On Aircraft Conceptual Design

A Framework for Knowledge Based Engineering and Design Optimization

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Abstract

THIS THESIS PRESENTS a design framework where analytical tools are linked together and operated from an efficient system level interface. The application field is aircraft conceptual design. Particular attention has been paid to CAD system integration and design optimization.

Aircraft design is an inherently multidisciplinary process. The goal is to search for the design that, in the best of possible ways, fulfills the requirements. It is therefore desirable to be able to effectively investigate and analyze solutions from a variety of points of view, weighting together the results and gathering a general figure of merit. At the same time, increasing competition on a global market forces to shorten the design process and to reduce costs. Thus a system that allows a tight and efficient integration of different disciplines and improving data flow and storage plays a key role.

Integrating a CAD system to the framework is of central relevance. The geometrical model includes most of the information; specific data, required to carry out particular analysis, can be extracted from it. This is possible adopting parametric associative models that are controlled from a spreadsheet user interface. Strategies for building CAD models with a very high degree of flexibility are presented. Not only the external shape can be changed, but also the internal structure can be completely modified. Structural elements can be added or removed, and their position and shaping changed.

In this work the design of an Unmanned Aerial Vehicle is used as test case for comparing three different optimization algorithms. The presented framework is also used for automatically design Micro Aerial Vehicles, starting from a short list of requirements and ending with a physical prototype produced by a rapid prototyping machine.

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Linköping, April 2008

Kristian Amadori

Nomenclature

Notations

Symbol	Description
α	angle of attack
B	semi wing span
c_{d0}	parasite drag coefficient
C_{di}	induced drag coefficient
c_f	skin friction coefficient
C_L	lift coefficient
$c_{L,\alpha}$	lift coefficient as function of the angle of attack
$c_{L,\alpha=0}$	lift coefficient at zero angle of attack
C_m	moment coefficient
$C_{m,\alpha}$	moment coefficient as function of the angle of attack
C_R	root chord length
C_T	tip chord length
d	airfoil tail deflection angle
D	aerodynamic drag force
e	Osvald's Efficiency Factor
E	endurance
L	lift force
R	range
S	wing area
S_{wet}	wetted area
$S.M.$	Static Margin
t	thickness to chord ratio
V	flying speed
W_0	maximum take-off weight
x	generic design parameter vector that describes a concept
Λ_{LE}	leading edge sweep angle
σ_{eff}	effective stress in the internal structure material
$\sigma_{eff,\,all}$	effective stress in the internal structure material maximum allowed

Abbreviations

CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
MAV	Mini/Micro Aerial Vehicle
MDF	CAD datums model
MDS	CAD surfaces model
SOA	Service Oriented Architecture
SOAP	Simple Object Access Protocol
UAV	Unmanned Aerial Vehicle
UDF	User Defined Feature
WSDL	Web Service Description Language

Papers

THIS THESIS IS based on the following three appended papers, which will be referred to by their Roman numerals. The papers are printed in their originally published state except for some changes in format and the correction of some minor errata.

In paper [I] and [II] the first author is the main author, responsible for the work presented, with additional support from other co-authors. In paper [III], the work has been divided between the two authors with additional support from the third.

[I] Amadori, K., Jouannet, C. and Krus, P., "*Use of Panel Code Modeling in a Framework for Aircraft Concept Optimization*", 11th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference, Sep. 2006, Portsmouth, VA, USA

[II] Amadori, K., Jouannet, C. and Krus, P., "*A Framework for Aerodynamic and Structural Optimization in Conceptual Design*", June 2007, 25th AIAA Applied Aerodynamics Conference, Miami, FL, USA

[III] Amadori, K., Lundström, D. and Krus, P., "*Distributed Framework for Micro Aerial Vehicle Design Automation*", Jan. 2008, 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, USA

The following publications are not appended to this thesis, but constitute an important part of the background.

[IV]   Amadori, K., Johansson, B. and Krus, P., "*Using CAD-Tools and Aerodynamic Codes in a Distributed Conceptual Design Framework*", Jan. 2007, 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, USA

[V]   Jouannet, C., Lundström, D., Amadori, K. and Berry, P., "*Design of a Very Light Jet and a Dynamically Scaled Demonstrator*", Jan. 2008, 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, USA

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Introduction

AIRCRAFT ARE VERY complex products. Their design and development is an extremely challenging task that requires balancing together considerations from a variety of different disciplines. Aerodynamics, structures and weight, system choice and installation, production and cost, propulsion system, stability and control are only some of them. Moreover there may be conflicting aspects within one and the same discipline. For instance the requirements set on the wing by an aircraft that is required to fly at subsonic, transonic and supersonic speeds are very much different from each other. At the same time, the aircraft industry has experienced in the last decades an increasing competition that has forced manufacturer to review their processes and strategies in order to shorten the time-to-market for new aircraft [25], [39]. Even more, new challenges are offered by new and tougher environmental requirements that contribute to make the task even more complex. For instance, the Advisory Council for Aeronautics Research in Europe (ACARE) [1], responsible of the definition of a strategic research agenda for all aeronautical research programs in Europe, aims at reaching in year 2020 a reduction of CO_2 by 50%, NOx by 80% and external noise by 50%.

Moreover, as pointed out by Scott [40], during the fifties and sixties, the pace at which new aircraft appeared was very tight. Probably it did not take longer than a couple of years between new airplanes were introduced to active service. On the contrary, nowadays it can take as long as twenty to thirty years, or even more, before a model is retired and substituted. From an engineer perspective this means that if back then a designer was likely to experience and live through a number of different design projects, today he or she may not be involved in more than a single one! This means that even the depth and broadness of experience that designers are likely to gather during their professional career is very different. In such scenario, the availability of a framework where to store the company's know-how and that enlightened a clear design methodology, would be of sure help.

From a tools point of view it can be noted how a large number of them is usually used in a single project. To visually clarify this complexity Nickol [31] proposed a table that describes how for each discipline a different tool is adopted, but also that within the same discipline there might be an influence by the fidelity level required, which is related to the design stage (see Fig. 1-1). Since the table was limited to six fields (aerodynamics, structural analysis and weight estimations, noise, emissions, systems and controls and geometry generation), Price et al. [35] completed the table by including other disciplines, namely cost and manufacturing as disciplines to cope with, which also implies that even more tools are required. It is interesting to note that it appears to be gaps between the tools used at different fidelity levels and that there are no indications of aids of any kind that help to handle the information flowing across the disciplines. Jumping between these varieties of systems implies also an increased work load for the design team, which is required to control and verify the accordance of data from one level to another.

Figure 1-1.   *Table of disciplines versus fidelity according to Nickol [31]*

Therefore it would be of great help to have a framework available, where all the tools needed for the the different disciplines could be easily linked, enabling data to flow across them and towards increasing fidelity levels. There are commercial packages available that are developed for model integration. Among them MODELCENTER by Phoenix Integration [34] and iSIGHT by Engineous Software [8]. Compared with a self-designed integration framework ,they represent an increase in cost due to licences to be purchased, and they limiting the integration to the supported tools. On the other hand, an in-house framework, as the one presented in this thesis, requires time and resources to be developed. Thus it would be easier to proceed seamlessly along the design project, avoiding or greatly limiting to repeat the same tasks when moving from a discipline area or from a fidelity level to another. Off course it is also of highest importance that it should be simple to substitute any software as soon the necessity arose, without jeppardizing the overall functionalities.

1.1 Aim and Limitations

With the present work the author intends to propose a novel strategy for the use of high-end tools already from the initial early design stages and to evaluate to which extent the proposed ideas are feasible in a design task. In most cases the first steps in designing a new aircraft are dominated by the use of very simple low-fidelity empirical or statistical-based models.

The key idea is to try to find a way of anticipate the use of complex *CAD* systems and analytical tools already to the conceptual design phases without the burden of complex and time consuming repeated operations. In other terms, enabling the use of high fidelity systems, connected together in a flexible and user friendly architecture. This thesis presents a solution for allowing designers to maintain a comprehensive perspective of the aircraft during the conceptual phase, in order to avoid the view being dominated by one discipline only (Fig. 1-2).

