



# 1 Introduction

## 1.1 Motivation

The design of aircraft is a fascinating yet challenging task. Frequently, opposing goals are to be fulfilled and limitations, often imposed by regulations, are to be met. However, the main design goals have always been safety and reliability, though in the last decades ecological and economical issues have complemented the former. Therefore, an aircraft design is always the result of careful consideration of all these aspects and consequently a, not only technical, compromise. The basic geometrical layout of aircraft has not changed much since the beginning of the 20<sup>th</sup> century; nonetheless, its technological complexity has changed tremendously. One example is lightweight design where new possibilities to save weight have been used by introducing high performance aluminium alloys and composite materials. Another example are the advances in avionics and electrical systems design, resulting in a more and more “electric” aircraft. All these developments require judging their influence on an aircraft’s design and performance at an early development stage to avoid economic misjudgement. This is where conceptual and preliminary aircraft design comes into play (cf. chapter 2).

Besides transportation at subsonic and transonic speeds, the dream of supersonic travel is appealing to many people and institutions. However along with military aircraft, only Concorde and the TU-144 have been introduced into the airliner market. Both aircraft have been used on very few routes and their commercial success was remote, being a good example to show that what is technically feasible must not always be economically sensible. Nevertheless, the thrill to “go supersonic” prevails and research effort and money are still being invested into the topic. Yet the focus shifts from airliners to supersonic business jets (SSBJ) and the niche of high-net-worth individuals. It is especially attractive for executives and VIPs because of prestige, convenience, comfort and the reduction of travel time. *“This listing does not claim to be complete; however, these parameters could result in an increase of corporate productivity, hence justifying supersonic business travel. The sonic boom, noise at take-off and landing, high fuel consumption, and resulting emissions are seen as critical issues for supersonic operations”* (Schuermann et al., 2015). Advances in engine technology and airframe design help to find adequate answers for the ecological and technical challenges that are related to supersonic flight. Since these issues are strongly related to the aircraft’s size, an aircraft of the size of a business jet can be seen as a good starting point into practical supersonic flight. *“Recent market research has revealed that a significant number of premium passengers are willing to change to supersonic service”* (Schuermann et al., 2015). It has been shown that supersonic aircraft of the size of a business jet may seem to find a



## 1 Introduction

market (Henne (2005); Liebhardt & Lütjens (2011); Liebhardt et al. (2011)). The book by Davies (1998) should not be left unmentioned here as a document of critical thinking on the issue.

The aim of this thesis is to introduce methods and methodologies to aircraft conceptual and preliminary design that allow to judge supersonic aircraft concepts. The aim of this thesis is NOT the design of an optimized aircraft for a given task! Therefore, the Preliminary Aircraft Design and Optimisation tool (PrADO) of the Technische Universität Braunschweig, Germany, is extended to suit this purpose. The focus lies on the introduction of an inviscid flow solver to obtain aerodynamic data and finite element analysis to provide means to assess structural weight. Thoughts and ideas on the principle of fully stressed design and on the sizing of structures built from composite materials are being developed and discussed.

### 1.2 Research Efforts and Existing Supersonic Projects

A great deal of research effort has been put into the investigation of commercial supersonic flight over the last decades, with concepts of supersonic business jets dating back into the late 1990's. "*Mavris & Hayden (1996) present results from a conceptual design study for a supersonic business jet serving the Pacific Rim. The results are obtained by applying the response surface methodology and design of experiments. The resulting cruise speed is Mach 2.0 with a cruise range of 3160 nautical miles*" (Schuermann et al., 2015). A different approach is proposed by Chudoba et al. (2008, 2009). They establish the hypothesis that the conversion of an existing airframe will lead to a reduction of production and purchase costs. The set of papers includes a market study and a feasibility study. The authors' goal is to be "*first in the market*" rather than providing a high technology aircraft. It is concluded that such approach is feasible, however Chudoba et al. (2009) state that "*the overall design suffers from operational limitations which are expected to severely reduce its market penetration potential*". Other publications focus on issues that are generally of importance for a supersonic business jet and commercial supersonic flight. Notably these are emissions as pointed out e.g. by Grewe (2007), the noise of the sonic boom and general aircraft noise as outlined by, e.g., Simmons & Freund (2005), Aronstein & Schueler (2004) or Mack (2003).

