Aircraft Design Support using Knowledge Engineering and Optimization Techniques

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Summary

Optimisation theory makes a distinction between design variables and design parameters. For aircraft design problems, variables specify differences within an aircraft configuration while parameters relate to intertype differences, i.e. differences in configuration. During an optimisation, parameters are normally fixed and the optimisation is limited to finding a combination of values for the design variables that will minimize or maximize an objective function like weight or range. The mathematics required to optimise at a higher level and support the choice between different concepts are not available nor are product models that allow seamless variation between configurations. In this paper the latter problem is attacked and the use of Knowledge Engineering for parametric modelling of aircraft is discussed. It will be shown that a proper combination of object oriented programming, rule based instantiation of objects and a geometry engine allows parametric modelling in the optimisation sense. The principle and implementation of High Level Primitives, i.e. functional building blocks, is shown to be a proper approach to the problem. It is also shown how these parametric models can be used and initialised in so-called Design and Engineering Engines, which allow multiple-views on the aircraft and offer a framework for design decisions in the conceptual design phase.

Introduction

In the last decade several new aircraft configurations have been suggested for civil transport aircraft. The blended wing body, box wing and joint wing aircraft [1] are some illustrative examples. However, none of these new concepts has made it to an application stage so far. The financial risks involved with deviations from the so-called Kansas City type of aircraft [2] are high and prohibitive for exciting experiments. In addition some of the ‘oldies’ in the field of conceptual aircraft design claim that the dominant configuration is dominant for many good technical reasons and none of the so-called innovative configurations offer sufficient advantages or even advantages at all that would justify their application to civil transport aircraft. Their right or wrong will never be proven based on real experience so we will have to obtain ‘virtual experience’ to verify their statements.

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This virtual experience should be obtained through multi-disciplinary studies of the innovative configurations, including parameter studies, what-if studies and trade-offs, to find the required proof. Some experience with this approach was gained with a study on the Multi-Disciplinary Optimisation of Blended Wing Body Aircraft, the MOB-project, [3, 4]. This experience will be summarized in the next section. The lessons learnt have lead to follow-up research that will be discussed in the subsequent sections. These sections address: parametric modelling in the optimisation sense, the paradigm of the Design and Engineering Engines (DEE), and the use of optimisation techniques and rule based reasoning for the initiation of the parametric models for use in a DEE.

The experience from MOB

The MOB project concerned the development of an automated multi-site, multi-disciplinary design process validated with a demonstrator conceptual aircraft design, in this case a Blended Wing Body aircraft. The study lead to the definition and implementation of a so-called Computational Design Engine (CDE), Fig.1, a collection of interconnected modelling and analysis tools that where connected through the internet to perform a multi-disciplinary

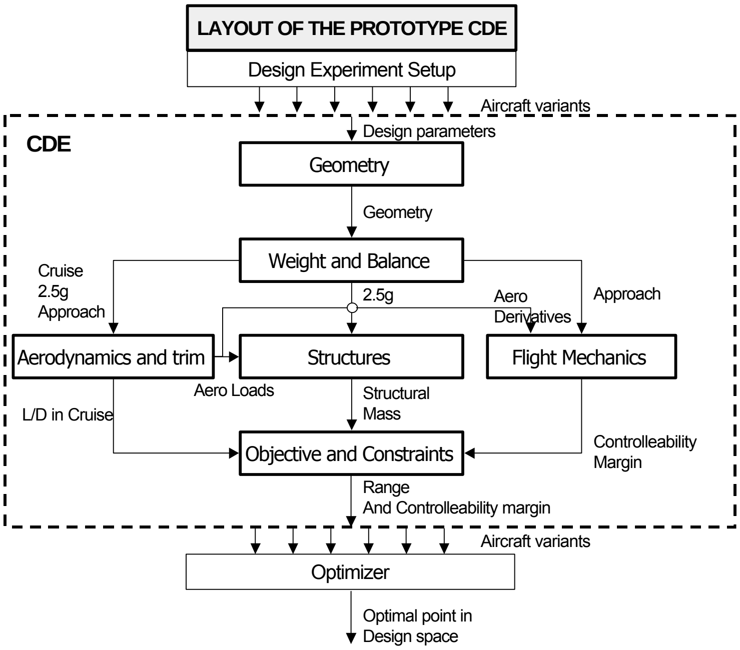


Figure 1 *The MOB Computational Design Engine concept*

optimisation of a freighter version of a Blended Wing Body aircraft [3, 4]. The CDE included a geometry module, a so-called Multi-Model Generator (MMG), that supplied models to the different analysis tools. The functionality of the MMG is illustrated with Fig.2. The different models produced by the MMG allowed multi-disciplinary analysis and optimisation.