Aerodynamics group

Propulsion group

Flight control systems group

Manufacturing group

Stealth group

Structure group
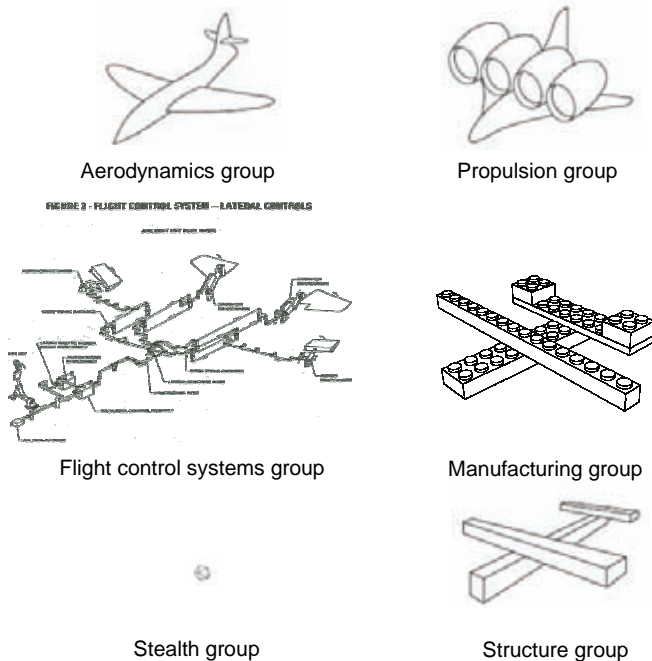
Figure 1-2. *Designers have different views of the same aircraft depending on their area of responsibility (adapted from Jouannet [19])*

The presented work has to be seen as an effort to continue the research carried out at Linköpings universitet, aimed at developing modern and efficient system design tools [16]. The Modulith distributed framework which originates from this research has been adopted as a base upon which to continue building, and into which to plug in the wanted software.

Please note that, since the whole concept is still under development, the tools and systems presented shall not be thought to be ready for a broad industrial deployment or to be offered as a mature and finished product for commercial use.

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Aircraft Design
Fundamentals

Acording to a largely accepted process description [6], [15], [37], [42], aircraft design is usually described as sequence of three different phases:

- Conceptual Design
- Preliminary Design
- Detail Design

This is the same sequence that is generally adopted design theory [33], [44]. In this chapter a very brief description of the phases will be provided as a theoretical background, together with an overview of the traditional methods and tools that most often are adopted during each phase. To some extent, the three phases listed above can be coupled to the three fidelity levels introduced by Nickol in the table in the previous chapter. Figure 2-1 provides a possible graphical representation of the design process. Starting in the top left corner from the conceptual design phase, it can be seen how the phases succeed one another. It is worth noting that overlapping between different phases is possible in order to greatly shorten the time required to get the product on to the market. Also important to observe is how the cost increases drastically with time. It is clearly important to avoid large design changes in the later stages when the modification would impact on a very large number of components, the human resources involved are very large and parts have already started being manufactured.
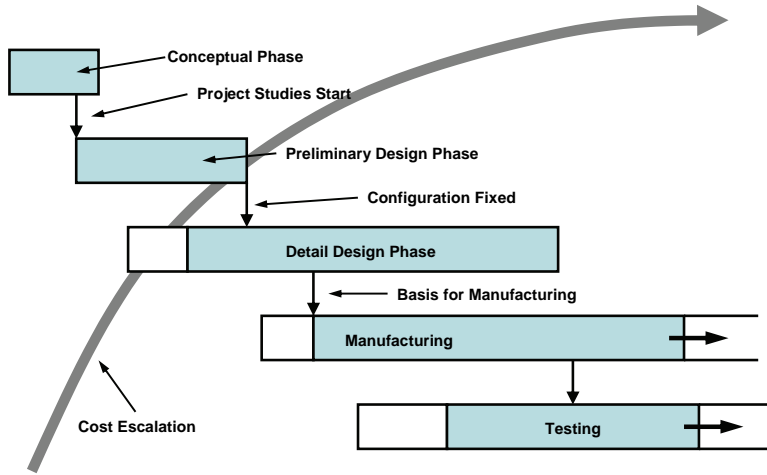
Figure 2-1.   *Design and manufacturing schedule (adapted from Jenkinson et al. [15])*

2.1 The Design Phases

Like basically any product, aircraft design originates from a set of requirements that will function as a guide during the whole process. Hereby is a very short description of the design phases, from a traditional point of view.

The first step is the *Conceptual Design Phase*, which goal is to select one, or very few, workable concepts and optimize them as much as possible (Brandt et al. [6]). During this phase a large number of concepts are generated and evaluated against each other, in order to try to roughly define the main characteristics of the aircraft that better meets the requirements. The level of detail is on average approximate and the number of people involved is still limited. There can be quite a difference between the fidelity levels of the tools used in each discipline. The focus is at this stage to explore as many different solutions as possible and to narrow the number of feasible concepts to be taken into further analysis to one or very few layouts. It is important to reduce the number of layouts to keep, in order not to waste precious and expensive time and resources during the upcoming work. During this initial phase key decisions are to be made based on only limited information. Nevertheless their importance is huge since it is at this time the key features of a new aircraft are decided.

Following is the *Preliminary Design Phase* where the selected concept(s) is(are) looked into more detail. At this point a much larger number of designers are involved and specialists start defining the characteristics of the aircraft. Detailed analysis and simulations are carried out to finely tune the geometries, while all sub-systems begin to be shaped. The aim of this phase is to completely define the aircraft that is going to be manufactured and to 'freeze' its design. If the previous phase has been successful, only minor and very limited changes will be made at this stage to the layout of the aircraft. A

large amount of people are now allocated to the project. Specialists will carry out analysis and simulations of their respective systems and even some testing can start taking place. Also manufacturing and production planning will be carried out, starting from larger sub-assemblies.

The final step of the design process is the *Detail Design Phase* during which all components and parts are defined in all their details. It during this phase that all (or at least most of it) manufacturing documentation is produced. The number of people involved in this phase can be extremely large and so are the costs. Only aircraft that have been decided to be produced reach this phase. The tools adopted during the detail design phase may not be very different, but they are of highest accuracy, in order to precisely define every single aspect of each system. Therefore careful simulations are performed also at this stage. Clearly it is now very hard to make important changes to the layout of the aircraft. If any mistake was made during the conceptual or preliminary design phase, the aircraft will have to either live with it or in the worst case force the project to be cancelled. As an example, the Fairchild T-46A trainer aircraft got cancelled – among other reasons - after discovering a huge discrepancy in the predicted drag and the values measured during the test flight campaign, which negatively effected performances [10].

2.2 (Traditional) Tools and Methods

The type of tools that are used is strongly related to the phase of the design process (Fig. 2-2). Typically, the earlier in the design, the simpler the tools are. One of the main reasons is that in the beginning the number of persons involved and the resources available are very limited while the number of design concepts to evaluate is very large. Therefore it is imperative for the tools to furnish answers as quickly as possible.
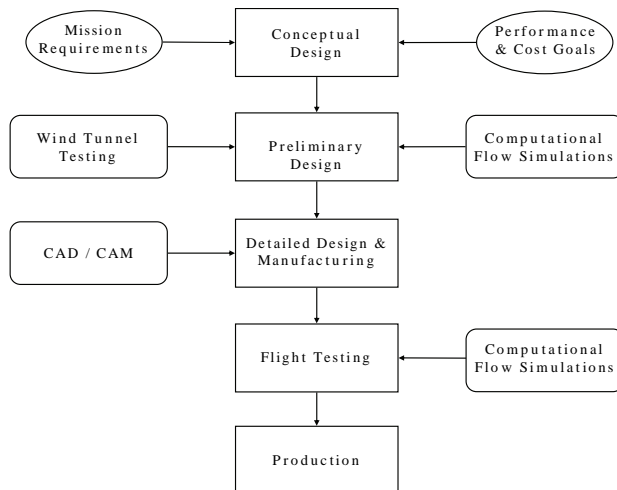
Figure 2-2.   *Aircraft development process according to Brandt et al. [6]*

In general, early design analysis is dominated by very simple empirical, semi-empirical or statistical models. Their strength is that they allows for quickly gathering significant information based on extremely limited input. On the other hand, these same models can not be very accurate and precise. Moreover, they can show large margin of error if trying to extrapolate answers that fall outside the validity range of the model. For instance, if using a statistical model to predict the aircraft weight, the result can be misleading if the model is used to calculate the weight for an aircraft that adopts new materials, or new manufacturing technologies or that has an unconventional geometrical layout that is not represented in the population upon which the model is based on.

Computing power has become extremely affordable, and the trend is not going to change in the future. Already in 1997 Jameson [14] pointed out how times were mature enough for coupling *CFD* simulations with wind tunnel testing in order to cut time and costs for the design of new aircraft. He showed that the two methods effectively completed each other. Wind tunnel tests require expensive physical models whose manufacturing is very time-consuming. Once the model is ready though, several tests in different conditions can be quickly carried out. On the other hand, *CFD* simulations require long computing time, but there is almost no additional expense for changing the model. Thus they enable to effectively enlarge the design space. And indeed this thesis was confirmed in 2005 by Johnson et al. [17]. They presented a review of how *CFD* had been applied at Boeing Commercial Airplanes during the last thirty years. They showed that the number of wings tested in wind tunnels was drastically reduced every time a new *CFD* code was introduced, thus saving huge amounts of money.

It is though very important to note that the same considerations can be made for other tools also. The argumentations just reported are true for the aerodynamic design of an aircraft, but many other fields and disciplines are equally important to successfully design an airplane. This thesis will present a framework through which keeping an overall system perspective on the aircraft, where not only one aspect at a time is analyzed.