*"Two prominent commercial projects linked to supersonic business travel are driven by the Aerion cooperation and by SAI (Supersonic Aerospace International). Both companies are based in the United States. The Aerion configuration aims at transporting up to twelve passengers in a comfortable cabin arrangement over a range greater than 4000 nautical miles (transatlantic capability) at a cruise speed of Mach 1.6. Its key technology is a Natural Laminar Flow (NLF) wing. A Pratt & Whitney JT8D-200 engine has been chosen to power the 41-ton (90000 lb) take-off weight jet"* (Schuermann et al., 2015). The aim is to comply with modern noise regula-



tions. Wind tunnel testing and in-flight testing of components have been conducted according to Aerion (2013).

The SAI design has been developed in cooperation with Lockheed Martin. It is a “low-boom design”, which in this case means that the sonic overpressure is not higher than 24 Pa (0.5 psf). Extensive feasibility studies have been conducted, including in-flight testing of sonic boom mitigation methods. Range and payload characteristics are similar to that of the Aerion jet. SAI (2013) and Paulson (2013, 2007) give insight into the projects.

*“In addition, the European research project HISAC (environmentally friendly High Speed AirCRAFT) lead by Dassault Aviation has been launched within the sixth Framework Programme of the European Union”* (Schuermann et al., 2015). According to Stoufflet et al. (2008), the HISAC project’s aim was to establish *“the technical feasibility of an environmentally friendly supersonic business jet . . . ”*. The project incorporated three different aircraft configurations, a “low-noise”, “long-range” and “low-boom” arrangement. *“Its mission characteristics are similar to the ones mentioned above. Herrmann and Laban published two conference papers regarding the subject of multidisciplinary optimization applied to small supersonic aircraft”* (Schuermann et al., 2015). The first paper (Laban & Herrmann, 2007) focusses on the multidisciplinary framework, whereas the second paper (Herrmann & Laban, 2007) presents the results. The authors optimize a wing exposed to a single load case with results being fed back into the overall design loop. Their work is related to the HISAC project. Brezillon et al. (2011) present results with regard to low-boom considerations that are linked to the HISAC project. A good overview on the emergence of supersonic business travel is provided by Wiley (2007). Liebhardt et al. (2013) put some effort into the routing of supersonic aircraft to satisfy noise and supersonic boom regulations.

### 1.3 Thesis Outline

The concept of multidisciplinary aircraft design is outlined in Chapter 2. Chapter 3 presents the relevant theoretical aspects, providing the necessary background for the upcoming considerations and investigations. The focus is put on aerodynamics, structural mechanics and propulsion since these are the major disciplines on which work has been done and the author’s ideas and suggestions are developed. The content of Chapter 4 gives insight into modelling aspects, explaining how the discussed theories are put to use. Verification examples are given in Chapter 5 and the field of temperature in supersonic flight is briefly discussed as an excursion in Chapter 6. All previous efforts are used to finally design a supersonic business jet, portrayed in Chapter 7. In Chapter 8 the thesis is summarized, conclusions are drawn and suggestions on future work are made.

