Cost Optimization of Aircraft Structures

MARKUS KAUFMANN

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Optimization is intrinsically tied to our desire to excel, whether we are an athlete, artist or engineer.

Garret N. Vanderplaats [1]
Acknowledgments

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"Why Sweden?" I’ve been asked many times during the last four years. Well, I’ll never forget my professor’s words while he showed me corrugated sandwich structures six years ago. "Plastic’s fantastic!" – Dan, the idea of designing exceptional things with an exceptional material was one of the reasons to follow your invitation and pursue a PhD under your guidance. You and my co-advisor Malin Åkermo were a constant source of enthusiasm, inspiration and motivation.

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Markus Kaufmann

Stockholm in 2009
Abstract

Composite structures can lower the weight of an airliner significantly. Due to the higher process complexity and the high material cost, however, the low weight often comes with a significant increase in production cost. The application of cost-effective design strategies is one mean to meet this challenge.

In this thesis, a simplified form of direct operating cost is suggested as a comparative value that in combination with multidisciplinary optimization enables the evaluation of a design solution in terms of cost and weight. The proposed cost optimization framework takes into account the manufacturing cost, the non-destructive testing cost and the lifetime fuel consumption based on the weight of the aircraft, thus using a simplified version of the direct operating cost as the objective function. The manufacturing cost can be estimated by means of different techniques. For the proposed optimization framework, feature-based parametric cost models prove to be most suitable.

Paper A contains a parametric study in which a skin/stringer panel is optimized for a series of cost/weight ratios (weight penalties) and material configurations. The weight penalty (defined as the specific lifetime fuel burn) is dependent on the fuel consumption of the aircraft, the fuel price and the viewpoint of the optimizer. It is concluded that the ideal choice of the design solution is neither low-cost nor low-weight but rather a combination thereof.

Paper B proposes the inclusion of non-destructive testing cost in the design process of composite components, and the adjustment of the design strength of each laminate according to inspection parameters. Hence, the scan pitch of the ultrasonic testing is regarded as a variable, representing an index for the guaranteed material quality. It is shown that the cost for non-destructive testing can be lowered if the quality level of the laminate is assigned and adjusted in an early design stage.

In Paper C and Paper D the parameters of the manufacturing processes are upgraded during the cost optimization of the component. In Paper C, the framework is extended by the cost-efficient adaptation of parameters in order to reflect the situation when machining an aluminum component. For different weight penalties, the spar thickness and stringer geometry of the provided case study vary. In addition, another cutter is chosen with regard to the modified shape of the stringer. In Paper D, the methodology is extended to the draping of composite fabrics, thus optimizing not only the stacking layup, but also the draping strategy itself. As in the previous cases, the design alters for different settings of the weight penalty. In particular, one can see a distinct change in fiber layup between the minimum weight and the minimum cost solution.

Paper E summarizes the work proposed in Papers A-D and provides a case study on a C-spar component. Five material systems are used for this case study and compared in terms of cost and weight. The case study shows the impact of the weight penalty, the material cost and the labor rate on the choice of the material system. For low weight penalties, for example, the aluminum spar is the most cost-effective solution. For high weight penalties, the RTM system is favorable. The paper also discusses shortcomings with the presented methodology and thereby opens up for future method developments.
Dissertation

This doctoral thesis is based on an introduction to the area of research and the following appended papers:

Paper A

Paper B

Paper C

Paper D

Paper E
Parts of this thesis have also been presented as follows:


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Part I

Introduction
1 Background

"In a switch that could make Airbus’s next jetliner more competitive with rival Boeing Co.’s new 787 Dreamliner, the European plane maker plans to build the frame of its planned A350 model from advanced composite materials instead of metal. The lighter structure – similar to that of the Boeing plane – reduces fuel consumption, increases a plane’s range and reduces wear on key parts such as landing gear. The shift also cuts the need for costly maintenance inspections. […]"

This article, published by the Wall Street Journal on Saturday, September 15, 2007, summarizes the achievements in the field of aerospace structures over the last couple of years. Material configurations are undergoing a change from metals to composites, thus lowering the structural weight and avoiding fatigue and corrosion. No cost aspects, however, are mentioned in the article. How much more does the composite version cost compared to the metallic baseline? And how far could an increase in manufacturing cost be motivated by the saving of weight?

![Airbus A350](image)

**Figure 1.1:** Airbus A350
The aircraft market’s competition forces the airline operators to save costs. Hence, efforts are made to lower acquisition and operating costs. One possibility to lower the latter is to reduce the fuel consumption of the aircraft. In Figure 1.2, the development of the price for A1 jet fuel since the year 2000 is shown. As can be seen, the fuel price quickly quadrupled in 2008 before returning to a level roughly twice the price of 2000. Thus, the aircraft manufacturers are pushed even more to design products with lower fuel consumption. But is there a way to balance these low-weight and low-cost design objectives?

A first estimation of the impact of the structural weight on the lifetime fuel consumption can be made by means of a simple fuel burn calculation. According to Scandinavian Airlines, an airliner in the A330 class with 260 seats and a take-off weight of 233 tonnes typically consumes 0.035 l/seat/km. Let us assume that the average gross weight is about 200 tonnes and that the aircraft flies for 25 years, 300 days/year a range of 2\cdot7000\text{ km/day}. Thus, the total flown distance in the life of the plane is estimated to be 100 million km. With the above fuel consumption and passenger utilization, the total life fuel consumption is 1 billion liters of jet fuel or about 5000 liter per kilogram flight mass. At a fuel price of about €0.40/l (or US$ 740/metric tonne), the lifetime fuel cost per kilogram gross weight is €2000/kg aircraft.

This calculation is made for the average gross weight of an aircraft. The airframe weight is only 20-30% of the gross weight. Thus, one can expect the monetary impact of structural weight savings to be even higher, as any weight savings during the very early design phases can be looped back through the whole aircraft design process: any weight saving is also accompanied by the use of smaller engines or smaller wings. As a consequence, the net savings in aircraft take-off weight is much greater than the weight saved on the structure alone.