CAD systems that traditionally are introduced only at later stages can effectively be adopted from the very beginning. The geometrical model will grow in detail level as the project proceeds and will serve as a basis for all analysis to be performed: aerodynamics, structure, costs, manufacturing simulations, weight estimation, on-board systems packing and performance simulations, stability and control. The key issue is to determine how to efficiently couple all disciplines and to find a clever strategy for quickly and easily generating *CAD* models.

3

Theory

A S PREVIOUSLY DISCUSSED, the design task requires using several different tools, which needs to be connected. In this work, a novel conceptual design framework has been studied. It originates and uses as a basis the *Modelith* framework developed within the research group [16]. The *Modelith* framework is based on so-called *web services* implemented in *Service Oriented Architecture* (*SOA*) which enables distribution and integration at the same time. *SOA* contains a set of standards for distributed computing developed by World Wide Web Consortium, where two standards are the major ones applicable in this work. The first is the Web Service Description Language (*WSDL*) [7] which defines the computational interface to the models. The second is the Simple Object Access Protocol (*SOAP*) [4] which standardizes the messages sent between the distributed models. These standards and general technical aspects of the computational framework are described in more detail in [16] and [43].

3.1 Design Framework

During last years a research project at Linköping University has been aimed at developing a novel design framework to be used from the very beginning of the conceptual design phase of new aircraft (Johansson et al. [16], Amadori et al. [I]-[IV]). The framework is intended to be a multidisciplinary optimization tool for defining and refining aircraft designs, with respect to its aerodynamic, stability, weight, systems, stability and control.

The presented design framework is also thought to meet requirements of modern complex product development. Many companies have design bureaus and production sites located all over the world and are tightly involved in several global partnerships, so that modules of the product are designed and manufactured at different locations. This is especially true in the aerospace and automotive industry where the end products are more or less assemblies of subsystems from different suppliers. This implies that today's

product development is carried out in a distributed, collaborative and competitive fashion and this forms a rather complex environment for the employment of modeling and simulation technology. These aspects must therefore be supported by the modeling and simulation tools.
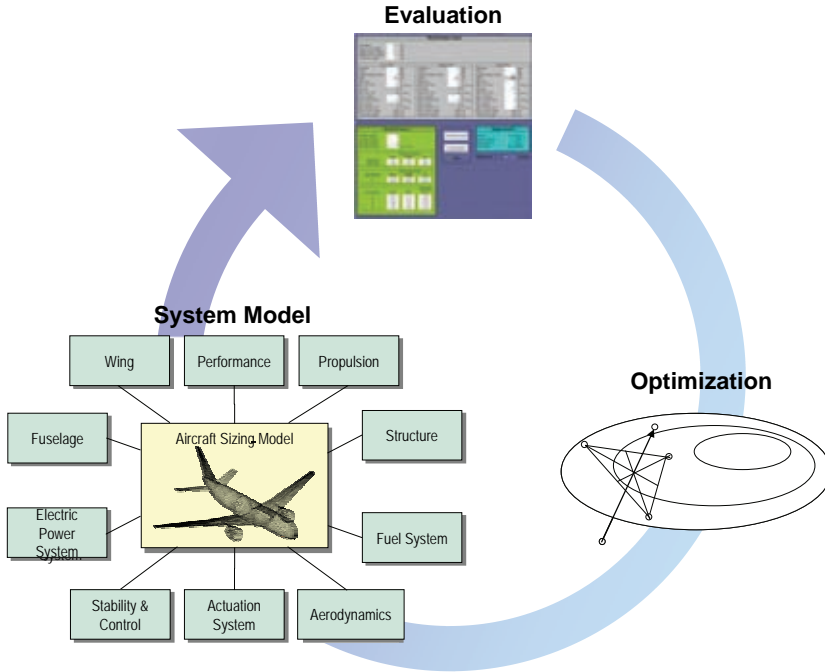
Figure 3-1.   *The complete aircraft design framework*

It is nowadays accepted among the research teams working in this field that the conceptual design phase could take advantage of a novel methodology that would not be based on empirical or semi-empirical equations to estimate e.g. weights, as the method presented by Ardema et al. [3], performances, costs and loads. It should instead relay on analytical models to a greater extent. Previous work carried out by the research group at Linköping University has, for instance, taken into consideration ways to determine the weight of aircraft concepts by means of *CAD* tools [18]. Using a parametric three-dimensional model of the aircraft, it has been shown that the structural weight could be estimated with good precision while the high degree of parameterization ensures that the model can cover a wide range of concepts.

Thanks to the experience gathered during the development of the framework, key requirements have been pinpointed. Among them, the model's flexibility, reliability and robustness are of highest importance and have been key aspects during the development of each part of the framework modules. When compared with examples of similar applications that can be found in the literature, the presented work shows a much higher grade of design flexibility.

The interface between the framework and the designer shall be kept as simple and intuitive as possible. The focus during the conceptual design phase should be on the product to design and on designers' creativity. Thus the tools used shall not steal attention being too complicated to use. The presented framework uses a simple spreadsheet created in Microsoft Excel, where all design parameters are entered and that helps gathering a full system perspective on the aircraft. Due to Excel's high flexibility eventual customizations are simple to add. There is a huge variety of optimization algorithms available that can be used for i.e. design analysis and optimization. Moreover Excel incorporates all the application programming interfaces (*API*) required to directly link it to the *CAD* system (CATIA V5) to control the geometrical model. Another important strength of this type of interface is that no particular skills in the specific *CAD* system are required by the designers. All geometries are created, governed and modified through the interface in a fully automated manner. Also, gathering all results from the *CAD* model is done automatically by the system, so that all relevant data are clearly presented to the designer in the spreadsheet as soon as they are available. The figure below shows how the interface could look like for a wing design application.

Figure 3-2.   *The framework interface is a simple spreadsheet*

3.1.1. CATIA and Parametrical Modeling

The most important characteristic of the *CAD* model is to be highly flexible in order to be able to represent a variety of designs as large as possible. Secondly the model must be robust and reliable, since there will not be a specialist manually entering new parameters and supervising the update process. It is fundamental that the model does not produce mathematical errors within its whole allowed design range. In order to guarantee a high degree of flexibility and robustness, the *CAD* model must be built in a proper way. Figure 3-3 shows the relational links between the different elements of the model of a UAV. The input parameters govern directly the "Datums Model" (*MDF*) and the "Surfaces Model" (*MDS*). The *MDF*-model is a wireframe model where all reference planes and lines, needed to define the aircraft and its structure, are defined. It is important to notice that all the structure components in the *CAD* model depend on both the *MDF*-model and *MDS*-model, that depend instead only on the top level input parameters. The *MDS* surfaces model contains all the external surfaces. The structure is obtained by instantiating a general structural element that is designed to adapt itself to a specified context, which is specified in the *MDF*-model and *MDS*-model. This general element is used for all the structure parts of the aircraft: frames, ribs and wing spars. The elements' geometries are governed by individual parameters, allowing for optimization of the structural design, even at a component level.
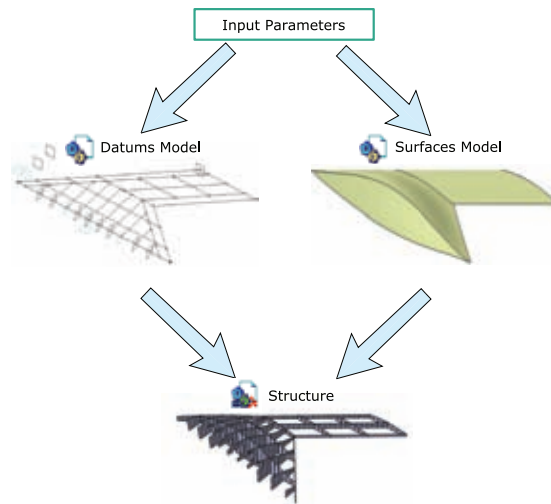
Figure 3-3.   *Relationships between elements in the CAD model*

All geometries are created in an automated fashion in CATIA. Through the spreadsheet interface the designer decides the general dimension and shape of the aircraft and the number and position of all structural elements. Then the *CAD* model is updated to reflect the input in the spreadsheet.

To achieve this level of automation the programming possibilities offered by CATIA V5 have been largely taken advantage of. The system allows using several layers of automation and parametrization [24]. With reference to Fig. 3-4 here next, following is a description of the different approaches, starting from the lowest level.
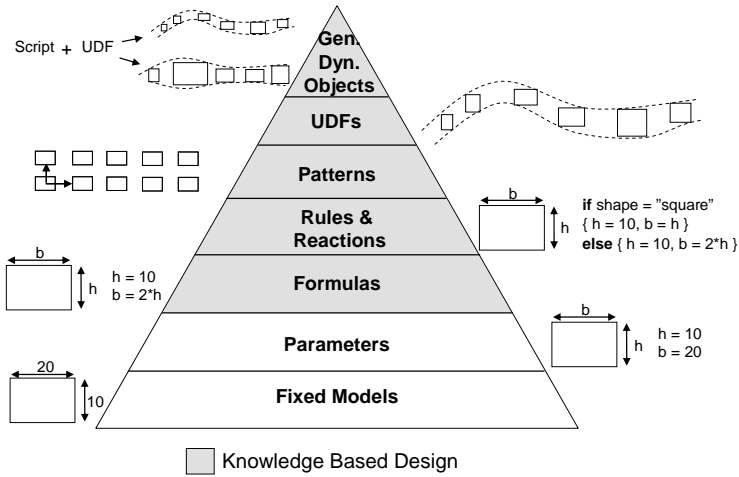
Figure 3-4.   *Different levels of parametrization (adapted from Ledermann et al. [24])*

Fixed models are simply geometries where governing parameters or properties (for instance a thickness or a length) can be modified accessing the object containing the geometry and, searching through the object specifications, manually changing the value of the parameter of interest.

