KNOWLEDGE BASED ENGINEERING TO SUPPORT AIRCRAFT MULTIDISCIPLINARY DESIGN AND OPTIMISATION

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Abstract

This paper discusses structure and functionalities of a Knowledge Based Engineering application, called Multi Model Generator (MMG), developed to support aircraft multidisciplinary design, analysis and optimisation. Designers can use the MMG as an advanced modeling tool to swiftly generate geometrical models of many and diverse aircraft configurations and variants, by combining and adjusting a limited number of parametric objects, called High Level Primitives. Besides capturing the geometric aspects of design, the MMG has also the capabilities to automate large part of the lengthy and non-creative preprocessing activities involved in the design verification process. The proposed KBE application has demonstrated to be a valuable solution for some of the critical needs indicated by the MDO community, namely: a flexible and robust generative tool to increase the level of automation in aircraft design, including the development of novel configurations; the exploitation of high fidelity analysis tools already in the early design phases; the management of the design activities across distributed networks of disciplines specialists.

1 Introduction

Despite the great advances in computer technology and the continuously increasing capabilities of computer aided engineering tools, innovation in aircraft design is actually restrained by the lack of fully adequate design methodologies [1]. Improved design approaches and supporting design technologies are required to keep enhancing the design of current aircraft configurations, as well as to investigate novel air vehicle concepts, such as blended wing bodies and joint wing configurations [2,3]. The ACARE Strategic Research Agenda [4] envisions a future scenario, where next 20 years aircraft will differ from those of today, as much as the latter differ from those of the 30ies. How this can happen in the rather conservative civil aviation sector, is very difficult to imagine. First, new design technologies will have to be developed aiming at *lowering the risk* associated with the development of new and unconventional configuration. Indeed, before committing to any radical innovation, there is the need to generate adequate knowledge of new concepts by means of detailed multidisciplinary analysis and simulations.

In this sense, the Multidisciplinary Design and Optimisation (MDO) approach seems to be the most promising so far. However, after 15-20 years of tools and methodologies development for an effective, efficient and systematic exploration of the design space [5,6], large scale exploitation of MDO *at industry level* is not yet a reality. Many are still the barriers, not only of technical nature, that are constraining MDO application to limited cases [7-9]. The concepts of *lean engineering*, originated in the area of production and manufacturing, need to be adopted also in the design process, where there is still a large unbalance (in the order of 20:80%) between the time dedicated to creative work and that consumed by the lengthy and repetitive activities associated to data and models processing. In order to exploit such a discipline as MDO, which by definition requires many iterations of (re)design and analysis processes, improving the *level of automation* is a fundamental goal.

According to the authors, knowledge based engineering (KBE) technology has the potential to address exactly the abovementioned criticalities. As more extensively elaborated in [10-14], KBE can be defined as a technology that allows capturing and reusing *product* and *process* multidisciplinary knowledge in an integrated way, in order to reduce time and costs for engineering applications, through the automation of the repetitive design activities. Actually, within large aircraft companies, like Boeing, Lockheed Martin and Airbus, KBE is already a mainstream technology since years. However, so far, its application has taken place mostly in the *detail design phase* of structural components and subsystems, as illustrated in Fig. 1 from [15]. On the other hand, this paper discusses a possible use of KBE in the *conceptual and preliminary phases* of the aircraft design process, where the configuration of the vehicle is not yet frozen and can still be influenced by all the disciplines.

This paper is structured as follows: section 2 provides a critical analysis of designers' needs including those specifically indicated by the community of MDO specialists. Section 3, which is the core of the paper, is dedicated to the description of the Multi Model Generator (MMG), a KBE application developed at Delft University of Technology, to support multidisciplinary design and optimisation of aircraft. The working principle of the MMG, its modular structure, capabilities and functionalities are discussed in this section. Section 4 presents an example application and some conclusions are drawn in Section 5.

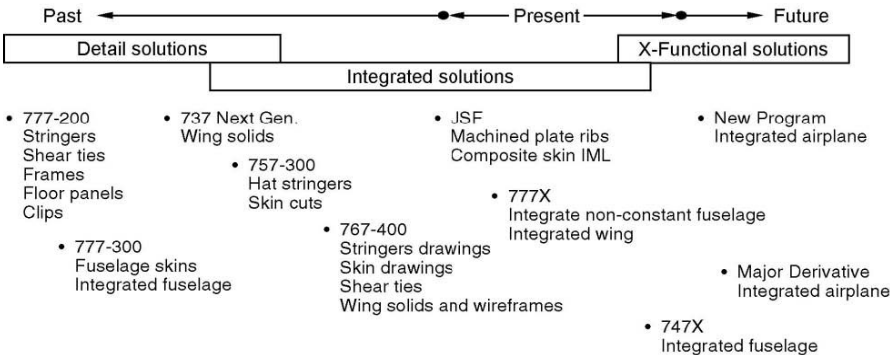


Fig. 1. KBE evolution/implementation history at Boeing

2 Modeling Challenges in Engineering Design

During the conceptual and preliminary design phases of aircraft (or any other hardware of similar complexity), designers need tools (1) to facilitate the instantiation of their ideas and creative insight and (2) to analyze and evaluate the quality and performance of such ideas. Concerning the first need, CAD systems are by far the most widespread tools at date. However, despite their indisputable impact on the overall design process, they are not capable by their nature to support a true conceptual design approach. Designers think in terms of *functions* rather than *low level geometric primitives* like points, curves and solids, as typically offered by a general purpose CAD system. When designing an aircraft, designers are actively busy considering and rearranging possible solutions to fulfill a number of functionalities, such as storing payload, generating lift, provide control, etc. For this purpose some kind of *high level design objects* (rather than the CAD primitives) would be preferable to accelerate the transition of a given aircraft concept from the designer's head to a (geometrical) model that can be communicated.