Figure 1.2: Development of the price for A1 Jet fuel since 2000
(Data provided by Nordea Bank AB)
We could change the design objectives and consider a possible increase in revenue instead of the fuel saving. Assuming an aircraft with one transatlantic return trip a day, 300 days a year for 25 years and a ticket price of €500 would result in a revenue of €3’750’000 per chair. If we further assume that 125 kg weight saving is needed per additional passenger, a total of €30’000 could potentially be earned per kilogram structure.

A lot of work has been performed in the field of pure weight optimization. The application of a lifetime cost per kilogram airframe structure, however, provides us with a tool to include cost and weight in the optimization of aircraft structures.

Gutowski et al. described the composite’s drawbacks already back in 1991 [2]. The cost of the composite raw material is roughly ten times the cost of aluminum. The material cost, however, reflects only a small part of the total cost of the final product. First, the labor cost to manufacture a composite component is much higher than for a comparable metal part. Second, the production of composite components brings a need for an extensive quality management and rigorous non-destructive testing. Third, the increased design complexity comes with an increase in development cost.

These risks were also identified by Rais-Rohani and Dean [3]. According to them, the high material, fabrication and tooling costs may make the use of high-performance materials cost-ineffective. Thus, the costs of raw materials, tooling, fabrication, assembly, scrap, repair, certification and environmental factors should be included in the design of composite structures. Sobieszczanski-Sobieski and Haftka observed an absence of cost optimization frameworks for composite components [4]. Soutis pointed out that early composite designs were “replicas of those that employed metallic materials” from the 40s, as most composite parts were manufactured with expensive hand-laid carbon epoxy prepregs using quasi-isotropic stacking sequences. According to the authors “the high material cost and man-hour-intensive laminate production jeopardized their acceptance” [5].

In this thesis, a framework for the cost optimization of aircraft structures is proposed. In Chapter 2, the three phases in the structural design of aircrafts are presented. Chapter 3 introduces the field of multidisciplinary design optimization. By means of a literature survey, existing cost/weight optimization frameworks and their differences are presented. Chapter 4 deals with the definition of direct operating cost and the estimation of manufacturing cost, followed by an overview of composite forming in Chapter 5. Finally, an introduction to the proposed optimization framework and the appended papers is given, followed by a short discussion and the identification of possible future work.
2 Structural Design of Aircrafts

2.1 Design Phases

The design of aircrafts can roughly be divided into three design phases, the conceptual design phase, the preliminary design phase and the detail design phase. They all have a distinctive multidisciplinary character, the result being a tradeoff made by all stakeholders.

Conceptual Design

In the conceptual design phase, numerous design alternatives are compared and evaluated, based on cost/weight/passenger/range tradeoff studies. The result is an initial aerodynamics and propulsion concept, including overall dimensions, weights and global loads.

Preliminary Design

In the preliminary design phase, a global finite element model is built up from which local loads and loading conditions are derived. An illustration of typical loads on an airliner is given in Figure 2.1. As can be seen, aeroelastic loads such as tensile, compressive and torsional loads in wing, fuselage and empennage represent only a fraction of the load cases the structural engineers have to consider. Other loads arise from the cabin pressure (hoop stress), bird strike or impact loads on the tail. Very high local stresses can be found in the landing gear ribs, the sidestay fittings and the pylon structure.

The task of the structural engineers is the design of the inner structure of the aircraft. The design is constrained by the aerodynamic configuration. It has to withstand all loads and should be as light as possible. Different levels of detail are investigated in the preliminary design phase, see Figure 2.2. First, the structural arrangement of the major parts, such as ribs and spars in the wing and lap joints and butt joints in the fuselage are defined. Then, the structure is designed on a panel level. The strength and stiffness of the structural members are defined and verified by means of finite element models, while changes in the configuration (e.g. stiffener distance, flange type, rib stiffeners, etc.) are still possible. According to Assler [6], the design process is influenced by a variety of factors at this stage. Examples are
- Airworthiness regulations
- Environmental considerations
- General aircraft requirements (operational profile, maintenance, etc.)
- Specific requirements for structural details
- Available materials and technologies
- Manufacturing capacities and capabilities
- Non-destructive testing and investigation capabilities
- Design cost

Detail Design

In the detail design phase, the structure is analyzed by means of high-fidelity models, and the fabrication, tooling and assembly processes are defined. The result is a detailed work breakdown structure including all structural parts, mounting, bolts and rivets, clips, doors, brackets, etc. Each part has to fulfill its particular requirements, based on structural failure, fatigue, corrosion resistance, lightning strike, sealing, conduction, maintenance or testing.

2.2 System Integration

As the development of a new aircraft type involves great cost and – in turn – a great financial risk, aircrafts are not designed, fabricated and assembled by one single manufacturer anymore; the latter have been replaced by consortiums of system integrators and suppliers. In Figure 2.3, the supply hierarchy in the commercial aerospace industry is shown.

On top of the supply pyramid, a system integrator (e.g. Boeing or Airbus) is responsible for the coordination, the overall design and the final assembly of the
aircraft. In a subordinate position, other members of the consortium take part in
the development of sub-systems (such as wing structures), its manufacturing, sub-
assembly and delivery. Further down in the hierarchy are equipment and component
suppliers. They do not take part in the design process and are restricted to the
manufacturing and delivery of components. Estimated profit margins are the highest
in the top position of the pyramid and – according to Johansen et al. [7] – the higher
the position in the hierarchy, the greater the risk for that company in the overall
project.

The embedding of a sub system supplier (e.g. Saab, Bombardier or Alenia)
occurs in the conceptual design phase, sometimes already within pre-development or
research projects. The benefits of this approach are the early exchange of knowledge
and experience, and a good integration of the otherwise widespread design teams.
As the risks are shared, each of the partners are under pressure to continuously
increase the efficiency in terms of low cost, low weight and producibility. The
main drawbacks mentioned in [7] are communication problems across the company
borders, such as cultural differences, hierarchical misunderstandings and delayed
information flows. Further mentioned is the need for an extensive product lifecycle management database (PLM). In the case of the A380, the PLM is used by more than 5000 engineers and contains more than 3000 CAD drawings of about 150’000 parts.