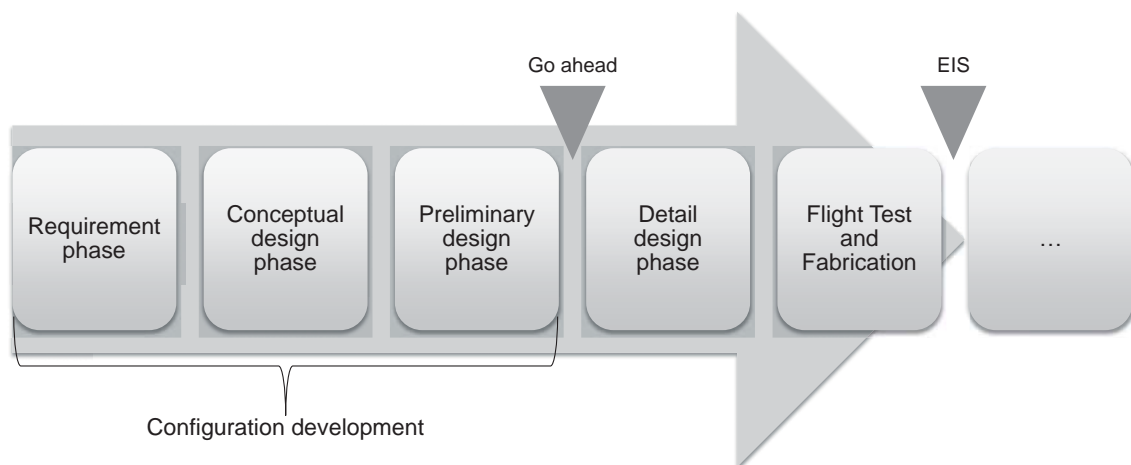


## 2 Multidisciplinary Aircraft Design

The multidisciplinary aircraft design process is outlined in this chapter. Special emphasis is put on the conceptual and preliminary design phase in Section 2.1, since this is the context within which the author's work is carried out. Furthermore, an overview of existing aircraft design tools is given in Section 2.2 and the herein used Preliminary Aircraft Design and Optimisation tool (PrADO) is introduced in Section 2.3.

### 2.1 The Aircraft Design Process

The development of a product beginning with the idea, advancing further to its market entry and finally to its end of life can be subdivided into multiple phases. Figure 2.1 shows such a very simplistic scheme for an aircraft, where it should be noted that phases taking place after the “entry into service” (EIS) are not shown.



**Figure 2.1:** Basic outline of the aircraft design process

At the very beginning of the product development process, the question arises of what are the requirements to create a successful product. In the so-called *requirement phase*, data from market analysis resulting in a thorough description of customers needs is used to write a product definition. Furthermore, the requirement list is supplemented by technical constraints and regulations.

The *conceptual design phase* is initiated after successful completion of the requirement phase. This process is highly creative as solutions of any kind are considered. Thus, the impact of key technologies on the design is determined and the assessment of technological and economical risks is a vital part of the process. Analysis is usually



## 2 Multidisciplinary Aircraft Design

done by the means of statistical methods, handbook methods and existing know-how. The number of input parameters is limited to a few. The investigated designs are ranked by their compliance with the list of requirements, technical feasibility is judged and economic aspects are reviewed. Based on the results of this process, a desired solution is selected for further investigation. The outer shape of the aircraft is fixed at the end of the conceptual design phase, that is, the arrangement of its components is decided on, and key technologies are selected.

The designs being selected at the end of the conceptual design phase provide the starting point to proceed into the *preliminary design phase*. In this phase of the process, the level of detail is increased and methods of higher accuracy, often based on physics, are applied during analysis. Wind tunnel and structural tests provide input to increase accuracy. Here again, risks are assessed. At the end of the preliminary design phase, a detailed set of data for the design is available, providing a sound basis for a possible realization of the project. After completion of this phase the management will decide whether to pursue (“go ahead”) or stop the project. If the decision is positive, the aircraft will be offered for sale and the *detailed design phase* will be launched. The goal of the detailed design phase is to design the aircraft for production, hence manufacturing drawings of every single part will finally be available and the manufacturing processes will be implemented. In the end, flight testing is carried out and after successful certification by the authorities, the aircraft enters service (EIS) with the customers.

The above text suggests that the design process is rather rigid and sequential. However, the contrary is true. The process is highly dynamic, iterative and the described phases overlap. Some remarks regarding the time line shall be made. The time between “go ahead” and certification is between four and six years for commercial transport aircraft. Torenbeek (2013) groups the requirement phase, the conceptual design phase and the preliminary design phase into a *configuration phase*. This phase takes two to five years prior to “go ahead”. A note from above is valid in this context as well: The process is dynamic and varies depending on the company and the type of aircraft.