Parameters of different kind can be adopted to define geometrical characteristics or properties, even outside the object or part. This allows changing the geometry without the need to actively access the object containing the geometry itself.

Formulas are mathematical relations that link parameters together (for instance the length of an object that is required to be a given fraction of the object's volume). This feature is the first level that allows incorporating not visible knowledge into the model.

Rules and *reactions* are more sophisticated ways to include knowledge into the model. Rules are a more general and powerful way to describe relations between all kind of parameters, properties and elements in an object. They are not limited to numerical parameters. Reactions, as the name suggests, allows defining how the model shall react to a given input (for instance a parameter or measure change). Reaction are trigged by the occurrence of a specified event, while rules are always are always active.

Patterns are used to instantiate features that repeat themselves in the geometry. Key characteristic of a pattern is that the feature is repeated always in the exact same way and there is no chance to modify individually the elements in a pattern. Pattern can be dynamically operated via parameters.

*UDF*s (user defined features) are generally described features that adapt to the context in which they are instantiated in the model. They allow each instance to be individually modified but are not dynamically governed.

Generic Dynamic Objects are obtained adding scripts to *UDF*s. In this way *UDF*s become dynamically instantiated. Driven by scripts, even highly complex features can be automatically and dynamically instantiated in the wanted context and they can be given all the desired characteristics.

3.1.2. Aerodynamic Code: PANAIR

At the moment, the aerodynamic analysis tool adopted is a panel code, PANAIR [26] that was developed by The Boeing Company and NASA during the late seventies and early eighties to be able to model and simulate complete vehicle configurations. Panel codes are numerical schemes for solving (the Prandtl-Glauert equation) for linear, inviscid, irrotational flow about aircraft flying at subsonic or supersonic speeds (Erikson [9]). As pointed out by Amadori et. al. [I], panel codes are not as precise as modern *CFD*s can be, but they have other advantages. Considering that during a conceptual design phase, the aircraft geometry and its outer shape is not precisely defined and that the detail level is quite rough, it is clear that it can be unpractical and not justified to use tools that have a much higher accuracy. Moreover *CFD*s requires the space around the studied body to be accurately meshed, while for a panel code it is sufficient to approximate the aircraft's outer surfaces with proper rectangular panels. Therefore the meshing time required by a panel code is lower by several orders of magnitude, compared to a *CFD* code. It should be kept in mind that, in this framework, PANAIR is used mainly to compare the effectiveness of different concepts with each other, rather than to gather exact and absolute figures of their aerodynamic efficiency. When more powerful and faster computers will be available or if higher accuracy was required, PANAIR could be substituted with other solvers, thanks to the modular nature of the framework.

The data that is gathered from the panel code analysis are the lift coefficient (c_L), calculated using Trefftz plane analysis, the induced drag coefficient (c_{Di}) and the pitching moment coefficient (c_m) and thus the aerodynamic forces and moments acting on the airplane.

The upper and lower surfaces of the wing are meshed with rectangular panels using an in-house developed meshing application. This application is based on a set of script-procedures that can be activated from the spreadsheet interface and that also handles all steps required for starting the aerodynamic analysis. The surfaces are at first split along the front and aft spars. This is done to simplify the aerodynamic loads retrieving operations. This is done because PANAIR presents results for each surface separately and then assembled for the whole aircraft. Since only the load-carrying structure is analyzed, the air loads coming from the forward and aft surfaces are then simply applied along the front and rear spars.
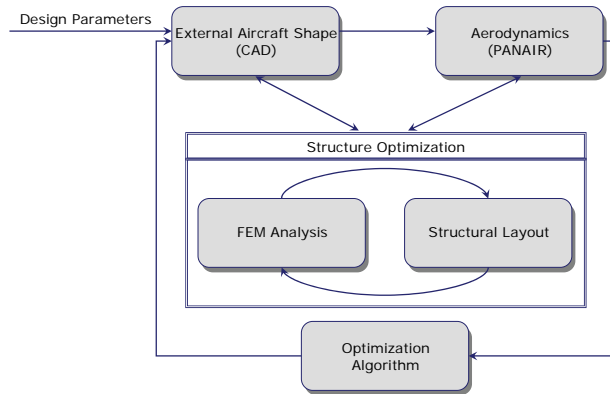
Figure 3-5.   *Links between disciplines in the structural analysis*

An advantage of using a tailor made meshing tool is that the coordinates for each one of the meshing nodes can be stored directly in the appropriate order for PANAIR to correctly interpret them. Thus data handling is in this way simplified and speeded up.

3.1.3. Structural Analysis

Having a detailed geometrical model of the aircraft and being able to run an aerodynamic analysis of it means that it is possible to perform a relatively accurate initial structural analysis as well, with only a relative additional cost or expense. The pressure distribution around the aircraft represents the load case to be considered. Since the pressure field will be varying accordingly to the deformations provoked in the structure, even some preliminary aeroelastic couplings can be studied already at this early design stage. Figure 3-5 shows the links between the different disciplines. The inner loop between 'Structural Layout' and '*FEM* Analysis' is required if aeroelastic effects are to be taken into account.

In other structure design studies [13], [27], [38], [39], [45], the structural layout has already been decided and frozen before the optimization can start. Then the system modifies thicknesses and maybe slightly moves the structural elements from their starting position. This work will instead demonstrate that it is possible to design concepts with a much higher degree of freedom, allowing also the number of elements to be varied. Therefore the kind of structural analysis will get close to a topological optimization of a much more general design. Thus it can be ensured that the solution obtained will be of a more general character.

3.2 Optimization

The optimization algorithms that are usually adopted in engineering type of problems can be divided into two main categories: gradient and non-gradient based algorithms. Gradient based algorithm computes the partial derivatives of the objective function in order to individuate the direction along which to move to reach an extremum. They can be of the first or second order depending on the order of the derivatives they require to

calculate to define the search direction [32]. These algorithms are fast but usually not quite able to avoid stopping at local extrema, in case of non-convex functions.

The other family of algorithms, the non-gradient based ones, as the name suggests, do not use gradients for searching for extremum in the objective function. This could represent an advantage in those optimization problems where the objective function is obtained from both simulation results and analytical calculation, thus making it hard to extract the derivatives [1]. The techniques involved in these algorithms are various. They can use 'Random Search', where the design space is searched randomly. An alternative is 'Hooke and Jeeves Method' that "is based on a sequence of exploratory and pattern moves" [32] to explore the surroundings of a given point in the solution space. Other methods try to emulate natural or biological systems to try to reach to the objective function's extremum. To this category belong the 'Genetic Algorithms', the 'Ant Colony Optimization' or the 'Swarm Optimization'. Other algorithms are the 'Simplex Method' [30], [41] and the 'Complex Method' [5], [12] that use geometric shapes to decide the search direction starting from a given point in the space. Non-gradient based methods can be aggravated by heavier computational expenses required to reach to a solution, but are capable of handling also non-convex objective functions without ending up in a local optimum as a gradient method would do. Here below is a brief description of the algorithms that have been used in this work.

3.2.1. Fmincon

The method originates from Wilson in 1963 and was first implemented by Pschenichny (1970) and Han (1977). According to Onwubiko [32], the popularity of the method relays on its capability of finding the optimum solution starting from an arbitrary point in the design space. Moreover Fmincon requires less function evaluations compared with other algorithms suited for constrained optimization problems.

Fmincon is an optimization algorithm that can be found in MatLab's Optimization Toolbox. Quoting the documentation accompanying the algorithm itself, it is a constrained nonlinear optimizer that uses the second order gradient method Sequential Quadratic Programming (SQP) to find a constrained minimum of a scalar function of several variables starting at an initial estimate.