2.3 Design of Composite Structures

As mentioned, the fuel consumption stands for a considerable part of the operating cost of an airliner. As shown in Jacobsen [8], the fuel cost can be reduced by developing more efficient engines, by minimizing the aerodynamic drag, by optimizing the flight trajectory of the aircraft and by reducing its mass. The latter was the main motive to change from metals to composite materials, and the portion of composite materials of the total structural weight is continuously increasing in commercial airliners, see Figure 2.4.

The first application of composites to commercial aircrafts were radar domes in 1940. Since then, composite materials have increasingly replaced their metallic counterparts. In 1975, NASA developed a series of composite parts for research purposes, and the elevators of the B727 and B737 and the vertical fin of the DC10 were redesigned. Secondary structures (e.g. the leading edge, trailing edge, flaps, ailerons and rudder) were made of carbon fibers in the Boeing 777, and with the center wing box of the A380, composites were used also for primary (load-carrying) structures. The latter enabled weight savings of 1500 kg compared to the aluminum baseline, see Marsh [9].

A comparison of the specific strengths and stiffnesses is presented in Figure 2.5. As can be seen, the specific strength of carbon fiber reinforced plastic is much higher than for aluminum or titanium, whereas the specific moduli are approximately the
same. A composite component that is designed for stiffness will therefore have a higher safety factor against material failure than its metallic counterpart. This characteristic accounts for the good fatigue behavior of composites, cutting down the maintenance cost for the airlines. Another advantage is the possibility to tailor composites specifically to a desired function. This is done by either adjusting the fiber angle distribution or by unifying the geometry and thus reducing the number of parts.

![Graph showing specific strengths and stiffnesses](image)

**Figure 2.5:** Specific strengths and stiffnesses of different metals and alloys, quasi-isotropic glass fiber reinforced plastic (Glass/QI) and quasi-isotropic carbon fiber reinforced plastic (Carbon/QI)

### 2.4 Constraints and Allowables

The structure has to withstand anticipated external loads. For composites loaded in tension, material failure might be the limiting constraint. For composites loaded in compression, material failure and stability concerns form the topology of the structure. The situations under which the integrity of the structure needs to be proved are described in regulations published by the aviation authorities. Structural constraints, for example, are based on the airworthiness requirements, defined in JAR 25.613 *Material Strength Properties and Design Values*. This document is released by the Joint Aviation Authorities\(^1\), a European body representing the civil aviation regulatory authorities of a number of European states. Similar regulations exist also in the United States (FAR). Therefore it is often referred to the FAR/JAR regulations.

The determination of an allowable stress and strain limit is based on statistical evaluation of specimen tests. A typical design strength, for instance, is the stress level where at least 90% of the population pass with a confidence of 95%. These

\(^1\)http://www.jaat.eu
tests have to be performed for filled or unfilled holes, as stress concentrations around fastener and bolt holes can be the cause for material failure. The test phase can include up to 4000 coupons to generate complete data for a certification program, see Niu [10].

A composite laminate can fail by different modes, e.g. by fiber failure, microbuckling, matrix failure or fiber/matrix debonding. Other effects are delaminations due to pull-off loads, free-edge effects, poisson’s ratio mismatch or compressive buckling. Therefore, most engineers (and aeronautical engineers in particular) tend to use rather conservative failure criteria.

Unlike metal structures, composite structures are limited by strain and not by stress concerns. The strain limits of composite laminates are only indirectly related to the strain levels of the matrix or the fibers; it is rather a design strain based on coupon tests. One of the limiting load cases of coupon tests is the compression after impact test, simulating prior damage from tool drops and runway debris. There, the remaining compressive failure strain of a damaged composite panel is evaluated. Typically, values around 0.4% are obtained which is much lower than for unnotched coupons.

Albeit not being the most elaborate failure theory, the maximum strain criterion is still widely used in the aerospace industry. The maximum strain criterion is given as three independent sub-criteria

\[
\hat{\varepsilon}_{1,c} < \varepsilon_1 < \hat{\varepsilon}_{1,t} \\
\hat{\varepsilon}_{2,c} < \varepsilon_2 < \hat{\varepsilon}_{2,t} \quad \text{and} \\
|\gamma_{12}| < \hat{\gamma}_{12}. 
\]

The indices \(c\) and \(t\) denote compression and tension, respectively; 1 and 2 denote the ply’s longitudinal and transversal direction, and \(\hat{\cdot}\) denotes the allowable strain value.

Apart from material failure, the design of composite laminates is governed by a series of other rules. Examples given are the requirement for symmetrical stacking, a minimum amount of 10% of each ply angle, or the location of fiber splits. Aircraft engineers maintain a stacking sequence consisting of 0\(^\circ\), 90\(^\circ\) and ±45\(^\circ\) plies. Although there exist stacking sequences that allow a significant weight reduction, certification issues prevent their use yet.

### 2.5 Non-Destructive Testing

The Federal Aviation Administration’s regulations of airworthiness require the quality assurance of each assembled part. Unlike metallic structures, composite parts are fabricated \textit{in-situ} and the grade of these structures is highly dependent on process robustness and workmen skills. Typical manufacturing generated defects in composites are voids, porosity, fiber misalignment, wrinkling, poor cure, resin-rich or resin-poor areas, forgotten release papers and low-quality adhesive bonds. Therefore, each composite part undergoes rigorous non-destructive testing (NDT) prior to the assembly.
For metallic and composite aircraft structures, NDT is also part of the damage tolerance concept. Micro-cracks are basically tolerated under the condition that the airliner is regularly checked for structural integrity (continuous monitoring and sufficiently slow growth of cracks). In so-called D checks, complete overhauls at six to ten years intervals, the paint is removed and cracks or delaminations are sought. Apart from these regular checks, the integrity is also tested after bird strikes, hard landings or similar incidents. All these inspections are very costly due to the downtime of the aircraft.

Ultrasonic Methods

Due to the nature of composite structures, flaws can occur in monolithic structures (porosity, delamination, cracks), the adhesive layers (debondings), or sandwich cores (density irregularities, cracks). While flaws in the outer skin can be detected with single-sided access, the underlaying defects often need through-transmission scanning. Thick structures are generally more difficult to test than thin structures.