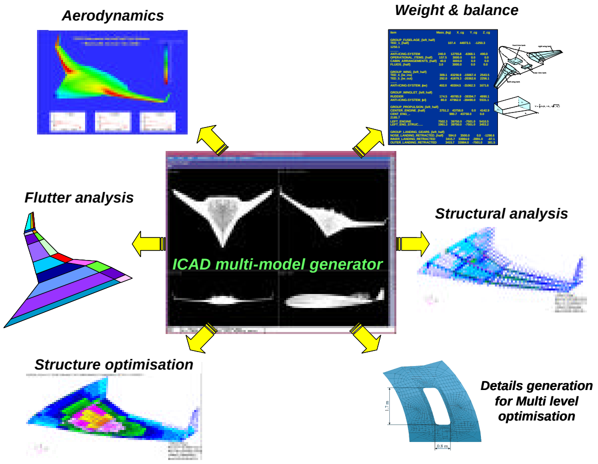


Figure 2 *Role of the ICAD Multi-Model Generator inside the MOB Computer Design Engine.*

The project showed that parametric modelling of aircraft is not possible with the traditional CAD-tools. Only so-called Knowledge Based Engineering (KBE) tools allow this parametric modelling in the optimisation sense: optimisation theory makes a distinction between design variables and design parameters. For aircraft design problems, variables specify differences within an aircraft configuration while parameters relate to intertype differences normally addressed as differences in configuration. During an optimisation, parameters are normally fixed and the optimisation is limited to finding a combination of values for the design variables that will minimize or maximize a certain objective function like weight or range for the specific configuration. In the case of the blended wing body study it was required to experiment with the application of, amongst others, fins and canards. This demands parametric model variation. This was achieved using KBE tools. A specific methodology was developed based on High-Level Primitives (HLP) [4, 5], which can function as aircraft building blocks. The HLPs are object-oriented modules that include rule bases for context sensitive instantiation. With these blocks a wide variety of aircraft can be modelled. The Blended Wing Body is a relative simple aircraft for parametric modelling that can be modelled with one HLP, the so-called wing trunk. The HLP approach also made it possible to arrive at a true multiple-view on the design. The KBE models allow the extraction of discipline specific information. The main advantage of KBE models is that the product model is not a geometric model but a structure of rules and objects. The geometry of a product is just one of the many views on the product and not the starting point from which other views are derived. Normally the geometric view does not contain sufficient information about the knowledge behind the design to generate other views.

The project showed some important gaps in the current engineering tools and methodology. Especially multiple view product modelling, process control of multi-site, multi-disciplinary design projects, equivalent modelling [6] and design information exchange need major improvements. Some of these topics will be discussed in the following sections.

Parametric modelling

Parametric modelling can be applied to capture commonality in a variety of configurations, shown in Fig.3, or to capture variation within a configuration, Fig.4. The examples shown in these figures have been created in the KBE package ICAD. Both cases show the type of variation that can be controlled with parameters. Within each configuration, determined by a parameter set, traditional optimisation of design variables values is possible. These variables can address sweep angles, span, dihedral etc. The HLPs used for the configurations shown below are the wing trunk, the fuselage, the connection elements and the engines

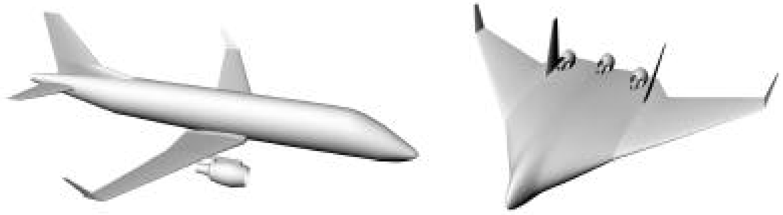


Figure 3 *Commonality between different aircraft configurations captured with KBE based Parametric Modelling*