3.2.2. Complex

The Complex method is a non-gradient optimization algorithm developed from the Simplex method, the main difference being that it uses more points during the search process. During its search, the Complex algorithm uses a set of m points, so that $m \geq n + 1$ where n is the number of variables of the optimization problem. The initial set of points is randomly selected. Then, at each step, the Complex algorithm evaluates the objective function value at each point of the set and replaces the worst point by reflecting it through the centroid of the $m - 1$ remaining points (see Fig. 3-6).
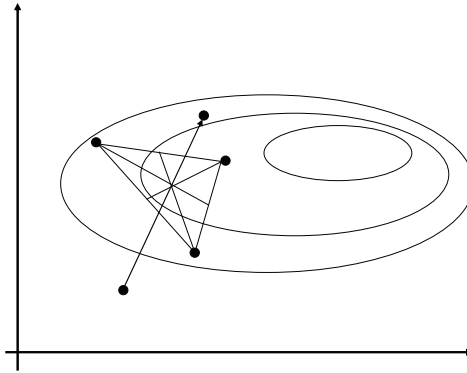
Figure 3-6. *The complex algorithm reflects the worst point through the centroid of the remaining points*

The Complex algorithm can also be tuned using the tolerance for function and parameters convergence. A modified version called Complex-RF [21] introduced also two more parameters, the so called "forgetting factor" and "randomization factor". The latter parameters are used to increase the robustness of the method. The first one ensures that the older points in the complex are neglected, which is useful if the objective function changes over time. The randomization factor adds a random noise vector to the new point being calculated. Thus the algorithm is made less prone to prematurely collapse on local optima, at the expense of an increased time required to get to convergence.

3.2.3. Genetic Algorithm

Genetic algorithms are mathematical schemes that try to replicate the natural selection process to search the extremum of the objective function. Each possible solution or point in the n-dimensional design space is represented by an individual whose n genes correspond to the n design parameters. Genes can be coded as numbers, strings or bits, depending on the nature of the problem. To be able to carry out the optimization the algorithm requires a population of individuals to be initially defined. The idea is then to mate the best individual in the population generating new individuals that are hopefully even better than their parents. There are several mechanisms through which the mating can be performed, as well as there are different ways to eliminate the overflowing individuals from the population, whose size is kept constant through the optimization. It is even possible to define mutation factors that randomly change some genes during the creation of new individuals, which increases the algorithm robustness and capability of exploring the whole space searching for the true optimum.

The strength of genetic algorithms is that they are able to locate the optimal solution even in problems that do not possess well-behaved objective functions. On the other hand they usually are computationally heavy, requiring to evaluate the objective function for each individual at every generation. Onwubiko [32] suggests population sizes between 20 and 100 individuals, depending on the number of optimization variables involved. Clearly, large population implies longer time to get to convergence, due to the larger number of objective function evaluations.

4

Proposed Conceptual Design Process

THIS CHAPTER DESCRIBES how the conceptual design framework has evolved to be used in several design projects, in order to test the validity of the tool itself as well as trying to verify its effectiveness in a given design task. As described in the previous chapter, the framework will include analysis tools to cover all the required disciplines that are involved during the conceptual design phase. It has also been described how the framework has been designed to guarantee flexibility and platform independence, so that tools can be linked and removed without harming the overall functionalities. With reference to the appended papers [I], [II], [III], in the following sections it will be explained how tools for aerodynamic analysis, optimization, geometry generation and structural analysis have been successively included and tested in the framework.

4.1 Panel Code and Optimization Algorithms

In order to be able to predict the aircraft's performances it is required to analyze its aerodynamics. As a very first step this means trying to estimate how much lift and drag its shape will generate when flying in different conditions. During the initial design phases designers have to cope with very basic issues regarding the aircraft's layout and shape, while more detailed investigations and fine tuning of details will be carried out only during later stages.

Having this in mind, a high order panel code, PANAIR, was tested in the framework, coupled to a simple geometry generator written in MatLab (Fig. 4-1) [I]. The design and optimization for a specific mission of an unmanned aircraft was taken into consideration as a test case. The choice of a panel code was dictated by the need for reducing the time

required to perform an analysis. It can be argued that *CFD* codes have much higher accuracy, but the time they required is at least an order of magnitude higher. Moreover they require the three-dimensional space around the aircraft to be accurately meshed, while a panel code only needs the wetted surface to be meshed. Moreover, panel codes are much more forgiving in terms of meshing accuracy.
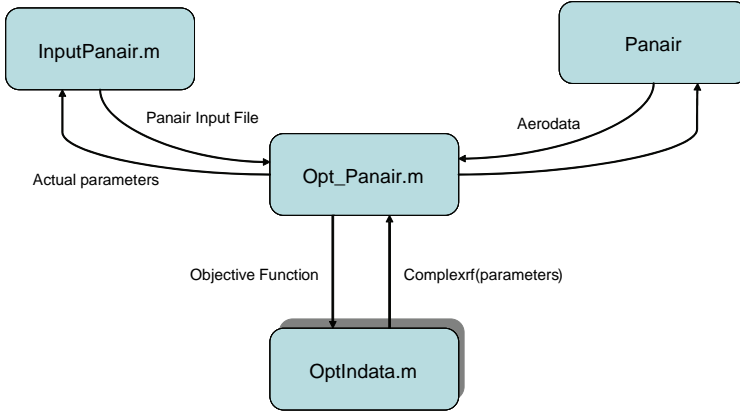
Figure 4-1.   *Actual dataflow in the framework for testing PANAIR [I]*

The aim was to test PANAIR and evaluate different optimization algorithms. Therefore all the other tools and disciplines required where "simulated" in the framework using simpler rules of thumb, empirical equations or statistically based formulas taken from the literature [6], [15], [37], [42]. Hence the scheme shown in Fig. 4-1 only marginally resembles what is pictured in Fig. 3-1 in Chapter 3.

The biggest drawback of using a panel code is that it can not take into consideration viscous effects, but only information regarding the induced drag are given. That means that the other drag components need to be estimated in other ways. What has been done so far is to use well known approximated formulas, with inputs as precise as the tools adopted allows. For instance, the parasite drag is calculated as:

$$C_{d0} = c_{fe} \cdot \frac{S_{wet}}{S_{ref}}$$

(4.1)

where c_{fe} is an "equivalent skin friction coefficient" that can be found in tables as the one reported by Raymer [37]. If using precise *CAD* tools for representing the geometry of the aircraft, both S_{wet} and S_{ref} will be exactly known.

Even with these drawbacks and even if other types of aerodynamic codes could produce more precise results, it must be remembered that the main goal is to test the use of an analytical tool for initial aerodynamic estimation rather than trying to find the tool that promises to achieve the best "precision-to-performance" ratio. Keeping this in mind, panel codes are perfectly suitable for the challenge. They are able to analyze virtually any type of three-dimensional geometry, they produce significant results and, very important, they are fast.

As stated above, the design of an unmanned flying wing aircraft was used as a test case for evaluating PANAIR and different optimization algorithms. Figure 4-2 shows the plan-form of the vehicle and the parameters used to describe it.
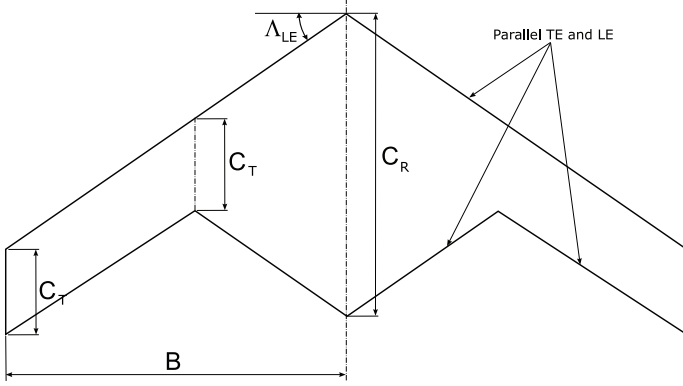
Figure 4-2. *Design parameters defining the outer geometry of the aircraft. Not shown are the wing root and wing tip thicknesses*

The framework was then used to optimize the shape of the aircraft minimizing its maximum take-off weight needed for completing a given mission. The object function was written as following:

$$ObjFun = K_1 \left(\frac{W_0 + P_{TC} + P_\alpha + P_{C_m} + P_{fuel} + P_S}{W_{0,nom}} \right)^{\beta_1} + K_2 \left(\frac{B}{B_{nom}} \right)^{\beta_2} \qquad (4.2)$$

The factors K_1, K_2, β_1 and β_2 are constants used to assign the wanted weight to the two terms of the equation. $W_{0,nom}$ and B_{nom} are the take-off weight and the span width of a nominal configuration used as reference. P_{TC}, P_α, P_{Cm}, P_{fuel}, and P_S are penalties that are used, together with constraints, to lead the optimizer away from unwanted configurations.

- P_{TC} is aimed at ensuring that the considered configuration allows the engine and the payload bay to be fit inside the aircraft.
- P_α: in order to reduce drag and radar cross section, the angle of attack in cruise condition is linked to a penalty function that aims at positive and not too large values.
- P_{Cm}: one basic condition the aircraft should fulfil in order to be controllable is to have a negative slope of the pitching moment coefficient as function of the angle of attack, i.e. $C_{m,\alpha} < 0$. P_{Cm} has then been introduced to penalize layouts that do not satisfy this requirement.
- P_{fuel} penalizes configurations where the fuel tank size is not large enough to contain the fuel quantity required by the mission.
- P_S takes into account the static margin of the aircraft. For an aircraft of this kind it is not desirable to have a too large static margin, because it would

require large trim-deflections of the control surfaces. The aircraft could then result hardly controllable since the surfaces may not be able to be deflected enough before they reach the end position. Therefore it is usual to strive towards small static margins and then relay on the control system.