Eventually, it is the design verification phase (the second point above) that requires the most support. Performing a multidisciplinary analysis of an aircraft concept requires setting up dedicated models for many analysis tools, whose level of fidelity, typically, changes as the level of design maturity advances. Ideally, the abovementioned *higher level design objects* should also be able "to know" how to transform themselves in order to facilitate a multidisciplinary analysis. Again, CAD primitives cannot help here because of their inadequate knowledge recording and learning capabilities. As result, the models preprocessing burden is left to the patience and dedication of designers and analysts. Indeed, the multidisciplinary modeling capability is one of the most critical aspects of MDO:

- The generation of dedicated models is required both for *low and high fidelity* analysis tools. The latter in particular are the most critical and difficult to automate, whereas their use is essential to assess the design of new unconventional aircraft concept.
- Models are required both for commercial of the shelf and in house developed analysis tools. Typically, the latter excel in terms of computation performance, but lack in term of preprocessing and interfacing capability.
- Models must be tailored to the different views of the discipline specialists (and their tools). However, they have to be synchronized, consistent and coherent.
- To support the iterative nature of the MDO design, models should be generated on the fly, *hands off* and be accessible in remote both to human operators and/or software optimizing tools. This is an operational prerequisite to any *distributed* MDO framework.

The challenges discussed so far have actually provided the *use case* for the development of the Multi Model Generator, an advanced modeling system developed at TU Delft to support aircraft multidisciplinary design and optimisation.

3 The Aircraft Multi Model Generator: Working Principles, Internal Structure and Functionality

The *higher level design objects* envisioned in section 2 and their *capability* to transform themselves in suitable models to feed multidisciplinary analysis, represent actually the fundamental concepts at the base of the Multi Model Generator (MMG). In fact, the MMG provides designers with a suite of parametric functional objects, the so called *High Level Primitives* (HLPs), which can be adjusted and assembled to build up an extremely large number of aircraft configurations, including novel air vehicle concepts, and an infinite amount of variants. See the concept illustrated in Fig. 2 (more in 3.1 and 3.2). Furthermore, a number of so called *Capabilities Modules* (CMs) has been defined, where the engineering knowledge to process the HLPs geometry into suitable models/formats for various analysis tools has been captured for systematic reuse (more in 3.3).

The MMG has been developed using a commercial Knowledge Based Engineering system. Considering the “high concentration” of ingredients such as geometry manipulation, generative modeling, capture and reuse of engineering knowledge, KBE just appeared to be the most suitable technology at hand [10-14].