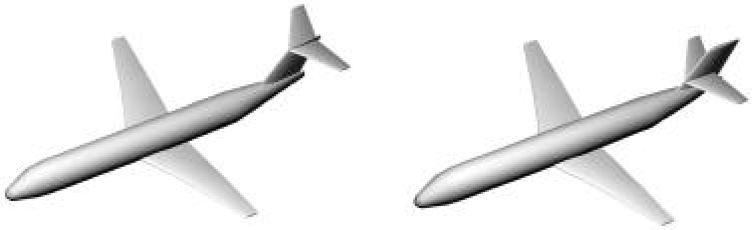


Figure 4 *Variation within an aircraft type captured with KBE based Parametric Modelling*

[4, 7]. These HLPs and their use are illustrated in Fig.5. The wing trunk HLP can be used as building block for wings, tails, control surfaces, fins, winglets and any other wing-like aircraft component. Some possible configurations are shown also in Fig.5.

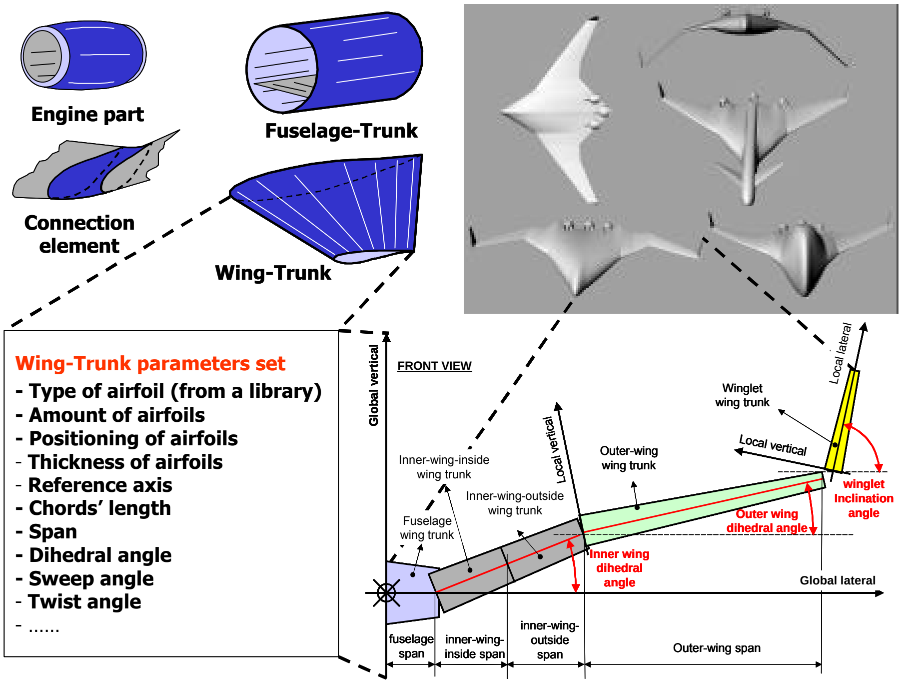


Figure 5 *The basic HLPs to define different aircraft configurations. Illustrated is how the wing trunk HLP can be used to define a family of aircraft. The wing trunk HLPs are interconnected with the connection elements. Note that all aircraft shown are made with the same number of wing trunks and with wing trunks and connection elements only, so with a true parametric model.*

The HLPs are reusable pieces of object-oriented code (modules) that are initiated based on rules and controls. These parameters and variables are addressable by basically any program and therefore allow these product models to be used in analysis and optimisation loops. The concept of the HLPs is implemented using Knowledge Engineering (KE, a term preferred by the author over Knowledge Based Engineering) instead of traditional CAD. The Knowledge Engineering principles will change considerably the design processes in companies and bring new possibilities for product optimisation. KE allows product models that are not starting from a geometrical view on a product but define a product as a collection of disciplinary views on a product. Geometry is just one of these views. In this way the intent behind a product and the methods required to analyse a product become part of the product definition.