The most common method for the inspection of aircraft structures is ultrasonic testing (UT). There, a transducer is passed over the area being tested. Ultrasonic waves penetrate the structure, while the receiver records the reflected (pulse-echo mode) or the transmitted (through-transmission mode) sound waves, see Figure 2.6. The screen on the diagnostic machine will show these results in the form of amplitude and pulse readings, as well as the time of flight.

![Ultrasonic test setup in through-transmission mode](image)

The presentation of the amplitude of the wave as a function of time (the so-called A-scan) is sufficient for manual detection of flaws. Scanning along a given route leads to the B-scan presentation with the in-depth position of the flaw as a function of scan distance and time of flight. The C-scan in turn represents an areal defect image of the scanned part by scanning a 2D-pattern, while the D-scan combines the in-depth information of the B-scan with the C-scan. In Figure 2.7, the procedure to obtain a C-scan is shown. The density of the scan pattern (separated by the distance later referred to as the scan pitch) determines the size of the detectable flaws.
The advantage of UT is the high sensitivity, permitting detection of extremely small flaws. The penetrating power of UT is higher than for other methods, thus allowing detection of flaws deeper in the part. Unfortunately, damping effects of local inhomogeneities of composite structures (e.g. due to stacked prepregs) reduce the reflected energy significantly. Thus, the resolution of a C-scan is very much dependent on the material system, the porosity level and the thickness.

Thick structures are difficult to inspect due to high damping characteristics and high structural noise. While air-coupled ultrasonic is possible in principle, this is restricted to through-transmission mode. For pulse-echo testing, improvements are still necessary, and water is therefore still common as the coupling medium between the probe and the specimen.

Referring to the literature, the design of composite structures has not been influenced by NDT aspects. In order to capture the full life cycle of a composite component, however, NDT should play a role in an early design phase. Therefore, a methodology was developed that included the parameters of the in-production and in-service testing in the design process. Hence, the scan distance of the ultrasonic C-scan was introduced as a variable in the design optimization. In a feature-based model, the NDT cost was calculated from the scan distance (the scan pitch). Further, the design allowables of the laminate were adapted, since the scan pitch had a direct influence on the detectable flaw size. This methodology is presented in Paper B.
3 Design Optimization

Product design is a process where ideas are generated and screened, and concepts are formulated, rephrased and rejected. This solution-finding process is iterative and – in a wider sense – an optimization process. The former methods of trial and testing, however, have been replaced more and more by abstract models. In the field of aeronautics, such models can include flow models, cost models, structural models, models of the material properties, or dynamic flight models. Often, several models from different disciplines are necessary in order to represent the behavior and characteristics accurately enough. Most of the costs of the final product are defined in the conceptual design phase, and to neglect relevant design aspects in this phase would be disadvantageous. Hence, the goal of concurrent aerospace engineering is to gather knowledge from different disciplines by involving a multidisciplinary group of engineers in the design process. Examples of involved areas are fluid mechanics, statics and dynamics (engineering mechanics), mathematics, electrotechnology, propulsion, control engineering, aircraft structures, materials science, production engineering, aeroelasticity, avionics, risk and reliability, or noise control.

In recent years, attempts have been made to perform these design tasks simultaneously rather than sequentially. However, difficulties were encountered related to the large amount of data that had to be shared, as well as cultural and communicative problems between members of different fields or with different backgrounds. Another obstacle is often given by the company’s hierarchy: the information flow is not provided, hierarchical structures do not promote concurrent engineering and different departments are separated and distributed spatially.

One approach to incorporate the different disciplines in aircraft design into an automated design environment is the use of multidisciplinary design optimization (MDO). As shown in Figure 3.1, an MDO framework combines relevant design disciplines and runs the analysis tools simultaneously. Feedback is given to an optimization algorithm that calculates a new design solution by means of mathematical programming or stochastic search methods, and provides inputs for the next round of evaluation. These steps are repeated until the objective function, e.g. the weight of the part, is judged to be sufficiently minimized.

For an overview on MDO applications in the field of aerospace, it is referred to the review article written by Sobieszczanski-Sobieski and Haftka [4]. They concluded that most of the literature on multidisciplinary optimization covers the interaction
between aerodynamics and structures (see Raymer [12] and Bartholomew [13]) or shape parametrization techniques (see Samareh [14]).

Multidisciplinary design optimization frameworks are continuously being developed, see Samareh and Bhatia [15] and Townsend et al. [16]. For implementations like NASA’s FIDO\(^1\) project, requirements like an intuitive user interface, handling of a large problem size and support of collaborative design aspects were important. Salas and Townsend [17] described the requirements of such frameworks in detail.

A short review on cost considerations in multidisciplinary aircraft design was given by Rais-Rohani and Dean [3]. In 1996, they proposed that costs of raw materials, tooling, fabrication, assembly, scrap, repair, certification and environmental factors should be included in the design of composite structures. They motivated their reflection with former studies on the weight-to-cost relation of structures made of advanced materials which showed that the high material, fabrication and tooling costs may make the use of high performance materials cost-ineffective. According to that article, material and fabrication costs of composite structures are the key drivers and of comparable importance as the assembly and maintenance costs of metal structures.

\(^1\)Framework for Interdisciplinary Design Optimization
3.1 Multiobjective Optimization

The multiobjective optimization framework proposed in this work contains the optimization of different, often contradictive goals, such as low-cost and low-weight. Several ways to capture multiobjective design problems exist, see Marler and Arora [18]. Two or more objectives should lead to an optimal geometry. Therefore, they have to be incorporated mathematically into one objective function $F$. The multiobjective design problem is given as

$$
\min \quad F(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_n(x) \end{bmatrix}, \quad n \geq 2
$$

subject to

$$
\begin{align*}
    h(x) &= 0, \\
    g(x) &\leq 0, \\
    \underline{x} &\leq x \leq \bar{x}.
\end{align*}
$$

In our case, $f_1$ and $f_2$ represent the cost and the weight of a composite aircraft part. Stability and failure criteria are represented by the inequality constraint $g(x)$, whereas $\underline{x}$ and $\bar{x}$ are lower and upper limits of the variable vector $x$. An equality constraint $h(x)$ is optional and not used throughout this work.