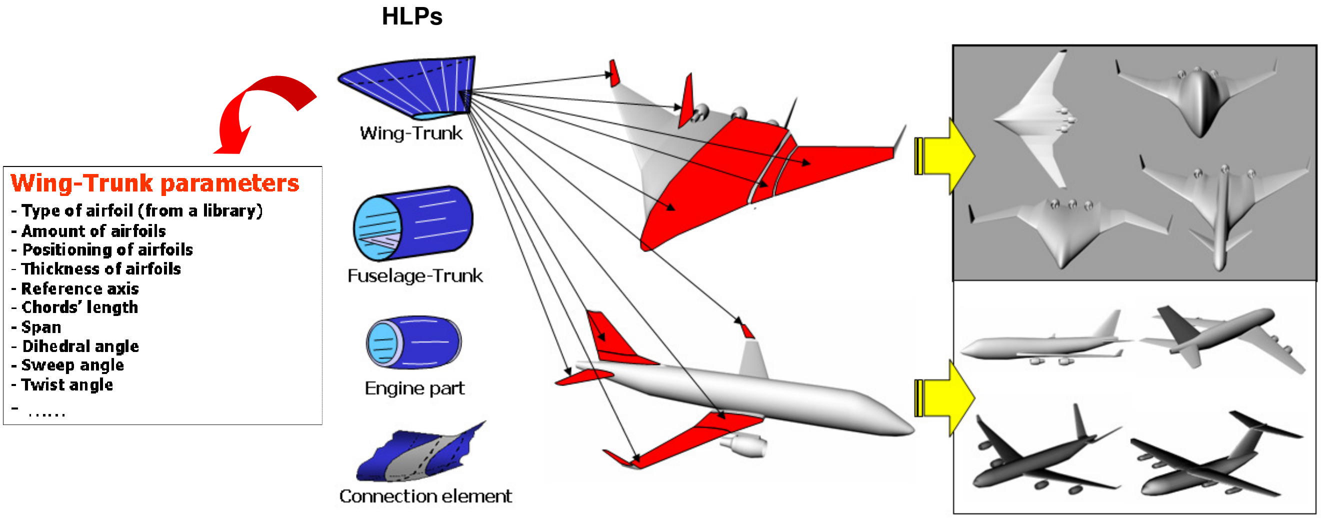


Fig. 2. The High Level Primitives build up approach

3.1 The High Level Primitives Modeling Approach: Capturing Product Similarities

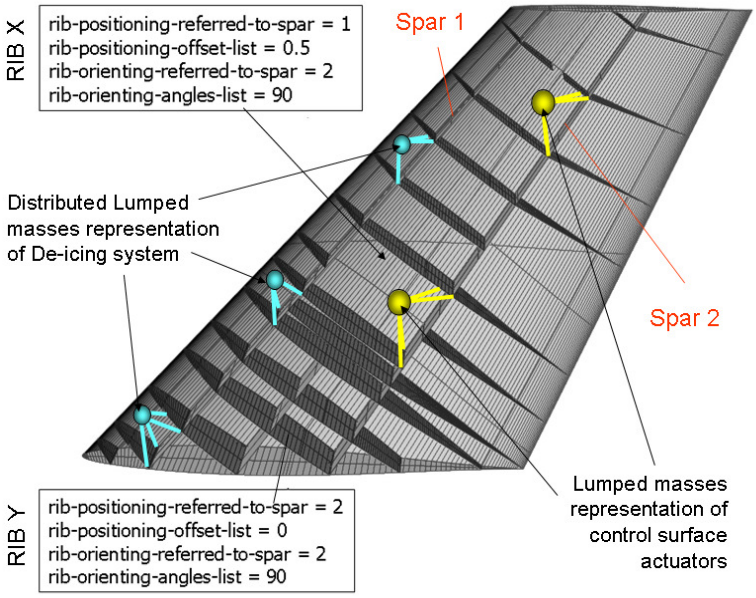
Though a traditional airliner and a blended wing body aircraft appear to have a very different configuration, they both feature similar components, which embody given functionalities like generating lift, supplying thrust and accommodating payload. Though these components have a different shape and are combined in different topological configurations, it is still possible to spot the recurrent presence of wing-like elements, fuselage sections, engines and connection parts as shown if Fig. 2. For each of these four entities, a so-called High Level Primitive has been implemented in the KBE system. Using the supplied lisp-based *objected oriented* language, each HLP has been defined as a *class* (see more in section 3.3). When a set of parameters values is provided to the given class, a unique instantiation is dynamically generated. Eventually, the HLPs can be considered as a kind of rubber LEGO® blocks, which can be individually morphed due to their parametric definition and assembled to build-up a potentially infinite range of different aircraft configurations and variants. Indeed, the parameters used to define the various HLPs represent the actual *degrees of freedom* of the HLP and determine the *typicality-range* of the specific instantiations that can be generated [16].

3.1.1 Definition of the Aircraft Outer Shape

The surfaces of the various aircraft shown in Fig. 2 have been generated using a different number of HLPs' instantiations and assigning different values to the parameters that specify their external shape. In case of the Wing-Trunk primitive, for example, some of the shape parameters are span and chords' length, sweep and twist angles, number, location and type of airfoils. In order to model a wing-like system with the MMG, the designer must specify the number and shape of the required Wing Trunk instantiations, whereas the number and the shape of the various connection elements are *automatically* determined by the MMG, in order to guarantee a smooth and water-tight wing surface. The connection-element HLP "knows" if its presence is required (e.g., in case adjacent wing-trunks are defined with different dihedral angles) and, in case, the required shape (which is based on the geometry of the adjacent wing trunks to be blended).

3.1.2 Definition of Aircraft Structure and Systems

The definition of the HLPs is not just limited to the parametric description of the aerodynamic surfaces, but includes also the internal structure. Number, position and orientation of main structural elements like spars, rib, riblets, frames, stringers and floors are defined parametrically. Therefore, it is possible to control and modify the complete structural configuration topology, just by providing the MMG with different parameter values. See in Fig. 3 the examples of a possible wing-trunk structure configuration and the parametric definition of two ribs. Rib X is positioned on a plane that intersects Spar 1 at 50% of the spar length and is oriented at 90 degrees with respect



RIB X
rib-positioning-referred-to-spar = 1
rib-positioning-offset-list = 0.5
rib-orienting-referred-to-spar = 2
rib-orienting-angles-list = 90

RIB Y
rib-positioning-referred-to-spar = 2
rib-positioning-offset-list = 0
rib-orienting-referred-to-spar = 2
rib-orienting-angles-list = 90

Fig. 3. Parametric definition of structural elements in the wing-trunk HLP and lumped mass representation of some systems

to the direction of Spar 2. Rib Y is positioned on a plane that passes through the root of Spar 2 (0% of Spar 2 length) and is oriented at 90 degrees with respect to the same Spar 2.

A remarkable feature of the MMG is the *associative definition* of the internal structure with respect to the HLPs outer surface. I.e., when the aerodynamic shape of the aircraft changes (e.g., because of the implementation of different airfoils or fuselage cross sections) the shape (and, in case, the topology) of the airframe *automatically* changes and adapt to the new mould line.

Apart form the outer shape and internal structure, the HLPs offer also the possibility to model the main aircraft systems (e.g., landing gears, APU, engines and actuators), as needed both for structural analysis and for the weight and balance discipline. All these systems are modeled as simple sets of lumped masses, which is just adequate to the needs of conceptual/preliminary studies. In addiction, the HLPs take care of the *connectivity* of the various aircraft systems by automating the generation of attachment links between the lumped masses and selected airframe components. See in Fig. 3 modeling examples of the de-icing and actuators system inside a wing-trunk. When the topology of the airframe changes (because of changes in the number and/or location of spars, ribs and floor beams, for example), *both position and connectivity* of the aircraft systems *automatically* adapt, because defined by means of parametric and logic rules, stored in the HLPs.

Finally, Fig. 4 shows the UML class diagram of a Blended Wing Body aircraft, generated using the HLPs build up approach. See how the aircraft center body, the wing, the fins and winglets are all instantiations of the same wing-trunk primitive, where the user can define a different shape and structure layout.