Frameworks

The parametric models become useful only when they can be integrated in a framework that takes care of the initiation of the parameters and variables of the HLPs and that takes care of the coupling of the model to analysis tools like FEM and CFD to derive design properties. If this set-up is completed with evaluation and optimisation functions, a so-called Design and Engineering Engine is created that can support the designer in the conceptual and preliminary design phase. This concept is illustrated in Fig.6. Important elements of the DEE are process control and initiators. These elements will be discussed now in more depth. The other components of the DEE like the evaluator and the optimiser will not be considered here.

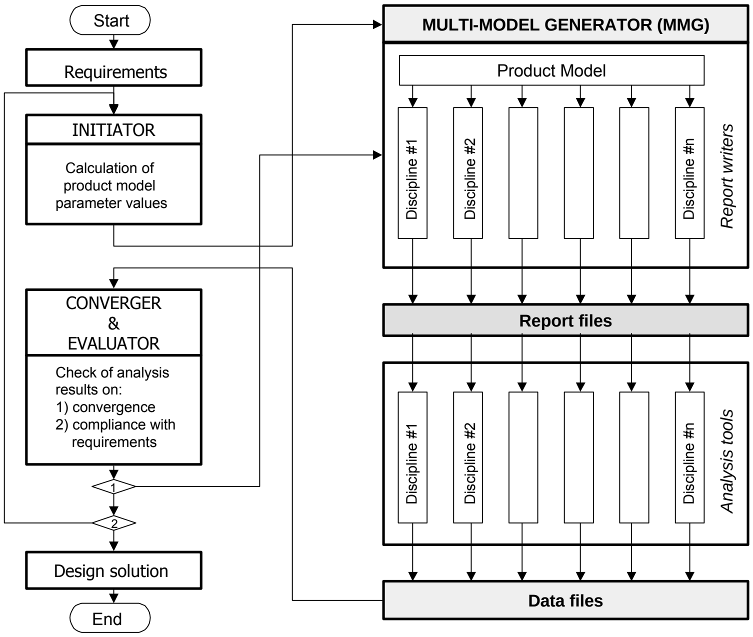


Figure 6 *The Design and Engineering Engine (DEE) concept*

Process control is required to start and control each process in the loop, supply it with the proper input and direct its output to the proper location. Flexibility requires this process control to be realized in a platform independent language that can function in a constellation of computers, operating systems and tools. An illustration of such a framework is given in Fig.7. This particular framework is created using the Python programming language. It is controlling the preparation and execution of a 2D car analysis to find the proper ground clearance.

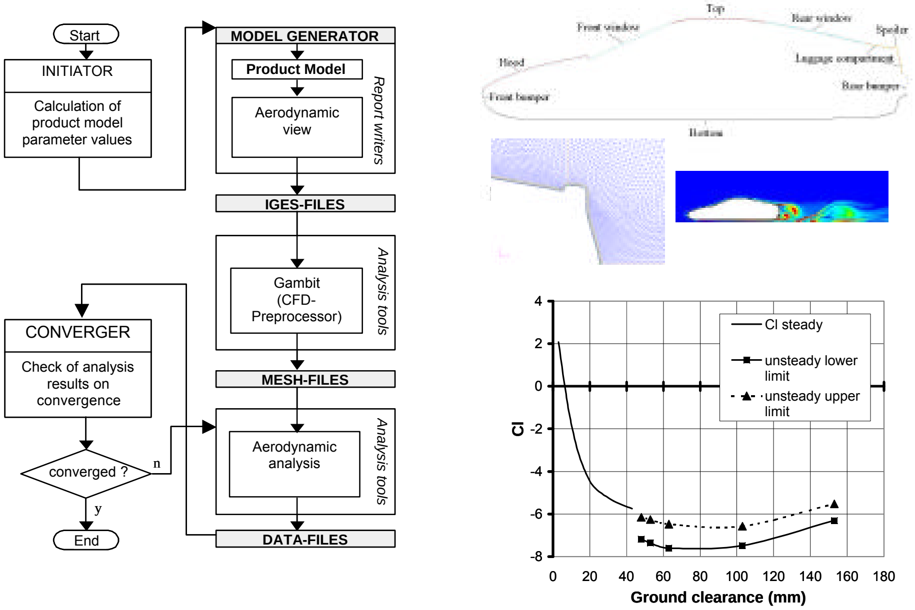


Figure 7 *The DEE concept applied for 2-D aerodynamic analysis of sports cars*

A second, more elaborative example is presented in the flow diagram of Fig.8. This framework automates the load analysis of conventional aircraft and supports the evaluation of major structural changes. In this case the redesign of a vertical tail can be specified on a parametric level and all the effects of the change on stiffness, mass and aerodynamic properties will propagate throughout the process [8].