At this point the impression could arise that the described process is applicable to a “clean sheet design” only, that is, the product is designed from scratch. This must not necessarily be the case. The described phases are also applied to advance an existing product. Accordingly, the processes and methods of the configuration phase are used to evaluate the impact of technology changes and other modifications on existing aircraft. If they are selected, such modifications are then designed in detail, introduced to production and finally offered to the customer as a derivative of the original product. Recent examples are the Airbus A320neo and Boeing’s 737MAX.

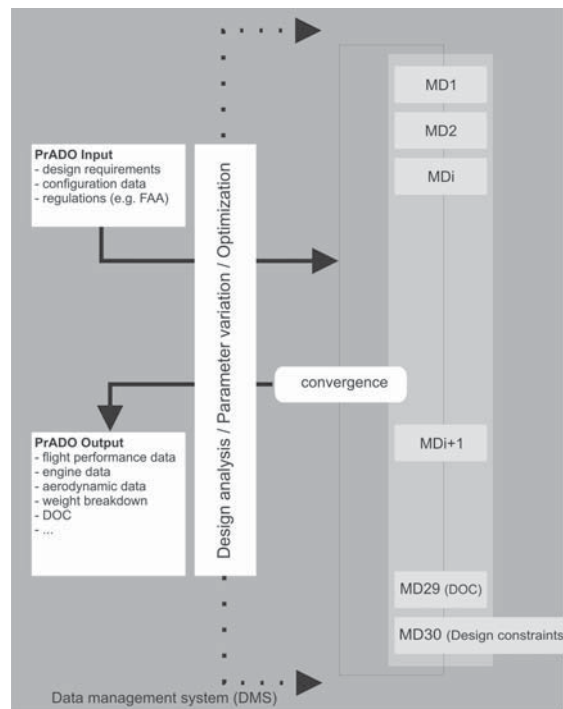
The author suggests the following textbooks, on which the above text is based, to be consulted for further information and studies: Gudmundsson (2013), Torenbeek (2013), Howe (2000), Roskam (1989b,a, 1990b,a, 1991, 1997c,b,a).

## 2.2 Aircraft Design Tools at a Glance

The availability of computer systems laid the foundation for software development encompassing the phase of configuration development in aircraft design. Such automated design synthesis systems aim at enabling designers to evaluate a higher number of configurations at a given time. Secondly such systems make the topic of parameter variation and optimization available in configuration development. At the bottom line automated design synthesis programs help to achieve more credible predictions and hence to reduce development risk. The listing in Table B.1 gives an overview of the tools applied in conceptual and preliminary aircraft design, although it does not claim to be exhaustive. For detailed information, the specified literature is to be consulted. Most of the programs originate in academia or are provided by consultancy firms. Information on programs used by aircraft manufacturers is not available to the author. This is reasonable, since such programs contain the expertise and proprietary information of a company. All automated design synthesis systems have in common, that the workflow of the conceptual and preliminary design phases is modelled. Differences are made as to how and up to which level of detail this is done. Programs which mainly use textbook-based methods are e.g. CAPDA, FLOPS, PASS, PIANO, PreSTo and RDS. These tools only require a limited number of input parameters, which is advantageous when exploring a larger design space. Programs which access physics-based methods are, e.g., AAA, ACSYNT, AIDA, CDS, CEASION, MICADO, PrADO and pyACDT. Such systems are commonly used within the preliminary design phase, because of their higher demand of analysis time and input parameters, as compared to the previously mentioned programs.

## 2.3 PrADO - An Aircraft Design and Optimisation Environment

As mentioned above, PrADO (Preliminary Aircraft Design and Optimisation tool) will be used for this work. PrADO is an in-house program of the Institute of Aircraft Design and Lightweight Structures, TU Braunschweig, which covers a wide range of aspects of aircraft preliminary design. The development of PrADO started in the late 1980's and has been continued ever since. In order to work with PrADO, an initial aircraft concept is required. This concept serves as a basis for various modules to calculate all relevant data to assess the design's quality. As a result, an aircraft description, its performance data and properties are obtained. PrADO features three analysis modes: single design analysis, multi parameter variation, and multi-parameter optimization. The basic concept of the program is outlined in Figure 2.2. In order to obtain viable results PrADO has to be configured by the user. The most important decision is to select appropriate analysis methods for each step of the design chain. PrADO therefore contains various modules, marked MDI in Figure 2.2, each of which is designated to fulfil one special task e.g. aerodynamic analysis, estimation of structural mass, mission analysis to estimate fuel masses, etc.



