 19. Transformation of the rotor controls to pilot inputs for different configurations.**

## EVOLUTION OF THE DESIGN DATASET DURING THE PROCESS CHAIN

In the following the data flow throughout the process chain will be outlined. As the CPACS format is used as a universal interface, every individual tool takes a CPACS dataset as an input and outputs another CPACS dataset, which is expanded by all data generated by the concerned tool. The size of a typical CPACS file rises from about 100 kB at the beginning (containing mainly fixed parameters for the tools as well as the various templates for the fuselage segments) to

over 500 kB after the geometry generation and finally to over 700 kB at the end of the process chain.

The minimum user input for the design cycle is the specification of the rotorcraft to be designed comprising forward speed, range, payload, and cabin volume. Other input data (such as rotor radii and speeds) can be obtained by the integrated optimizer. Additionally some parameters (such as lift and drag coefficient) are preset but can be altered by the user. The output of the COMRADE tool provides a variety of values for the subsequent modules, including:

- estimations of the maximum required power considering the specification,
- initial estimations of the fuselage dimensions, center of gravity and inertia,
- layout of the rotors and empennage dimensions,
- initial estimations of empty mass, fuel mass, and take-off mass.

The GEOGEN tool generates a detailed fuselage geometry based on the fuselage dimensions predicted by the conceptual design tool. There are predefined sets of fuselage components for conventional or tandem helicopters, such that the fuselage geometry can be generated automatically. Alternatively, the user can define a special fuselage using the different fuselage segment templates described above. Furthermore the tool adds the geometric definitions of the rotor and empennage airfoils using a database. The positions of non-structural masses (e.g. engines, cockpit avionics, seats) are set as well by the GEOGEN tool.

The fuselage and empennage aerodynamics (i.e. polars) are then estimated by the AEROFUSE tool. The mass estimation tool adds a detailed mass breakdown to the dataset, which includes statistical estimations of:

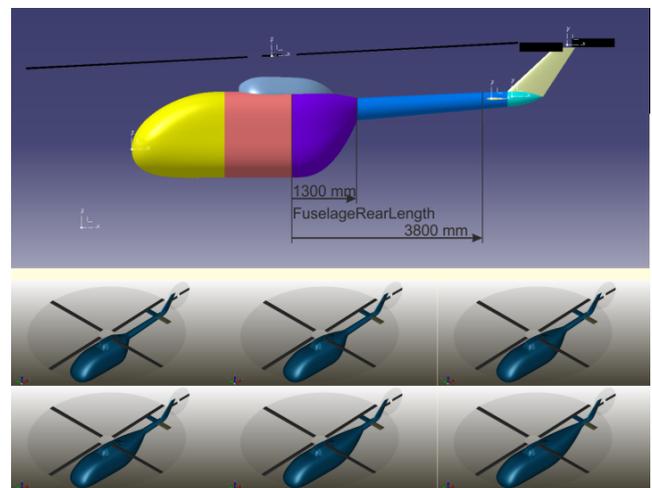
- the weight of the fuselage structure,
- the weight of the main and tail rotors,
- the weight of the fuel system, the engine, and other systems and equipment.

The structural design tools add a detailed structure of the fuselage. This is done fully automatic based on the fuselage geometry definition generated by GEOGEN.

The complete CPACS dataset is eventually converted to serve as an input for the flight mechanics simulation HOST. The HOST output data can then be used for the evaluation of the designed helicopter.

## EXEMPLARY RESULTS OF A FIRST PRE-DESIGN STUDY

The described toolbox can be used to evaluate the effects of certain design decisions on the performance of the helicopter. Thus, starting from the Bo-105-like configuration described above the effects of a fuselage enlargement have been studied. The easiest (although not always most practicable) way from a design perspective to enlarge the fuselage volume is to extend the fuselage rear end towards the tail rotor and to shorten the tail boom simultaneously. For demonstration purposes the helicopter rotor dimensions and positions as well as height and width have been chosen constant within the design study. Figure 20 shows the geometries used in this study resulting from the variation of the length of the rear fuselage segment from 1300 mm to 3800 mm in steps of 500 mm.



**Figure 20. Resulting geometries of a pre-design study with respect to fuselage enlargement.**

The mass estimation algorithm gives a constantly increasing empty weight ranging from 1475 kg to 1572 kg with increasing fuselage volume (see figure 21). The results of the fuselage drag estimation (figure 22) show a rapidly decreasing pressure drag with increasing length as the form of the fuselage becomes more streamlined. The trend of the predicted viscous drag component also seems plausible. Its constant increase corresponds to the increase of the ratio of the wetted surface to the frontal area. Finally, the power estimation of the HOST simulation tool (calculated for a maximum cruise speed of 130 kts) shows reasonable trends (figure 23). The parasite drag power corresponds well to the predicted total fuselage drag. The induced power is nearly constant with only a slight increase due to the relatively small increase in empty weight. The shape of the profile power curve can be explained with varying momentum coefficients and pitch angles.