The optimization problem was formulated as following:

$$
\begin{aligned}
&\min ObjFun \\
&s.t. \\
&x_{\min} \leq x \leq x_{\max} \\
&R \geq R_{req.} \\
&E \geq E_{req.} \\
&\sigma_{eff} \leq \sigma_{eff,all.} \\
&c_{m_\alpha} < 0 \\
&\alpha_{\min} < \alpha_{cruise} < \alpha_{\max} \\
&S.M._{\min} < S.M. < S.M._{\max}
\end{aligned}
\tag{4.3}
$$

Three different optimization algorithms were tried: Fmincon, Complex and a Genetic Algorithm (*GA*). What resulted clearly from the test was that Fmincon, which is based on a gradient based method, was most often unsuccessful in solving the problem, stopping the optimization as soon as it reached to a local extremum of the solution space. The Complex algorithm and the *GA* were instead both able to correctly solve the optimization problem, but showing different performances. To evaluate the two algorithms' performances a so called "performance index" was used [20], calculated as following:

$$
f_{obj,opt} = -\frac{Log_2(1 - P_{opt})}{k_m}
\tag{4.4}
$$

where P_{opt} is the probability of finding the optimum and k_m is the number of iterations required. The results are summarized in the table below.

| Parameter	t_R	t_T	Λ_{LE}	C_R	C_T	B	ρ	W_{MTOW}	$f_{obj,opt}$
Complex	20 %	8.13 %	44.2º	13.49 m	4.17 m	5.99 m	2.56º	18,716 kg	$5.6 \cdot 10^{-4}$
GA	20 %	8.15 %	44.11º	13.50 m	4.21 m	6.00 m	2.20º	18,656 kg	$5.0 \cdot 10^{-4}$

Table 4-1. *Optimization results for the Complex and the Genetic Algorithms*

As the table shows, the two algorithms showed almost the same performance index. The Complex-RF algorithm did find the correct solution one third of the times it was run, while the *GA* registered a hit rate of about 75%, but to do so it required three times as

many objective function evaluations when compared to the Complex-RF, which makes them roughly comparable.

4.2 CAD Modeling

In order to be able to achieve true multidisciplinary design analysis and optimization it is beneficial to use the same geometrical data as source for all disciplines involved [24]. This means that the *CAD* model assumes a very central role in the framework. Not only it has to contain all information that is required for all disciplines to carry out their analysis, but it also has to guarantee a degree of flexibility high enough to cover the widest possible range of different configurations. The cost and the time required to create a model with the characteristics described in section 3.1.1 is inevitably higher than for a conventional model. On the other hand, a parametric and associative model ensures that, within its validity range, all configurations and variants are covered and represented, so that the same model can be reused saving time and money. Ledermann et al. [24] presented a graph (reported herby in Fig. 4-3) that highlights these differences. It showed that, during the initial phases of the design of a new aircraft, a highly flexible parametric model will cost more, but that, as time goes on, the total cost becomes lower. This is also because in an aircraft design there are many repetitive features that such a model enables reusing instead of repeatedly recreating them. Moreover, the cost of a parametric model can be split over several projects, if its flexibility allows reusing it. The major problem is to identify the level of parametrization and automation that is required for a given project and that represent the right balance between built-in functionalities and cost.
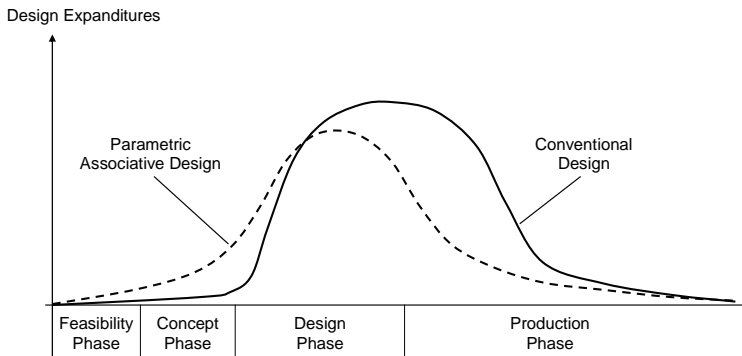
Figure 4-3.   *Design expandituress in an aircraft design project (Ledermann et al.[24])*

The *CAD* model created for the framework application was intended to meet five specific requirements:

1. to include the outer surfaces of a flying wing type of aircraft or of a wing of a conventional aircraft;
2. to include the main structural elements such as frames, ribs and spars;
3. to guarantee high flexibility so that both the external shape and the internal structure layout can be changed as wanted;

4. to be operated from an Excel spreadsheet so that no knowledge of the *CAD* system would be required by the designer;

5. to allow for design optimization and automation.

The external surfaces were parametrized in the same way as in the test case described in the previous section. They are obtained sweeping a surface using the wing airfoil contours as profiles and the leading and trailing edge as guide lines. The choice of the airfoil mathematical representation is critical to ensure a wide range of usage. Therefore the wing profiles were using the formulation suggested by Kulfan and Bussoletti [22] (see also Fig. 4-4):

$$
\left(\xi\right)_{Upper} = C\left(\psi\right) \cdot \left(\sum_{i=1}^{n} Au_i \cdot S_i\left(\psi\right)\right) + \psi \cdot \Delta\xi_{Upper}
$$

$$
\left(\xi\right)_{Lower} = C\left(\psi\right) \cdot \left(\sum_{i=1}^{n} Al_i \cdot S_i\left(\psi\right)\right) + \psi \cdot \Delta\xi_{Lower}
$$

(4.5)

where: $\xi = \dfrac{z}{c}$ is the non-dimensional airfoil ordinate;

z is the profile coordinate along the z-axis;

$\psi = \dfrac{x}{c}$ is the non-dimensional airfoil station;

x is the profile coordinate along the x-axis;

$C\left(\psi\right) = \psi^{N_1} \cdot \left(1 - \psi\right)^{N_2}$ is the "class function";

$S_i\left(\psi\right)$ is the ith-term of the Bernstein polynomial of order n;

$\Delta\xi_{Upper} = \dfrac{zu_{TE}}{c}$ is the non-dimensional upper surface trailing edge thickness ratio;

$\Delta\xi_{Lower} = \dfrac{zl_{TE}}{c}$ is the non-dimensional lower surface trailing edge thickness ratio;

Al_i, Au_i, N_1 and N_2 are coefficients to be determined to obtain the wanted shape.
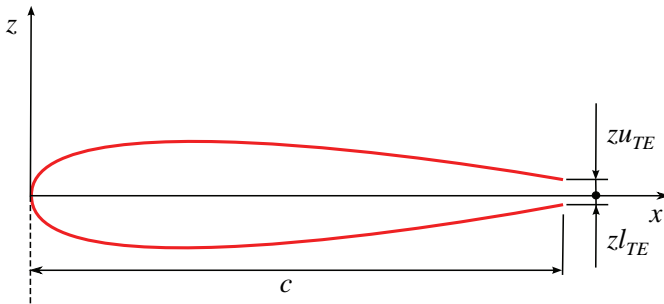
Figure 4-4. *General representation of a blunt base / round nose airfoil*

The strength of this formulation relies on its capability of representing any smooth airfoil with any required accuracy level. The smoothness is guaranteed by the formulation itself,

while the precision with which the airfoil is represented depends on the order of the Bernstein polynomial. It is also possible to represent with good precision even sharp-nose profiles, which is favorable when dealing with certain type of aircraft, that for instance have stealth requirements.

The *CAD* model enabled to modify the position of every single structural element as well as the number of elements. If new elements need to be added, using general dynamic objects (described in section 3.1.1), the system instantiates the parts where specified. It is important to notice that during this operation all required links to the references objects in the model are established so that the hierarchical product structure is respected and maintained. This is mandatory in order to preserve the operability of the model and its level of flexibility. Moreover it ensures that, later on, each part of the model can be readily used during the upcoming preliminary and detail design phases, without needing to rebuild any object. Details can be added to each part of the product assembly, still maintaining the correct links to the references. Figure 4-4 shows the *CAD* model of the aircraft.

Figure 4-5.   *Parametric CAD model of an aircraft*
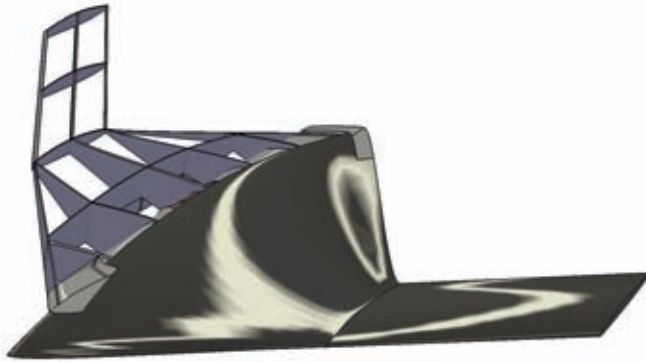
Represented are the external surfaces, the engine with its air intake and exhaust channels, and a tentative structure composed by upper and lower skins, fuselage frames and wing spars and ribs. All structural elements are characterized by a rectangular cross-section whose thickness can be individually varied through a specific parameter. The elements location and number are depending on the *MDF*-reference as previously explained in chapter 3.