Goal Programming

One approach to solve the problem above is referred to as goal programming. Goal programming uses one of the objectives as the objective function, whereas upper values (goals) are set for the other objectives. For example, one could implement a cost goal by setting an upper cost limit as a constraint to the optimization problem. This problem can be formulated as

$$
\min \quad \text{weight of a composite element}
$$

subject to

- prescribed load case
- maximum manufacturing cost.

On the other hand, one could do the reverse and optimize for cost only, while aiming for a prescribed structural performance (weight goal). This is given as

$$
\min \quad \text{cost of a composite element}
$$

subject to

- prescribed load case
- maximum weight.

Both formulations have the drawback that the target cost or the target weight has to be defined in advanced; being a one-shot technique, the goal has a great influence on the optimal solution, and a poor formulation could lead to inferior designs.
Multilevel Programming

Sometimes, the objectives can be ordered hierarchically in terms of importance. Hence, a top level objective function is defined and the set of points that minimize this first level objective is sought. In a second step, the set is reduced to the points that minimize the second level objective, and the method proceeds until the lowest level objective has been minimized. An example for multilevel optimization of aircraft structures is given by Gantois and Morris [19].

This work, however, deals with the tradeoff behavior of a combined cost/weight optimization. It is then not possible to order the two objectives, as they are on the same level and cannot be separated hierarchically. Thus, first weight, then cost or first cost, then weight approaches would not make sense here.

Pareto Optimality

A topic closely related to multiobjective optimization is Pareto optimality. Imagine a full search exploration of all possible designs of a structural part, e.g. the points given in Figure 3.2. Each design solution is represented by a variable set $x$, a manufacturing cost $f_1$ and a weight $f_2$. The points that constitute combinations of lowest cost and lowest weight are marked with cross symbols; they are called Pareto points.

A Pareto point is a point in the design space for which there is (a) no possible design solution with a lower weight and the same manufacturing cost or (b) no possible design with the same weight and a lower manufacturing cost. The curve that connects all Pareto points is called the Pareto frontier. The Pareto frontier is of great importance in multiobjective optimization, as it represents the tradeoff behavior of the two objectives. A lot of optimization algorithms deal with the generation of a complete Pareto frontier, thus providing a choice of possible solutions to the optimization problem. Two classes of optimization algorithms developed to perform this particular task are the Homotopy Techniques, see Watson and Haftka [20], and the Normal-Boundary Intersection, see Das and Dennis [21] and Huang et al. [22].
Minimizing Weighted Sums

More promising is an approach called *weighted sums* where two or more objectives are incorporated into one objective function and weighted by predefined parameters $\alpha_i$. These parameters represent the tradeoff between the objectives and result in a one-shot design solution. By varying $\alpha_i$, however, a range of solutions with different cost/weight tradeoffs can be obtained. The objective function is given as

$$F(x) = \sum_{i=1}^{n} \alpha_i f_i(x), \quad \alpha_i > 0, \quad i = 1, 2, \ldots, n.$$  \hspace{1cm} (3.4)

The approach of minimizing weighted sums is criticized by Das and Dennis [23], as the generation of evenly distributed Pareto points fails. However, in the case of a combined cost/weight optimization, one would use the parameters to establish a relationship between the manufacturing cost and the structural weight, and the generation of a Pareto frontier is not necessary. This approach is described in detail below, where this cost/weight relationship is called weight penalty, representing the "lifetime fuel burn cost per unit structural mass".

3.2 Weight Optimization

A lot of work has been done within the field of weight optimization. Representatively, the work of Kang and Kim [24] is mentioned, in which skin/stringer structures similar to those in Papers A and B of this thesis were weight-optimized. As a second example, Walker [25] studied the topology optimization of stiffened panels with different stiffener configurations. His aim was to maximize the buckling load for a given plate thickness by varying the ply angle of an angle-ply symmetric layup.

3.3 Integrated Cost/Weight Optimization

Research on cost optimization of aircraft structures started late, mainly due to the lack of sophisticated cost models. In 1997, Sobieszczanski-Sobieski and Haftka wrote "Very few instances can be found in which aerospace vehicle systems are optimized for their total performance, including cost" [4]. Since then, a lot of progress has been made. One of the earlier studies that integrated costing information into the design process was performed by Geiger and Dilts [26]. In 1996, they presented a conceptual model for an automated design-to-cost approach; the main aim was the provision of a framework that helped the structural engineer with the decision-making process. Heinmuller and Dilts applied this framework to the aerospace industry. They explained the design-to-cost concept as a tradeoff between operational capability, performance, schedule and cost. In 1997, they concluded that "enabling automated design-to-cost in a typical aerospace manufacturing company will be a difficult and time consuming process". The following ten years would confirm that they were right [27].
At Boeing, an approach for the life-cycle design of aircraft concepts was taken by Marx et al. [28]. Three material configurations for a wing of a high-speed civil transport aircraft were considered. It was concluded that lower operating cost could be achieved by a costly design with higher reliability (less maintenance, downtime, etc.), and – vice versa – that the lowest acquisition cost does not always signify the lowest life-cycle cost (LCC). As shown in Figure 3.3, the point depicted as Minimum Life Cycle Cost would be the best alternative for both the manufacturer and the airline. Marx et al. included R&D cost, manufacturing and sustaining costs, and revenue.

In 1999, Gantois presented a PhD thesis where manufacturing cost was taken into account for the multidisciplinary optimization of airliners [19]. The objective function was formed by weight and drag components, and a sub-level cost optimization was implemented in order to achieve the lowest manufacturing cost possible once the super-level goals were reached. The optimization was accomplished by a topological optimization (number of ribs, number of stiffeners).

At Rolls-Royce, it was observed that the traditional separation of an organization into a design and a cost department was a source of frustration and delay to the design process. Therefore, the Design Analysis Tool for Unit-cost Modeling (DATUM) project was launched in 2002. The aim was (a) an understanding of the current costing tools available on the market, (b) the development of an own costing tool that would support design decisions throughout the development process and (c) its application to an optimization framework. The DATUM project was described by Scanlan et al. [29].

Park et al. [30] pursued the optimization of structures considering mechanical performance and manufacturing cost. For the design of a resin-transfer-molded part, the stacking sequence of a composite plate was optimized in order to maximize the stiffness. Simultaneously, the mold filling time was minimized by changing the number and position of resin injection gates. They used a weighted sum approach with the displacement and the filling time as the two objectives.