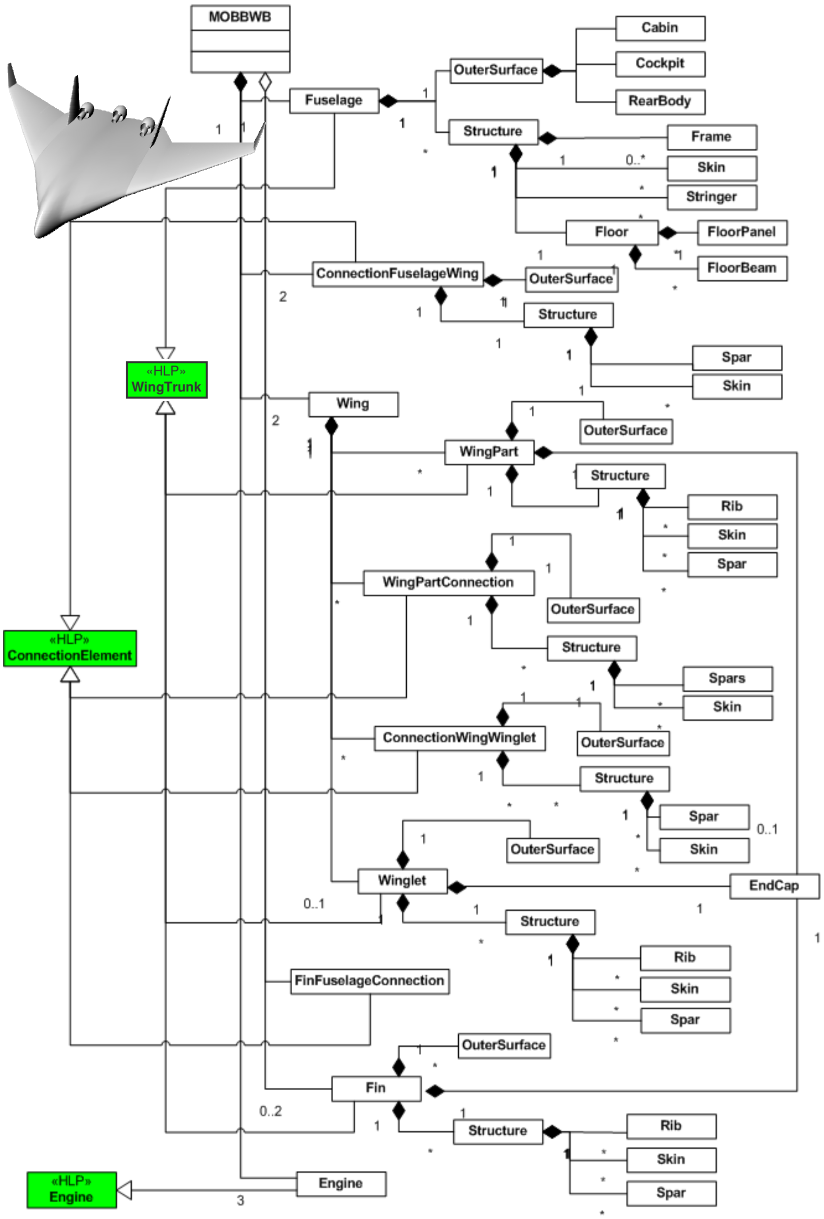


Fig. 4. UML class diagram of the hierarchical structure of a Blended Wing Body Aircraft, generated with the HLPs build up approach

3.2 Capability Modules to Capture Process Similarities

Quite independently from the aircraft concept under consideration, very similar analysis methods and tools are used eventually. As matter of fact, preparing for analysis takes a very large part of the overall engineering design effort. Indeed, the set up of dedicated disciplinary models for diverse analysis tools, particularly when high fidelity tools are involved, requires going through long sequences of tedious and repetitive activities, which inevitably slow down the design process.

However, the good news is that a large part of these activities is very well suitable to be formalized into sets of generic rules and algorithms, which can be captured into KBE applications. After some knowledge acquisition sessions with discipline experts to elicit their working practice, tips and tricks [14], a number of so called *Capability Modules* (CMs) has been programmed using the supplied KBE language. The CMs are classes with the peculiarity to encapsulate just *procedural knowledge*, i.e., they cannot be instantiated into geometric objects like the HLPs do, however, they have the capability to operate on the geometric data generated by the HLPs. Eventually, the CMs are able to automatically process the geometry of the various HLPs instantiations and support the preparation of the specific models required by the discipline tools. Examples of capability modules are *SurfaceSplitter* and *PointsGenerator*, which are used, respectively, to transform the geometry of the HLPs in sets of meshable surfaces for FE analysis (see details in [17]) and set of points/panels to support the generation of aerodynamic models [18,19]. Fig. 5 gives an impression of the CMs functionalities to translate a given aircraft model into a set of *different-but-consistent* representations for various analysis tools [20,13,21,22]. These discipline specific representations can vary from sets of standard data exchange files, like IGES and STEP, to custom generated XML files, ASCII tables, etc. In principle, the KBE programming approach allows the user to define whatever output form. Eventually, this is the powerful feature that allows the MMG communicating with a very broad range of external tools, both in-house developed and commercial of-the-shelf.

3.3 High Level Primitives and Capability Modules: Modular Definition and KBE architecture of the MMG

The software architecture of the system of High Level Primitives and Capability Modules is illustrated by the UML class diagram of Fig. 6 (for simplification, only the WingTrunk and ConnectionElement HLPs are shown). The diagram shows that the HLPs are not monolithic entities, but *aggregations of classes*. *WingTrunk*, for example, is built up from two other classes, one responsible for the definition of the external aerodynamic surface (discussed in 3.1.1) and another for the internal structure (discussed in 3.1.2). *WingTrunkSurface* has *AirfoilGenerator* as class component, which is responsible for the generation of the airfoils used by *WingTrunkSurface* to build the actual aerodynamic surface of wing like components. Also *WingTrunkStructure* is a composition of other classes, i.e., the *Spar*, *Rib* and *Skin*, which are responsible for the generation of the various structural components. The associative relation mentioned in 3.1.2, between the *WingTrunkSurface* and *WingTrunkStructure* classes is shown in Fig. 6, as well. The diagram shows also the links between some CMs and (the components of) the HLPs. The *SurfaceSplitter* CM, responsible of transforming the geometry of an aircraft into sets of meshable surfaces for FE analysis [17], is “linked” to the *Skin*, *Rib* and *Spar* classes. The *PointsGenerator* CM, responsible to transform the outer surface of an aircraft into *clouds of points* to support aerodynamic analysis [13,19], is “linked” to *WingTrunkSurface* and *ConnectionSurface*.