To simplify the aircraft structure modeling task, all structure elements are instantiated from the very same reference object using the so called Functional Molded Parts (*FMP*). *FMP* is a product available in CATIA V5 that was initially thought to ease molded, cast and forget parts. *FMP* features are history-free, meaning that the order in which operations are performed does not affect the end result. Instead they allow for functional specification of operations and references. An example will help to explain. Some of the elements require to be cut out to make room for the payload bay or the channel where to install the engine, air intake and exhaust. Using *FMP* they can be defined as protected volumes, meaning that an element is cut *if* it intersects one of the specified regions (Fig. 4-6). This way lot of time is saved, since it is not necessary to include any additional

control on weather the protected regions are violated or not, nor is it necessary to design parameters-regulated cut outs in the structural elements. Of course, *FMP* allows for further detailing the parts if and when required.
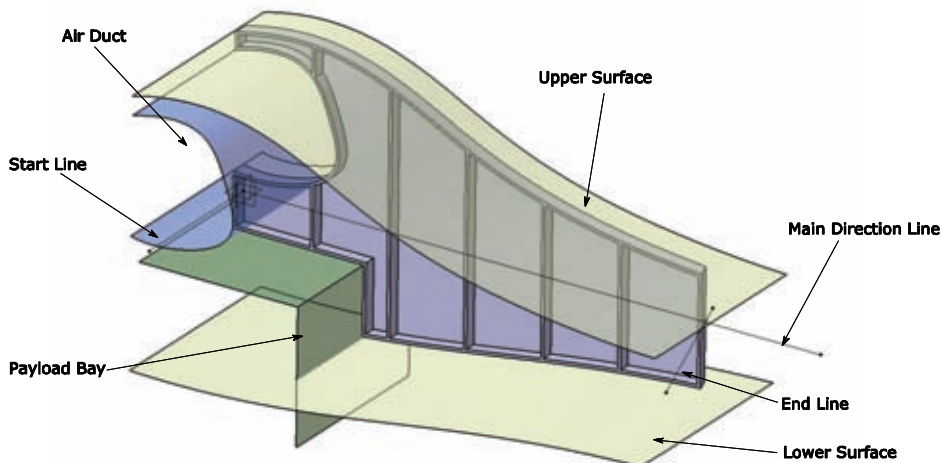
Figure 4-6. *The structural elements are all instantiated from a general part using Functional Molded Parts (FMP)*

Acquiring the loads working on each part, a new local optimization could be started to distribute all reinforcements on the part. This would resemble a topological optimization of the structural element, not too different from the wing rib optimization presented by Maute et al. [28]. In their work, they discretized the rib using small "pixels" that the optimization algorithm could later keep or discard, in order to minimize the weight. Using *FMP*s, reinforcement ribs can be defined starting from a simple sketch that is superimposed on a given solid geometry. By using this type of approach, the optimization algorithm would be used to draw the sketch, by choosing the number, position and direction of each line that is then used as reference for the reinforcement ribs (Fig. 4-7). The same technique adopted for the rib and spars placement can be implemented to describe and optimize the reinforcement sketch.

The result is an extremely flexible and robust model. Not only the outer shape can be modified as wished through a set of global parameters, but also its internal structure layout will follow accordingly, thanks to the hierarchical and associative nature of the model. All changes are trigged and governed by editing an Excel spreadsheet that is connected to the model. Therefore a designer does not require any knowledge of the *CAD* system to proficiently operate it and beneficiate of it. Least but not last, the use of a spreadsheet to control the geometry helps maintaining a broader system overview of the whole vehicle.
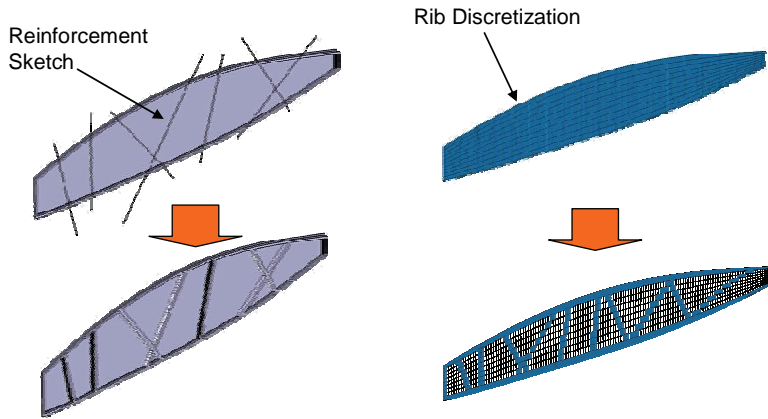
Figure 4-7. *Two different approaches to topological optimization of strucutral elements: using FMPs (left) and using geometry discretization (right).*

4.3 Design Optimization and Automation

The techniques and methods described in the two previous sections were implemented in a design optimization study of a micro/mini aerial vehicle (MAV). Micro or mini aerial vehicles are characterized by being simple and inexpensive to build and, due to their small size, they need to be carefully optimized. They are also likely to be built in relatively small series and to be tailored for the sensors and equipment available at the time of deployment. Therefore "design and build on demand" is very attractive, where a modular concept with an automated design process is desirable: a scenario driven design, where the MAV quickly can be designed and built for a specific mission. A major part of the process is to create a design tool and optimization methodology for MAVs.

Design automation is of general interest in aeronautics, and automated methods for coupling aerodynamic calculations, *CAD* modeling, *FEM* analysis, etc. are getting an increasing importance in the design of manned aircraft. Completely automating the design from concept to production is however still far from possible. MAVs on the other hand are small, simple to build, and requires relatively few components, which means that fully automated design becomes suddenly a viable and realistic option.
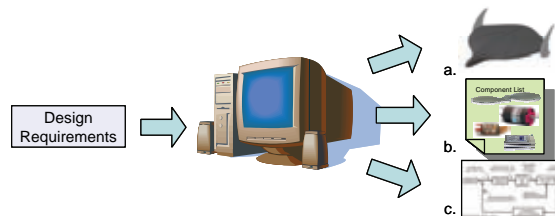
Figure 4-8.   *MAV design automation [III]*

The ideal design automation procedure is described in Fig. 4-7. Starting from a set of requirements, an automated design tool selects the optimal geometry for the aircraft, together with a complete list of off-the-shelf components (engine, servos, batteries, etc) and the control scheme for the flight control system. The aircraft is designed as a composite material shell, with two winglets for yaw stability and a nose installed propeller engine. The geometry output from the system is a full three-dimensional *CAD* model that can be readily be used for production, either for milling the molds or to be sent to a three-dimensional printing machine. The control system design has yet to be included in the framework. As for the previously illustrated studies, also in this application the aerodynamic analysis relies on PANAIR, which is linked though an Excel spreadsheet. There is also the possibility to use much simpler handbook formulas for aerodynamics evaluation. These equations are based on the lifting-line theory, and are therefore not able to take into consideration all the aspects that the panel code does (i.e. the influence of the wing profile). On the other hand they do not require the full geometry to be modeled in the *CAD* system, thus requiring much less time to execute an analysis. In the figure below it can be seen how the framework has been set up.
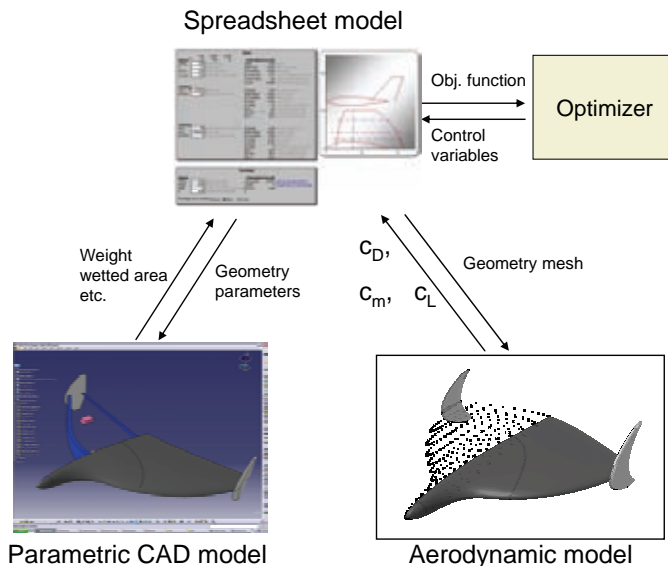
Figure 4-9.   *The automation design framework for MAVs*

The propulsion system consists of propeller, electric motor, PWM motor controller, and battery. Each component is modeled individually, and for each of them a large database has been created storing data from many off the shelf components used in hobby applications. To ensure a broad spectrum of possible designs the database contains as much as 130 motors, 15 motor controllers, 30 propellers and 30 batteries. The performance of the aircraft is calculated from the results of the *CAD* program weight predictions, the panel code aerodynamics calculations, and propulsion system modeling. Endurance, range, and climb are presented as a function of speed. Interesting parameters

such as efficiency of individual components, propeller rpm, motor current, etc. can also be plotted.