Edke and Chang published a paper entitled “Shape optimization of heavy load carrying components for structural performance and manufacturing cost” in 2006 [31]. They presented a cost optimization framework that minimized the machining cost
of an aluminum torque tube subject to stress constraints. A Sequential Quadratic Programming method was chosen for the optimization of six design variables, and the objective function was formed by the material cost, the machining cost and the tooling cost. The machining times were estimated in a virtual machining model in Pro/MFG. The part weight, however, was not included in the formulation of objective function or constraints.

In 2007, Curran et al. proposed a method to include the manufacturing cost of a metallic skin/stringer panel in Dassault’s V5 platform [32]. The manufacturing cost was processed in MS Excel, whereas structural constraints were formed by means of closed-form solutions provided by the Engineering Sciences Data Unit (ESDU) [33]. This enabled cost optimization of metallic structures, automatic update of a CAD model and simulation of assembly processes.

Cost/Weight Objectives

As seen above, most research was performed on minimizing weight or manufacturing cost while maintaining a given structural performance (goal programming). When reduction of both cost and weight is sought, however, the two objectives have to be incorporated into one objective function.

Preparatory work was done by Kassapoglou [34–36]. First, stiffened composite panels were optimized separately for minimum cost \( C_{\text{min}} \) and minimum weight \( W_{\text{min}} \), and in a second step, the objective functions

\[
F(x) = \alpha_1 \frac{C - C_{\text{min}}}{C_{\text{min}}} + \alpha_2 \frac{W - W_{\text{min}}}{W_{\text{min}}}
\]

(3.5)

or

\[
F(x) = \sqrt{\alpha_1^2 \left( \frac{C - C_{\text{min}}}{C_{\text{min}}} \right)^2 + \alpha_2^2 \left( \frac{W - W_{\text{min}}}{W_{\text{min}}} \right)^2}
\]

(3.6)

were applied. Here, \( C \) and \( W \) represented the actual cost and weight in each iteration, respectively. The idea was resumed by Kelly and Wang [37] and Wang et al. [38]. They proposed a simplified objective function on the form

\[
F(x) = C + 500 \cdot W
\]

(3.7)

where $500/kg represented the ratio between cost and weight. This methodology was applied to the optimization of a closed box structure, an aileron and a Krueger flap.

Curran et al. [39–44] developed a similar framework for the optimization of an aluminum fuselage panel. Structural constraints were formed by the von Mises criterion, and local and global buckling coefficients. The manufacturing cost consisted of material, fabrication and assembly costs, and the objective function was given as

\[
F(x) = \alpha_1 \cdot C + \text{fuel burn}
\]

or

\[
F(x) = \alpha_1 \cdot C + \alpha_2 \cdot W
\]

(3.8)
where $\alpha_1$ was 2 or 3.5 and $\alpha_2 = $300/kg. Only metallic structures were considered, presumably due to the readily available buckling data from ESDU.

A similar approach was used by Iqbal and Hansen [45] for the optimization of welded truss structures. Apart from balancing manufacturing cost and weight, they also proposed a tradeoff function between the weight and the structural compliance. In an outlook they suggested how the combination of weight (or cost including weight) and compliance could be integrated in the design of aircraft structures.

The approach of a weighted sum has some advantages when it comes to cost/weight optimization. First, it can easily be implemented in an optimization framework. Second, the combination of cost and weight (weighted by parameters $\alpha_i$) gains an economical significance. In this thesis, Curran et al.’s approach was extended and the component’s share of the direct operating cost was used as the objective function. For details it is referred to Chapters 4 and 6.
4 Cost and Cost Estimation

Before turning to the field of cost estimation techniques, it is worth to introduce the definitions and concepts of cost as given in Roskam [46].

- **Cost**: The cost of an aircraft is the total amount of expenditures/resources needed to manufacture that aircraft.
- **Price**: The price of an aircraft is the amount of dollars paid by customers, e.g. the operator.
- **Profit**: Profit is Price minus Cost.

Depending on the role in the lifecycle of an aircraft programme, another viewpoint is taken. A part supplier, for instance, might offer his product at the lowest possible price in order to stay competitive. His aim is therefore to minimize the manufacturing cost. The aircraft manufacturer (system integrator), on the other hand, needs to provide an aircraft which has low design and manufacturing cost and is competitive in terms of operating cost. The operator is interested in cost savings throughout the lifetime of the aircraft, i.e. low acquisition, operating and disposal costs.

### 4.1 Life-Cycle Cost and Direct Operating Cost

The life-cycle cost analysis investigates the cost of a system or product over its entire life span. According to Roskam [46], the analysis of a typical system includes costs for

1. Planning and conceptual design
2. Preliminary design and systems integration
3. Detail design and development
4. Manufacturing and acquisition
5. Operation and support
6. Disposal

Note that most of the cost impacts are defined in the earliest design phases, whereas the bigger part of the expenditures occurs during the operation and support phase.
The life-cycle cost (LCC) of an airliner program can be expressed as

\[ LCC = C_{\text{rdte}} + C_{\text{acq}} + C_{\text{ops}} + C_{\text{disp}} \]  \hspace{1cm} (4.1)

where

- \( C_{\text{rdte}} = \) Research, Development, Technology and Evaluation
- \( C_{\text{acq}} = \) Manufacturing and Acquisition
- \( C_{\text{ops}} = \) Operating Cost
- \( C_{\text{disp}} = \) Disposal Cost.

For details on LCC, it is referred to the articles on cost models and LCC cost estimation written by Asiedu and Gu [47], Durairaj et al. [48] and Woodward [49].