In the DEE the initiator generates the initial values for the parameters and the variables inside the HLPs. An example of an initiator is the process that calculates initial values for the structural elements in a HLP, e.g. a wing trunk contains spars, ribs and skins. If the HLPs are used to feed a FEM analysis, it is required that the FE-tool is fed with proper input data. In the conceptual design it is not desirable to have too much detail in the FE-model so equivalent models are normally used [6]. For the tail redesign tool, the initiator must be able to initiate the structural parts based on a structural concept selected by the designer. For example, if the designer specifies a blade stiffened composite shell solution for the skin, Fig.9, the initiator must be able to define a first set of feasible values for the design variables describing this structural concept.

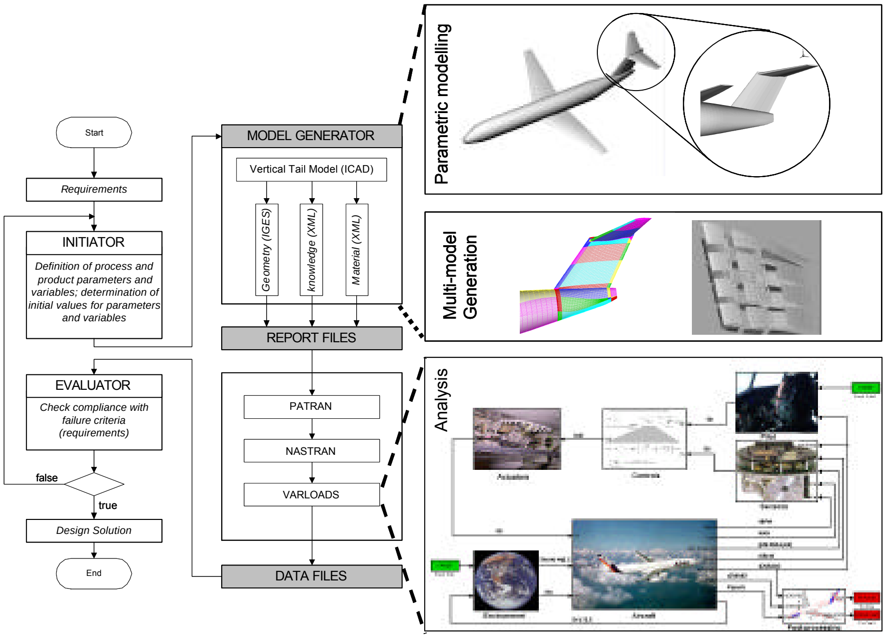
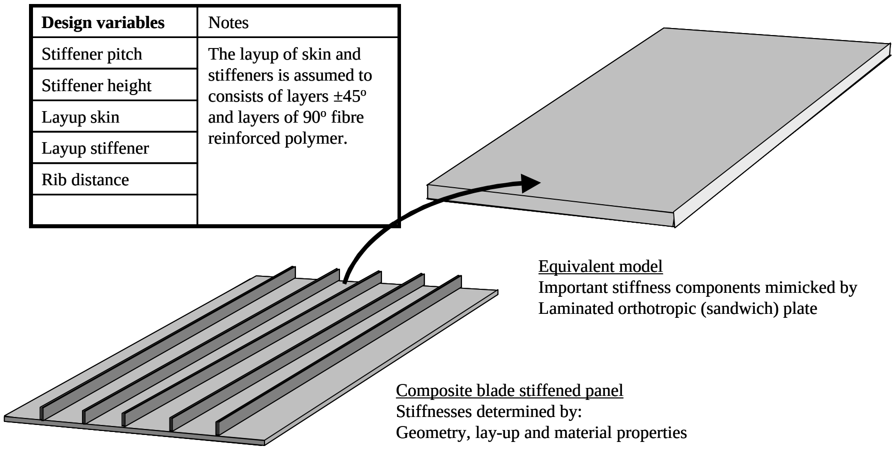