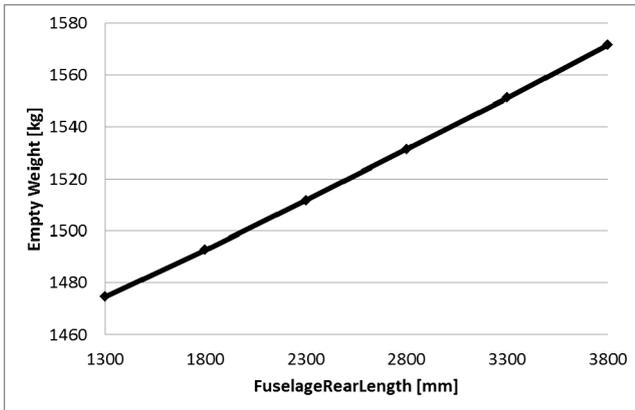


Figure 21. Pre-design study: weight estimation.

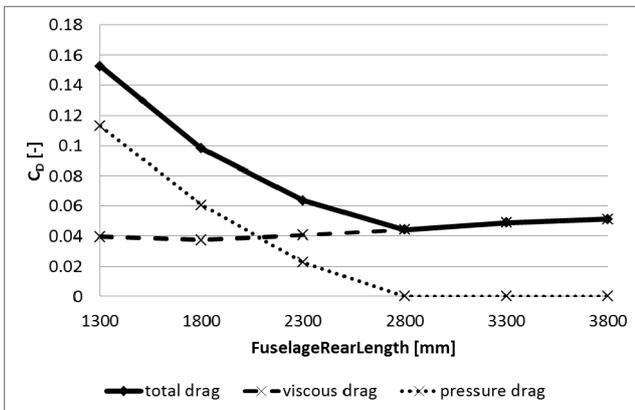


Figure 22. Pre-design study: fuselage drag estimation.

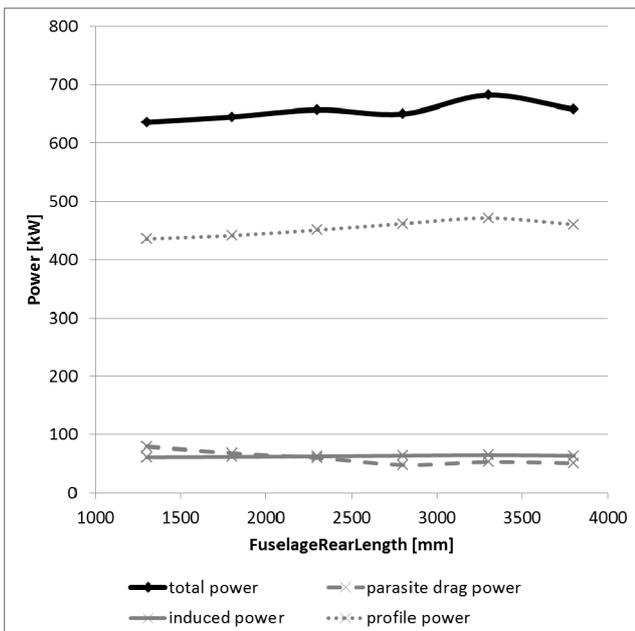


Figure 23. Pre-design study: power estimation.

## CONCLUDING REMARKS

In the course of the DLR project RIDE a truly integrated design environment for transport helicopters has been developed. A three-dimensional geometry and detailed structural design solution accompanied by profound data on flight performance calculated by HOST are determined starting from very few customer specifications. The RIDE toolbox allows the analysis of conventional configurations as well as a simplified modelling of tandem rotor arrangements. The use of CPACS as a common interface for all modules has proven to be successful. Thus, the definition of individual interfaces between interacting modules is not necessary, ensuring maximum flexibility regarding the process chain. Additionally, intermediate results are easily accessible and can be examined as all data generated by any module at a certain stage of the process are present in the CPACS data set exchanged between the tools. The process chain has been implemented in ModelCenter and is fully functional. One single calculation of the whole chain is executed in well under five minutes on a standard PC, which should be sufficient for a preliminary design study.

The current DLR project EDEN will further improve the toolbox with a strong focus on the modelling and design of novel rotorcraft configurations. This includes the extension of the geometry generation module to be able to automatically generate additional components like pylons, wings, etc. The generation of different fuselages for multi-rotor configurations is another work package. Regarding the structure generation future work will be spent on the generation of further geometries like cabin floor, cut-outs and variable profile geometries for the frames and stringers. Another focus lies on the generation of external geometries like additional lift generating devices (wings) to account for unconventional helicopter designs. Therefore, much work will be spent on different model ranges where the stringer distribution will differ significantly between different regions (e.g., the tail rotor segment that features less stringers than the cabin segment). As crashworthiness aspects are of particular interest in helicopter design, the CPACS-based tool AC-CRASH (AirCraft Crash) (Ref. 25) will be extended by integrating rotorcraft structures. This step will enable automated crash analyses by the use of the explicit FE solver PAM-CRASH (Ref. 27). Finally the various configurations have to be converted into a HOST dataset.

Concerning the whole process chain an iterative optimisation procedure has to be introduced as currently the only sizing task is done using the relatively simple model in the conceptual design phase. However, in order to further improve the design result all modules have to be integrated in a global sizing loop.

Another main task of the EDEN project is the development of simple models for the interaction of different components

of the rotorcraft (e.g. between rotors, between rotor and wings, between rotor and propellers, etc.). This is a crucial part of rotorcraft performance estimation, especially with respect to novel configurations. The aim is to develop models that are suitable for the use in a pre-design environment in terms of accuracy as well as complexity and calculation time, respectively.

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