The commercial aircraft operators are not particularly interested in LCC. For them, the operating cost and the direct operating cost (DOC) are more important, as they represent the cost of flying the aircraft. The latter can be described as

\[ DOC = C_{\text{flt}} + C_{\text{maint}} + C_{\text{depr}} + C_{\text{lnr}} + C_{\text{fin}} \]  \hspace{1cm} (4.2)

where

- \( C_{\text{flt}} = f(\text{crew, fuel, insurance}) \)
- \( C_{\text{maint}} = f(\text{maintenance, repair, overhaul}) \)
- \( C_{\text{depr}} = f(\text{price, flight hours}) \)
- \( C_{\text{lnr}} = f(\text{landing and navigation fees, registry taxes}) \)
- \( C_{\text{fin}} = f(\text{financing strategy}) \)

where the indices flt, maint, depr, lnr and fin denote flight, maintenance, depreciation, landing, navigation and registry, and financing, respectively. For the sake of competitiveness of an aircraft, it is desired to minimize the \( DOC \) given in Equation (4.2). On the basis of aircraft components, however, it is difficult to model the \( DOC \). Crew and insurance costs and the financing strategy, for instance, are unaffected by the structural design and could be excluded from the designer’s point of view. Therefore, most of the cost optimization approaches shown in Section 3.3 use a reduced form of the expression given above. Only the fuel cost (as a function of the weight) and the acquisition cost are included in these models.

Here, we go a step further and include the testing and maintenance cost as well. The items in Equation (4.2) examined in this work are marked in bold.

### 4.2 Design and Cost

Different design guidelines exist that integrate cost as an inherent element. These guidelines can be classified in concepts such as design to cost [50], design for cost [51, 52], design for manufacturability [53], design for assembly [54, 55], design for manufacturability and assembly [56], the Hitachi assemblability evaluation method [57] and integrated product and process development [58]. Two of them, design to cost (DTC) and design for cost (DFC), require some explanation.
Design to cost can be regarded as goal optimization with a specified cost target $C_{\text{max}}$ while the structural performance $F(x)$ is maximized. Thus, the mathematical formulation is given as

$$\begin{align*}
\text{max} & \quad F(x) \\
\text{subject to} & \quad g_j(x) \leq 0 \quad j = 1, 2, \ldots m \\
& \quad C(x) \leq C_{\text{max}}.
\end{align*}$$

Design for cost, on the other hand, maintains a prescribed structural performance $F_{\text{min}}$ while the cost $C(x)$ is minimized. This optimization problem is given as

$$\begin{align*}
\text{min} & \quad C(x) \\
\text{subject to} & \quad g_j(x) \leq 0 \quad j = 1, 2, \ldots m \\
& \quad F(x) \geq F_{\text{min}}.
\end{align*}$$

4.3 Estimation of Manufacturing Cost

According to Niazi et al. [59], there is a distinction between qualitative and quantitative cost estimation techniques. Qualitative techniques estimate the cost based on previously manufactured products and scale the manufacturing cost on the basis of similarities, whereas quantitative techniques are based on design features, manufacturing processes and the material. As seen in Figure 4.1, both groups of estimation techniques can be subdivided further. Two classes are highlighted: feature-based and parametric cost estimation techniques.

An example of a feature-based representation is a brick with a hole. The hole can be considered as a feature in the brick, closely connected to the manufacturing process used to create it, e.g. by drilling. In the same manner, the manufacturing cost can be estimated. Starting from raw material or semi-finished products, process features are added and their costs estimated.

Parametric techniques, on the other hand, are based on cost relevant design parameters, so-called cost drivers. The functions that relate the cost drivers to cost are commonly termed cost estimation relationships (CERs). In the example above, the brick would be represented by a cuboid and a cylinder, and a CER links the design parameters (height, length, depth, hole diameter) to the manufacturing cost [60].

Several commercial tools for the estimation of manufacturing cost are available. Most popular among them are SEER by Galorath Inc.\footnote{http://www.galorath.com} and the software package by Price Systems\footnote{http://www.pricesystems.com}. SEER-MFG (formerly known as SEER-DFM) was selected in this work, since it combines a feature-based approach (manufacturing processes can be added, removed and altered as features) with the advantages of a parametric
estimation. This provides a great level of detail and sensitivity for the optimization with respect to cost. Here, the basics of SEER-MFG are described in brief.

SEER-MFG uses kinematic and semi-empirical algorithms to derive direct and indirect labor and tooling times along with material and other expenses. In principle, the total cost of a unit subjected to an operation is given as

\[
C_{\text{man}} = C_{\text{labor}} + C_{\text{material}} + C_{\text{setup}} + C_{\text{tooling}} \tag{4.5}
\]

where

\[
C_{\text{labor}} = f(\text{time}, \text{directLaborRate}, \text{partComplexity})
\]

\[
C_{\text{material}} = f(\text{volume}, \text{density}, \text{price/kg})
\]

\[
C_{\text{setup}} = f(\text{setupTime}, \text{setupLaborRate}, \text{partComplexity})
\]

\[
C_{\text{tooling}} = f(\text{operationType}, \text{productionQty}, \text{toolingComplexity})
\]
First, the time needed to perform the operation is estimated as function of geometric parameters. Multiplied by the directLaborRate (which includes the cost for the operator, the cost for the machine or facility and some overhead cost) the labor cost is calculated. Similarly, the volume of the raw material is multiplied with its density and the price/kg. The setup cost is based on the time estimated to prepare each operation, whereas the total tooling cost (for molds, dies, etc.) is divided by the production quantity.

4.4 Estimation of Non-Destructive Testing Cost

It is possible to estimate the cost of NDT within SEER-MFG. However, in order to be more flexible regarding the calculation of in-production and in-service NDT, it was decided to implement an own feature-based cost model. Therefore, a generic database was developed in collaboration with Christophe Mattei from Linköping University. The database provides the following features:

- Thin flat laminate with access from both sides
- Thin flat laminate with access from one side
- Thick flat laminate with access from both sides
- Thick flat laminate with access from one side
- Adhesive bond
- Radius

Each of these features requires input data in form of length, width, thickness and – if applicable – radius. Further, the feature definition includes a scanning technique (pulse-echo or through-transmission), a complexity index, the educational level of the operator and, associated with the latter, a cost per hour or per scanned area. Hence, the cost for each feature is estimated, and the total cost of non-destructive testing is the sum of all feature costs. For more details it is referred to Paper B.
5 Forming of Composites

The material properties of a composite laminate are functions of the fiber orientations of the single plies. These fiber orientations are strongly dependent on the component’s geometry, the properties of fibers and matrix (e.g. the stiffness of a fiber bundle and its orientation) and parameters, such as temperature, applied force and deformation rate during the forming process.