**Figure 2.2:** Basic concept of PrADO

The available methods grouped within those modules range from statistical methods to physics based models. From an aircraft developers point of view PrADO is used within both, the conceptual and the preliminary design phase.

The modular structure of the software allows for the fast integration of additional methods which is beneficial for the work presented here. The following sections contain more detailed expatiations of the aerodynamic module, the structural analysis module and the propulsion module, because the work presented in this thesis focuses on adaptations to them. For further information the author refers to Heinze (1994), Heinze et al. (2001), Österheld et al. (2001) and Hansen et al. (2008).

### 2.3.1 The Aerodynamic Module

The aim of the aerodynamic module is to provide aerodynamic data for the aircraft design process. A basic input to the module is the parametric geometry description provided by the geometry modules of PrADO. Four aerodynamic settings are being analysed. These are a take-off, a cruise, an approach and a landing configuration. The calculated data is fed back into the design process with the help of an aerodynamic performance map and hence available to other modules. The methods currently used for aerodynamic analysis are based on the potential theory. The LIFTING LINE code (cf. Horstmann, 1987), which is based on the lifting-line theory and HISSS (cf. Fornasier, 1985), a panel code, are in use and give results of adequate accuracy for the preliminary design process provided that the flow is



## 2.3 PrADO - An Aircraft Design and Optimisation Environment

mainly attached and subsonic. A higher-fidelity method for aerodynamic data prediction is proposed here which uses the German Aerospace Center's (DLR) CFD code TAU (cf. Schwamborn et al., 2006) to solve the inviscid Euler equations. This has the advantage of being valid for a wide range of Mach numbers (sub-, trans- and supersonic) and geometries and to provide increased accuracy for complex flow problems (e.g. vortical flows). Details on the method were previously published by the author (cf. Schuermann et al., 2014). Viscous drag is estimated by handbook methods.

### 2.3.2 The Structural Analysis Module

Österheld (2003) states that the masses of the load bearing structure accounts for up to 65% of an aircraft's operational empty mass (weight). Consequently, the provision of reliable methods for the estimation of the structural mass of an aircraft is the main intention of the structural analysis module. PrADO provides statistical and semi-empirical methods for this purpose. On the other hand analytical beam-stick models and a finite element process are available. The available structural analysis module, SAM, provides a finite element model and is taken as a starting point in this thesis to develop the SAM2 module. In contrast to SAM, SAM2 implements the parametric geometry description delivered by PrADO more strictly. Furthermore, the discretisation level of the model can be influenced, which requires the use of shell and beam elements accordingly (cf. 4.2). Additionally, the distribution of secondary mass, fuel loading and payload distributions are taken directly from the respective PrADO modules. Loads for ground cases and trimmed flight cases are taken from the PrADO database, whereas the aerodynamic loads are calculated by solving the inviscid Euler equations. The model generation process is implemented into a multi-model generator (MMG). Structural sizing is performed by a newly developed structural sizing module (SSM) which provides various sizing routines and calculates mass and centre of gravity information.

### 2.3.3 The Propulsion Module

The purpose of the propulsion module is threefold. Firstly, the engine is designed on the basis of given input data (on design). Secondly, an engine performance map is calculated (off design) and thirdly the available thrust is compared with the required thrust. The first and the second steps are carried out either by reading from a fixed data set or by thermodynamic cycle analysis. The results are available to other modules at any stage of the design process. PrADO provides various models for the analysis of turbojet, turbofan and turboprop engines. The work presented here uses a newly implemented cycle for a turbofan engine with mixed exhaust flow based on Mattingly et al. (1987) and detailed, in Chapter 3.3.