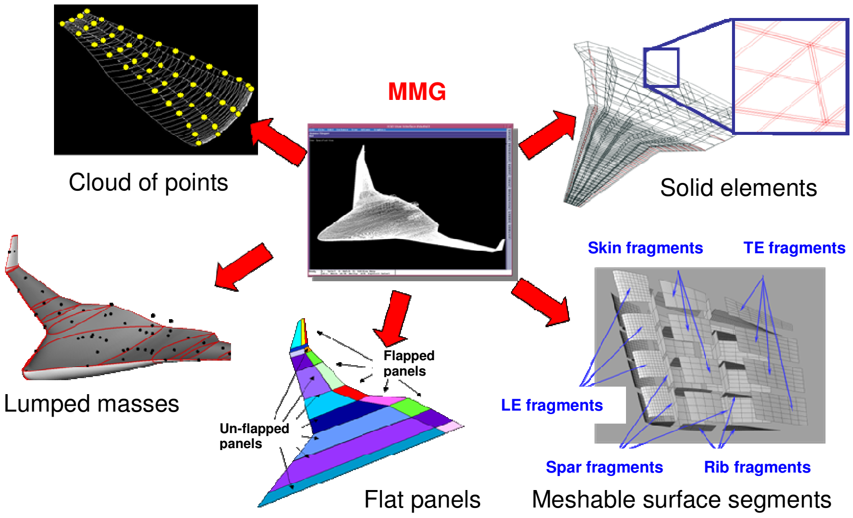


Fig. 5. Generation of dedicated models for various discipline analysis tools

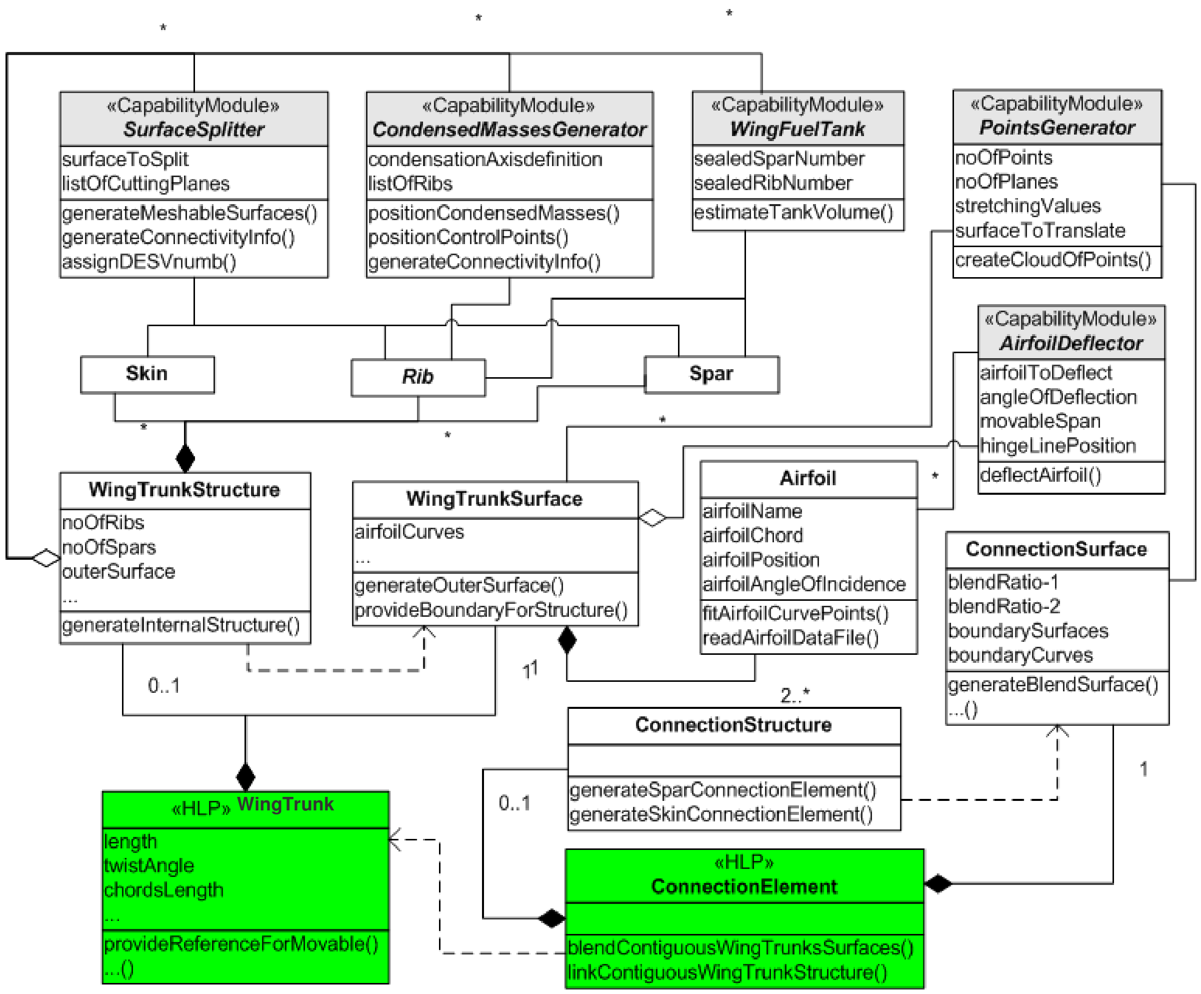
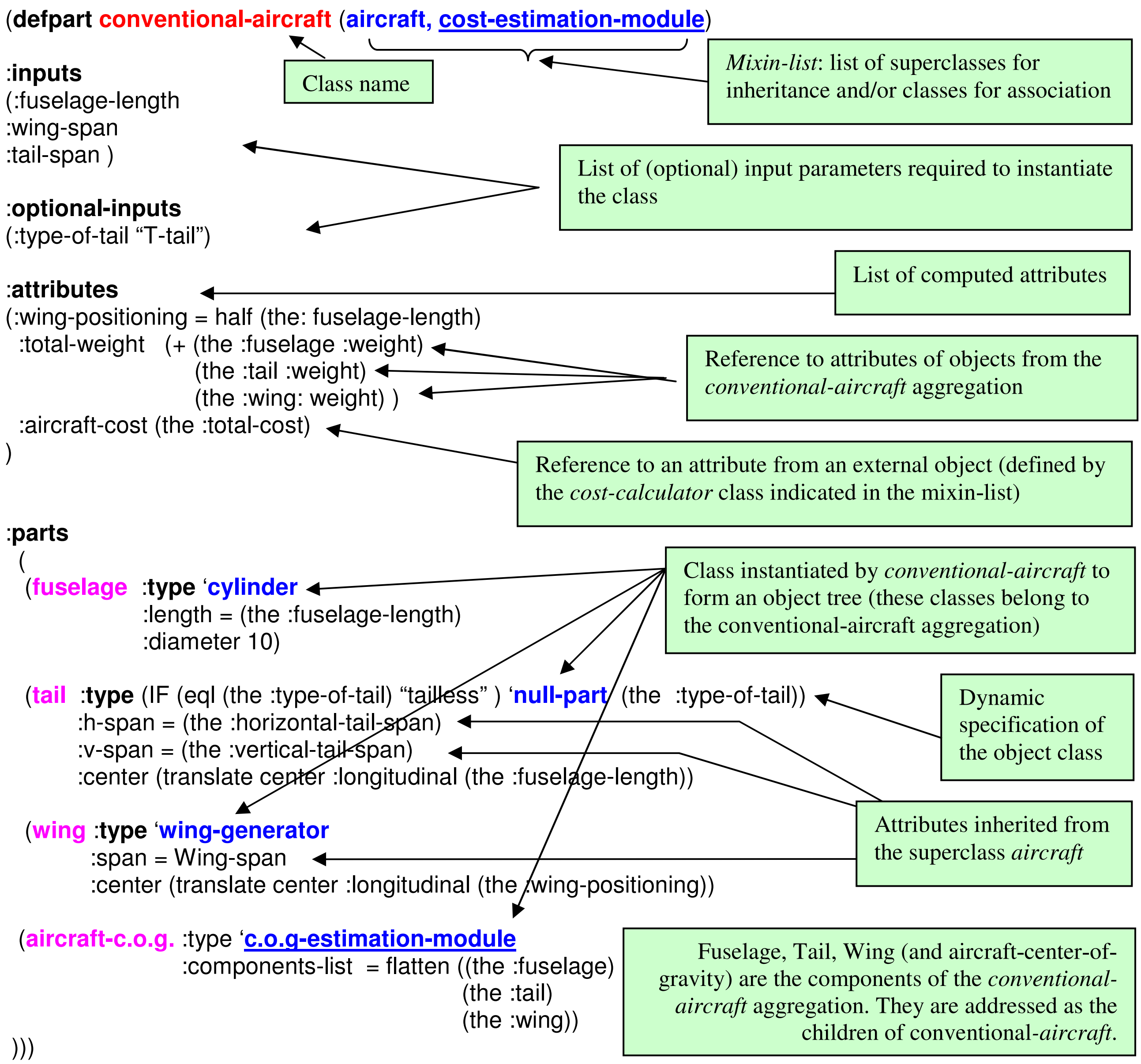


Fig. 6. UML class-diagram illustrating the modular definition of the wing-trunk and connection element HLPs, and the links with some capability modules.

Both the modular architecture of the HLPs and the definition of the CMs as "engineering service providers" for the HLPs represent essential factors for the flexibility, maintainability and scalability of the MMG system. E.g., new structure generation modules can be added to work with the existing outer surface generation modules, and vice versa. Specific HLPs features can be modified and improved, without the typical problems associated with debugging one large monolithic code. Eventually, new CMs can be added to support different analysis tools.

To give a better insight of the basic architecture of a KBE application like the MMG and show the way different classes and aggregation of classes (like HLPs and CMs) can be defined and interact, a sample from a fictitious KBE code is illustrated in Fig. 7. The hypothetical class *Conventional-aircraft* is defined by means of the macro *defpart*, provided by the KBE system at hand [10,12]. Next to the class name, there is the so called *mixin* list, i.e. a list of other classes (*aircraft* and *Cost-estimation-module* in our example) from which *Conventional-aircraft inherits* [23]. It means that all the *attributes* and *methods* of these two classes become ready available to *Conventional-Aircraft*. In this example, *Cost-estimation-module* represents a hypothetical CM, containing generic cost calculation procedures. By including it in the *Conventional-aircraft* mixin list, any *Conventional-aircraft* instantiation will inherit the capability of computing its costs, using the *Cost-estimation-module* CM procedures.