Figure 8 *A DEE for the evaluation of major redesigns of aircraft vertical tails*

The initiator can calculate, e.g., the required skin lay-up, stiffener pitch, stiffener lay-up and dimensions, and rib distance. Based on this result an equivalent model is generated that captures the relevant stiffness properties but does not require detail modelling of the stringer geometries. An example is shown in Fig.9. The initiator calculates the dimensions of a blade stiffened composite panels needed to support certain load intensities. A SQP optimisation routine is used to find the best values of the design variables for minimum weight. The nature of the problem is such that many local optima can be suspected. Therefore a set of starting vectors for the design variables is determined using a Design Of Experiments approach. From the different design options resulting from this approach a selection is made based on a trade-off criterion (minimal number of parts or thickest skin). Similar initiators can be built to do a first best guess using optimisation routines applied to variables like sweep angle, span, chord etc.

For the structural models the results are transformed into an equivalent model. For the tail-DEE the blade stiffened panel is part of a wing box and its relevant stiffnesses are its in-plane extensional and shear stiffness. An equivalent composite plate is used to match the relevant behaviour. Other options are given in [6].



Design variables	Notes
Stiffener pitch	The layup of skin and stiffeners is assumed to consists of layers ±45º and layers of 90º fibre reinforced polymer.
Stiffener height	
Layup skin	
Layup stiffener	
Rib distance	

Equivalent model
Important stiffness components mimicked by
Laminated orthotropic (sandwich) plate

Composite blade stiffened panel
Stiffnesses determined by:
Geometry, lay-up and material properties

Figure 9 *Equivalent modelling of airframe elements*

A second initiator example is illustrated with Fig.10. The interior of a passenger aircraft is initiated based on rules applied to a set of top-level requirements on payload. A layout is determined and a geometric model, including seats, containers, galleys, overhead bins etc. is generated automatically.

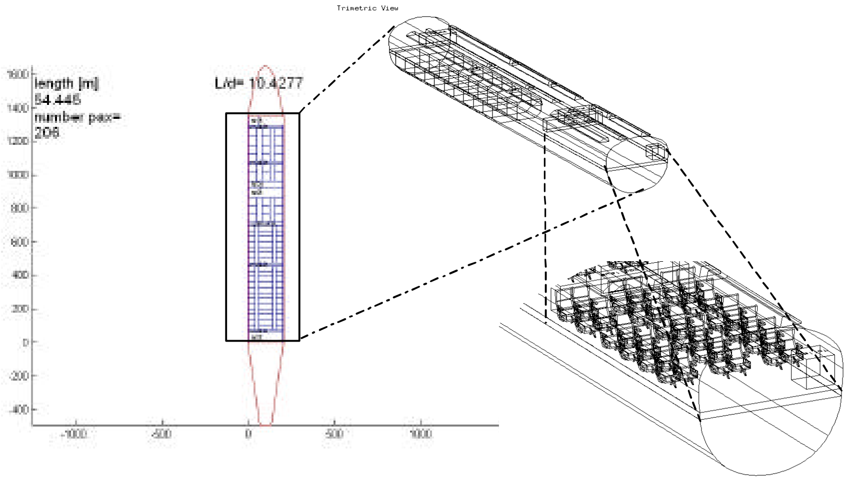


Figure 10 *Rule based initiation of a passenger cabin*

Improved multiple view modelling

Seamless connection of the parametric models to the analysis tools is very important to obtain a real multiple-view on the product. Many of the current practices in finite element and computational fluid dynamic modelling are restrictive for this coupling. However, meshless methods for structural analysis and Cartesian grids for CFD are promising developments that will improve the robustness of future DEEs. The advantage of meshless methods is the easiness of solution refinement by addition of points in the elements of interest. Main disadvantage is the definition of boundary conditions. The Cartesian CFD grids could assure a sound creation of grids controlled by the HLPs.

Some initial results with obtained for a Blended Wing Body aircraft are given in Fig.11. Parametric cost modelling and manufacturability simulation can be coupled to the HLPs as well to extent the multiple-view on the product.