An external genetic algorithm based optimizer is connected to the spreadsheet to optimize the design of the MAV. The design optimization has been divided into two successive parts. First the framework is run without invoking PANAIR and the *CAD* system for aerodynamics and geometry generation. This ensures much more rapid iterations at the cost of less accurate results. In this initial mode, a large number of parameters are involved in the optimization which comprises both the geometry layout of the aircraft as well as the selection of the propulsion system. When convergence is reached the system is restarted, this time involving both CATIA and PANAIR, using the optimum solution obtained as starting point. The propulsion system is frozen and the geometric design parameters are allowed to vary within a narrower range. In this second phase design parameters that could not be evaluated using the lifting-line theory can be included, such as the tip chord twist or the wing profile.

If the result from the second optimization would not agree with the first one, the whole process is repeated until convergence between the results is reached. The process is illustrated in Fig. 4-9.
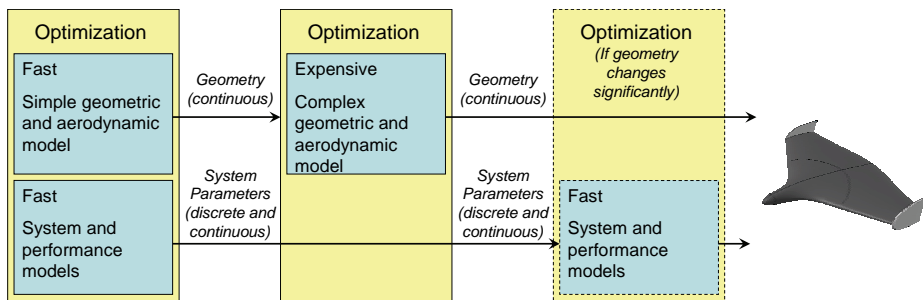
Figure 4-10.   *The optimization process*

The test design cases considered to evaluate the process and the framework showed successful results. From a mere product point of view, suitable propulsion systems were chosen and the overall plan-forms generated give a god impression for the aircraft that were suggested by the system. The hierarchical associative *CAD* model structure that had been developed ensured that all configurations within the design range could be represented and generated without incurring in errors. Also the connections between the Excel spreadsheet and both CATIA and PANAIR worked as expected. The biggest issue here was related to time losses due to inefficiencies within CATIA V5 scripting mechanisms. The time required by CATIA to carry out operations described in VB scripts is always quite high, since scripts are not compiled before execution. For the framework here described it could take between 30 seconds and one minute to complete one iteration cycle during the optimization.

The proposed process truly enables design automation of simpler aircraft such as MAVs. Trials have also been carried out to produce a flying prototype out of the *CAD* model coming from the framework at the end of the optimization using a 3D printing machine. The printer uses ABS material, depositing fused material in thin successive

layers, as thin as 0,17 mm, which gives a quite good surface definition and smoothness [36]. The only operation left on the model once printed is eventually to quickly sand away small imperfections on the surface and to install the electronic components. The resulting aircraft is heavier than what could be achieved by using composite materials, but the practicality of the 3D printing method is unbeatable for this type of application. Using composite materials that require molds imply a much longer production time and a capital investment that may not be justified if the amount of aircraft to produce is small. For 3D printing, on the other hand, only acquiring a printer is needed to be able to produce an infinite number of different MAVs.

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Discussion and Conclusions

R ATIONALIZATION OF THE design process and introduction of multidisciplinary optimization are no novel topics in aircraft design. In the literature there are examples that can be tracked back to the early seventies [11], emphasizing how the need and the benefits have been known for a very long time. On the other hand, much fewer are the cases in which systems, techniques and tools have been used successful on a larger scale. It is not uncommon that limited and tailor made applications have been adopted, but rarely the same solution is suitable for different tasks, or different problems, or, even harder, different companies. The main reason for this being that in most cases these multidisciplinary optimizations cope with very specific applications, where different software are connected by means of non-standard interfaces, or where even in-house codes are involved. The problem that is analyzed may also be very company related.

What has been proposed in this thesis is a framework architecture that focuses on its flexibility of application. The main goal is not to provide with a commercial tool ready to be installed and use, but to present a roadmap and a description of how a multidisciplinary environment can be efficiently set up to solve design optimization problems. There are several commercial products that enable design process automation (MODELCENTER, iSIGHT,…). These software will inevitably introduce compatibility limitations and increase license costs. The method proposed in this thesis is instead centered on Microsoft Excel, which is already widely available. The downside is the requirement for programming the connection between the spreadsheet and the modules used in the framework.

To avoid continuing using semi-empirical or statistical equation during the conceptual phase of aircraft design it has been suggested to make a larger use of analytical tools. For the aerodynamics a high order panel code – PANAIR – has been successfully employed

in an unmanned aircraft design optimization studies. PANAIR may not represent the state of the art for aerodynamic analysis, but it served the purpose of illustrating the process. Clearly any other panel code or *CFD* software could equally be used instead. At the same time three optimization algorithms were compared. Fmincon, a gradient based algorithm; Complex, an algorithm derived from the Simplex, is non-gradient based and a Genetic Algorithm (*GA*). Not surprisingly worse performances were showed by Fmincon that was not able to avoid the local extrema in the objective function, thus seldom reaching to the true optimal solution. Interestingly though, both the Complex algorithm and the *GA* showed the same performance index, which, in simple words, is a ratio between the number of function evaluations required to complete the optimization and the capability of the algorithm to find the optimal solution. The *GA* was able to produce the 'correct' answer nearly every time, while the Complex only every third run, but at the cost of one third of the function evaluations required by the *GA*.

It has been accurately researched how to proficiently include a high-end *CAD* system – CATIA V5 – during the initial geometry generation of the three-dimensional aircraft model. This is achieved by making a large use of the automation features that CATIA offers, mostly the User Defined Features (*UDFs*) together with scripts. *UDFs* ensures the context dependence of the automatically instantiated features, while scripts stand for the dynamic behavior of the whole system. The resulting model architecture has been verified in several cases; two among them were here discussed. First a UAV model that featured a customizable structure model, where not only the structural layout can be modified at will, but also all changes to the external shape of the aircraft will induce the structure to automatically adapt. Secondly a simpler model of a micro aerial vehicle (MAV) has been included in a design automation routine. Governed by an optimizer, an Excel spreadsheet controlled the *CAD* model so to keep the geometrical representation always up to date during the optimization. The resulting model has also been manufactured using 3D printing techniques, even more showing that it is indeed possible to go from requirements to finished product with one click.

One important effect of the process described in this thesis is that it allows to hugely increasing the detail level during the conceptual design. The cost of adding details is only connected to the computing time required for solving the optimization problem. Considering how available computing power has evolved [23], it is only a matter of a few years before problems that today seem to large to be solved, become an easy task.

From a design process perspective, this means that the border between conceptual and preliminary design is going to fade, and the two phases would collapse into one single, larger, more detailed and exhaustive phase. Hence the overall time span for a designing a completely new aircraft could also be reduced, as well as the decision making capability during the initial phases would be enhanced.

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Review of Papers

I N THIS SECTION the three appended papers in this thesis are briefly summarized.

Paper I:

Use of Panel Code Modeling in a Framework for Aircraft Concept Optimization

This paper investigates the possibility of using a high order panel code (PANAIR) for aerodynamic evaluations during the conceptual design phase. The design framework, to which PANAIR is connected, employs Web Service technologies for enabling distribution of the different modules. As test case, the design optimization of an Unmanned Aerial Vehicle (UAV) is carried out. Three different optimization algorithms (Fmincon, Complex RF and a Genetic Algorithm) are compared.

Paper II

A Framework for Aerodynamic and Structural Optimization in Conceptual Design

A highly parameterized and associative CAD model is employed within a design framework being developed at Linköping University to store all geometrical data. The

paper investigates how CAD can be included and efficiently connected to the framework, in a way that permits automatic design optimization. The framework connects together a high order panel code for aerodynamic analysis, a CAD system for geometry generation and a FEM environment for structural analysis. An aircraft wing box design is used as example.

Paper III

Distributed Framework for Micro Aerial Vehicle Design Automation

Micro Aerial Vehicles (MAVs) are very small aircraft whose dimensions are below 50 centimeters and 500 grams. They could be used to perform a huge variety of tasks, both civil and military, carrying different types of loads depending on the mission. The key idea of this paper is to enlighten how their design can be quickly and automatically tailored to a specific mission, rather than trying to design a vehicle serving as a platform for a larger set of missions. The design framework developed at the University is employed and its functionalities tested.

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