Fig. 7 shows (read below the keyword *parts*) also that *Conventional-aircraft* is actually an aggregation of three classes. I.e., any instantiation of *Conventional-aircraft* will be



```
(defpart conventional-aircraft (aircraft, cost-estimation-module)

:inputs
(:fuselage-length
:wing-span
:tail-span )

:optional-inputs
(:type-of-tail “T-tail”)

:attributes
(:wing-positioning = half (the: fuselage-length)
  :total-weight   (+ (the :fuselage :weight)
                     (the :tail :weight)
                     (the :wing: weight) )
  :aircraft-cost (the :total-cost)
)

:parts
  (
  (fuselage  :type ‘cylinder
             :length = (the :fuselage-length)
             :diameter 10)

  (tail  :type (IF (eql (the :type-of-tail) “tailless” ) ‘null-part (the  :type-of-tail))
        :h-span = (the :horizontal-tail-span)
        :v-span = (the :vertical-tail-span)
        :center (translate center :longitudinal (the :fuselage-length))

  (wing :type ‘wing-generator
          :span = Wing-span
          :center (translate center :longitudinal (the :wing-positioning))

  (aircraft-c.o.g. :type ‘c.o.g-estimation-module
                   :components-list  = flatten ((the :fuselage)
                                                (the :tail)
                                                (the :wing))
)))
```

Class name

Mixin-list: list of superclasses for inheritance and/or classes for association

List of (optional) input parameters required to instantiate the class

List of computed attributes

Reference to attributes of objects from the *conventional-aircraft* aggregation

Reference to an attribute from an external object (defined by the *cost-calculator* class indicated in the mixin-list)

Class instantiated by *conventional-aircraft* to form an object tree (these classes belong to the conventional-aircraft aggregation)

Dynamic specification of the object class

Attributes inherited from the superclass *aircraft*

Fuselage, Tail, Wing (and aircraft-center-of-gravity) are the components of the *conventional-aircraft* aggregation. They are addressed as the children of conventional-*aircraft*.

Fig. 7. Example of a fictive aircraft modeling KBE application

composed of the three objects *fuselage*, *tail* and *wing*, which, in turn, are instantiations of the classes *cylinder*, *wing-generator* and *T-tail*, respectively (actually, in this example, the type of tail object is evaluated *dynamically*, based on the evaluation of an IF-THEN rule). Though not shown in the example, clearly, this KBE application must contain the definitions of the defparts *wing-generator*, *t-tail* and *cylinder*, as well. We can also imagine that the defpart *wing-generator* will have as parts a number of instantiations of our *Wing-trunk* and *Connection-element* HLPs! Also, note the last part in the example, called *aircraft-c.o.g*. This is the instantiation of the class *c.o.g.-estimation-module*, which is another hypothetical CM, where the knowledge required for computing the center of gravity (c.o.g.) of a generic body system is stored. As result, any instantiation of *Conventional-aircraft* will be able to use that knowledge to compute its own c.o.g.

3.4 Functionality and operation of the Multi Model Generator.

The way the MMG works is that typical of KBE applications [11,13]: the core of the *product model* in our case consists of the HLPs and CMs definition, plus a light layer of code to organize them in a proper structure. All the main parameter values (those used to define the various HLPs instantiations) are exposed in a large input file, the so called MMG input file, which the designer can edit to generate the aircraft concept he/she has in mind.

The user can operate the MMG in interactive mode: he/she can modify the parameters values and inspect the automatically generated aircraft model via the GUI interface of the KBE system. Then, he/she can trigger the generation of the specific discipline models that are required to support the multidisciplinary analysis at hand. In the moment that a specific discipline model is requested (and only in that moment), the MMG generates first an aircraft instance (according to the parameter values indicated in the MMG input file) and then extracts and process all the data from this instance that are required to generate the requested discipline model. The needed type and amount of HLPs and CMs are utomatically and transparently to the user, are instantiated to produce the required output. In KBE parlance, all this is called *generative modeling*.

Anytime the designer provides a different set of aircraft parameters values, the MMG (re)applies systematically all the design procedures recorded in its product model (i.e., (re)use the captured product and process knowledge) and propagates automatically the configuration changes to all the output models for the various analysis tools. If the designer changes the length of the wing in the MMG input file, for example, such modification is automatically reflected in the generation of the outer surface model for aerodynamic analysis, as well as in the models for structural analysis and in the mould models used for toolings design [24].

The MMG can also be used in *batch mode*, which means the whole generative process can be performed without starting the MMG GUI, but just launching the KBE application from the command line. In this case, the designer will have specified via the MMG input file, also the list of discipline models required as output.

The batch mode is possibly the most interesting way of operating the MMG: even non-geographically collocated users, not only human operators but also other software tools like an optimizer, can submit their edited version of the input file and launch the MMG. In this way the MMG becomes a real enabler for a *distributed* multidisciplinary design and optimisation approach.