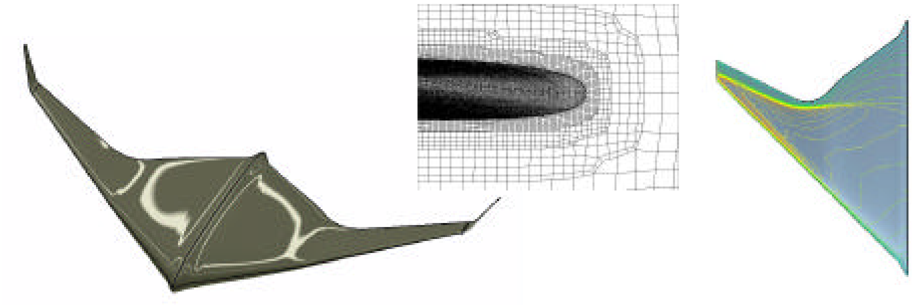


Figure 11 *CFD analysis of a BWB-Aircraft using parametric modelling and Cartesian grid. In the middle part of the grid around a profile is shown; on the right the mach contours on the body are plotted.*

Generalized data exchange

The elements within a DEE exchange considerable amounts of data, information and even knowledge. To assure transparency of the complex process flows it is necessary to use a formalized information and knowledge structure. In this case XML was used to standardize input, output and control files. An example of the XML definition for a process within the DEE, and an example for the definition of a structural element are shown in Fig.12. This formal structure allows easy extension of the functionality of the framework and also traceability of process runs.

```
<entitygroup class='GEOMETRY'>
   <entity isoparametric='FALSE' type='SURFACE' id='8000000'>
     <membership>FUSELAGE</membership>
     <type>QUAD-SEGMENT</type>
     <designVariableGroup>1030104</designVariableGroup>
     <material>AL_ZI_PLATE</material>
     <thickness>6.0</thickness>
     <disturbedByDoorCutout>FALSE</disturbedByDoorCutout>
     <attachedNonstructuralMassItem>NONE</attachedNonstructuralMassItem>
     <vertices>
       <vertex>20229.6 -1846.0 -3408.9</vertex>
       <vertex>20229.6 0.0 -3550.6</vertex>
       <vertex>4352.2 0.0 -2676.5</vertex>
       <vertex>6633.8 -1846.0 -2544.1</vertex>
     </vertices>
   </entity>
```

```
<?xml version="1.1"?>
<DEE product="Marcos-2">
  <module name="ICAD">
     <input>
        <file>/space/ICADdisk/DEE-caraero/ICAD-MMG/
              input/marcos-2d-color.igs</file>
        <geometry unit="mm">
          <height>315</height>
        </geometry>
     </input>
     <output>
        <file type="igs-file" root="/space/ICADdisk/
              DEE-caraero/ICAD-MMG/output/">
           <igs>"/Marcos-2-2d-ibb.igs"</igs>
          ................
          ................
           <igs>"/Marcos-2-2d-outer.igs"</igs>
        </file>
     </output>
  </module>
```

Figure 12 *Two examples of information exchange between processes in the DEE with XML. On the left the format for structural element exchange, on the right the XML format for a process to be handled in the Python Framework*

Innovative designs

So far the DEE principle has been applied to design problems limited in complexity, although the load analysis tool is an important first step to complex design problems. The real challenge will be to use the DEE to support the selection of an aircraft configuration for a specific mission profile. Only then it will become clear if innovative concepts like the one shown in Fig.13, will be valid replacements for the current dominant designs.

Figure 13 *A box-wing aircraft configuration*

Conclusions

The use of Knowledge Engineering tools allows the definition of true parametric models in the optimisation sense. Implementation of these models in a framework, the Design and Engineering Engine, could make selection of the optimal aircraft configuration possible. Optimisation plays a major role in the DEE both at the initiator stage, where initial parameter and variable values have to be assigned, and at the top-level optimisation supporting selection of the optimal configuration. Elements like formal communication with and within the DEE, new analysis elements like meshless methods for structural analysis and Cartesian meshing for aerodynamic analysis will make the DEE a viable process concept.

Acknowledgement

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