4. The Role of the MMG in Distributed MDO Processes: an Application Example

A successful validation case of the Multi Model Generator concept is provided by the European project MOB on multidisciplinary design and optimisation of blended wing body aircraft configurations [25]. Enabled by the MMG, the MOB consortium was able to address the design of an innovative complex aircraft configuration, for which no reference data or experience existed. In Fig. 8, the position of the MMG within the MOB computational framework is illustrated. The MMG, starting from a unique definition of a BWB aircraft configuration, extracts a set of different, yet coherent sub-models, which are tailored to the analysis tools

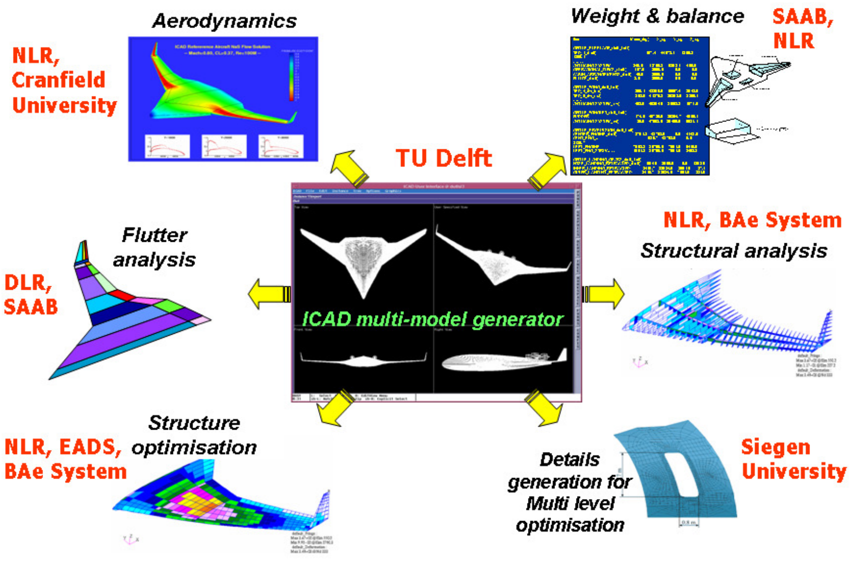


Fig. 8. Role of the MMG within the MOB distributed MDO framework. The MMG provides dedicated models to a large set of distributed analysis tools, both low and high fidelity, in-house developed and commercial of the shelf

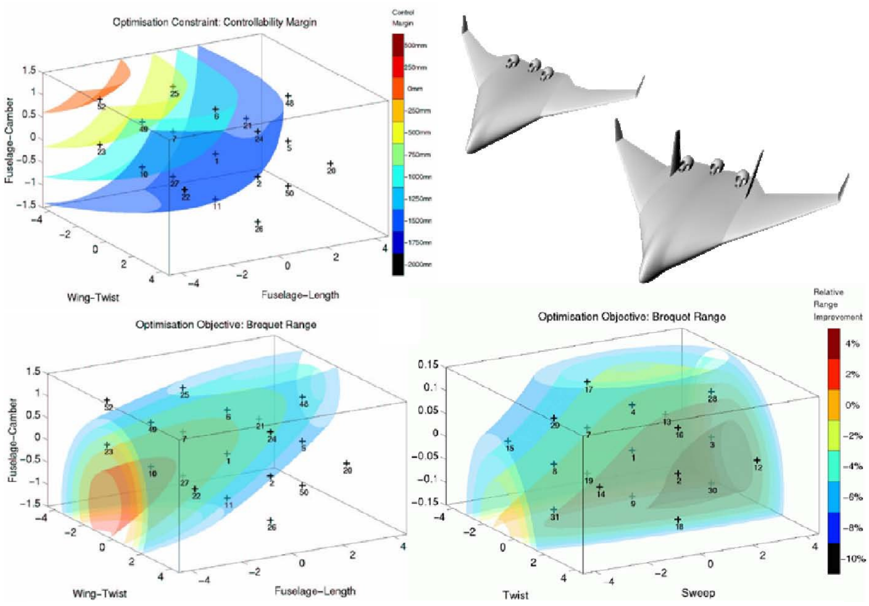


Fig. 9. Results of the analysis and optimisation process of the MOB BWB, visualized by means of response surfaces

provided by a broad group of partners, both from industry and academia. Among others, low and high fidelity models for aerodynamic analysis, 2-D planform models for aeroelastic analysis, structural models for FEM analysis and optimisation, fuel tanks and systems masses distribution for weigh and balance assessment are automatically generated by the MMG. The MMG provides also the capability to focus on a specific detail of the aircraft, a door cutout in this case, and provides the base to apply a multi-level analysis and optimisation strategy. Once the MOB computational framework was in place, more than 50 aircraft variants (including topological variations) have been evaluated just in a couple of days, totally hands off, making use of high fidelity analysis tools (including CFD and FE) running on a number of computers distributed across the multinational consortium. At the end of the design and optimization process, the results have been presented to the design team in form of response surfaces, showing the effect of the various optimisation parameters on the aircraft performance (Fig. 9). Without the use of the abovementioned design framework, such design study would have taken months!

In Ref [26,24,19] other study cases are described, where the MMG has been used, respectively, to support the redesign of a large passengers aircraft vertical tail, the automated structural analysis of aircraft movables and the controllability study of a blended wing body aircraft.

5. Conclusion

In order to meet the challenges of future aviation, new tools and methodologies are required to support the transition of MDO from an interesting research topic to a consolidated design technology at industrial level. The advanced modeling system described in this paper aims at tackling some of the urgent problems that hamper the exploitation of MDO in large distributed design frameworks. The use of Knowledge Based Engineering allows capturing design knowledge and best practices in software application for design automation. In particular, most of the repetitive activities slowing down the design verification process can be automated, giving designers the time to investigate more *what-if*'s and exploit their creativity. The High Level Primitives and Capability Modules approach described in the paper allows the generation of many different aircraft configurations and variants and their swift translation in dedicated models for both high and low fidelity analysis tools, either in house developed or commercial of the shelf. Besides, the MMG capability to be operated in batch offers the possibility to exploit it in real distributed design and optimization environment, as demonstrated at international scale by the MOB project.

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