Problems that may arise during manufacturing are voids, wrinkles and fiber bridges, fiber misalignment, tolerance mismatches, radius thickening or thinning, residual stresses, global shape distortions or spring-in effects. Thus, a lot of experience is needed to design components that are manufacturable.

In recent years, a lot of research has been performed in the field of forming processes. This research has led to better understanding of forming processes and the influence of process parameters, and to the development of simplified models for the design of producible complex composite components. Several existing material systems have been examined and ranked in terms of formability, and new material systems developed in order to improve the manufacturing process. This chapter gives a short overview of the mechanisms affecting forming of composites, draping models and commercial software. For more detailed information it is referred to the book "Composites forming technologies", edited by A.C. Long [61].

There are different composite manufacturing processes, such as hand-laid prepreg, RTM or vacuum infusion. They all share the complexity of forming a flat dry preform or a prepreg into a 3D shape before curing. The kinematics of ply draping are generally the same, which makes it possible to use fairly simplified models for the estimation of the fiber angles. The existence of the matrix, however, affects the friction between plies and the mechanisms in the ply.

5.1 Models for Composite Forming

During forming of composites, the fibers interact with each other and with the tool. The forming mechanisms are basically the same for dry fiber preforms and prepregs. The additional stiffness of the viscous prepreg matrix, however, raises the complexity in terms of temperature and rate dependencies. In Table 5.1, the different deformation mechanisms during forming of composites are shown.
<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Schematic</th>
<th>Characteristics</th>
</tr>
</thead>
</table>
| Intra-ply shear      | ![Schematic](image1) | - In-plane shear of the material  
                      - Rotation and slip between warp and weft yarns  
                      - Picture frame test and bias extension test for characterization  
                      - Rate and temperature dependency for prepregs  |
| Intra-ply strain     | ![Schematic](image2) | - Extension (or compression) parallel to tow directions  
                      - Standard tensile test for characterization  
                      - Initial stiffening due to crimp in weaves  |
| Inter-ply shear      | ![Schematic](image3) | - Relative movement between layers, and between layers and tools  
                      - Pressure, and (for prepregs) rate and temperature dependency  |
| Ply bending          | ![Schematic](image4) | - Bending of individual layers  
                      - Rate and temperature dependency for prepregs  
                      - Important for forming of structures with single curvature  |

Table 5.1: Deformation mechanisms during forming, see Long [61].

The orientation of the fibers, primarily the angle between warp and weft yarns, governs a series of properties, such as structural properties, the coefficients of thermal expansion, local fiber volume fractions and the permeability of the material. Thus, it is the aim of most material models to model the fiber reorientation as a function of the shape of the component and the process parameters. Several model classifications exist, whereof kinematic models and mechanical models can be seen as the two main groups.

**Kinematic Models**

The simplest draping model is the mapping algorithm based on research performed in the 50s by Mack and Taylor [62] and Van West et al. [63], also known as the Pin-Jointed Net model (PJN). This model is illustrated in Figure 5.1.
A raster of points is mapped to the tool surface by keeping the fiber segments constant. The algorithm solves the kinematic relationships given as

\[
(x_{ij} - x_{i-1,j})^2 + (y_{ij} - y_{i-1,j})^2 + (z_{ij} - z_{i-1,j})^2 = a^2
\]

\[
(x_{ij} - x_{i,j-1})^2 + (y_{ij} - y_{i,j-1})^2 + (z_{ij} - z_{i,j-1})^2 = b^2
\]

\[F(x_{ij}, y_{ij}, z_{ij}) = 0\]  \hspace{1cm} (5.1)

where \(x, y\) and \(z\) are point coordinates, \(a\) and \(b\) are the distances of the fiber segments and \(F\) is the surface equation. The algorithm is applied point by point, thus finding the coordinates of the new point \((i, j)\) based on the two existing points \((i - 1, j)\) and \((i, j - 1)\).

Examples for commercial design tools using a kinematic approach are PAMQUIKFORM\(^1\), FiberSIM\(^2\), Interactive Drape\(^3\) or Composite Modeler\(^4\). None of these tools account for yarn slippage, shear locking, yarn bending, or boundary conditions such as blank holding forces. This is subject to further research, see Potter et al. [64–66], Wang et al. [67] and Wiggers [68].

Truss based models are slightly more complex than mapping algorithms as they take into account the shear stiffness of the material. As can be seen in Figure 5.2, the model consists of truss elements which are connected by diagonal spring elements. The trusses represent the fibers, whereas the springs are responsible for the shear stiffness, see Nguyen et al. [69]. Little input and time is needed for the calculation in FE, which is one of the big advantages compared to the mechanical models described below. Main limitations are the missing matrix behavior, and the neglect of inter-ply shear in the simulation of hot draped composite stacks.

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\(^1\)http://www.esi-group.com
\(^2\)http://www.vistagy.com
\(^3\)http://www.interprot.com
\(^4\)http://www.simulayt.com
Mechanical Models

The mechanical models are most complex, as they rely on non-linear elastic or viscoplastic, and sometimes even bi-component material models representing the elastic fibers, the viscous matrix and the friction between yarns. The calculation is performed using non-linear and/or explicit FE code, thus being rather extensive in computation time, see Boisse et al. [70] and Badel et al. [71]. Tool and laminate geometries, material properties and appropriate friction laws have a great impact on the output and should therefore be given appropriate attention. Examples of commercial codes are AniForm\(^5\) and PAM-FORM\(^6\).

Multi-Layered Models

Most of the model approaches above can only describe single layers or an assembly of single layers. When draping a multi-layer material (such as hot draped prepreg stacks), the inter-ply behavior is important. The simulation can be done in two ways.

First, one can use a shell element for each layer of the stack, and implement friction laws which take into account the interaction between the shell elements while being formed. The total number of degrees of freedom (DOFs) and the number of contact evaluations grow linearly with the number of stacked layers.

Alternatively, one can use only one through-the-thickness element and incorporate the drape behavior (including slip, inter-ply and intra-ply shear) in this single layered shell element. This method is advantageous regarding the computation time. On the other hand, an extensive number of material parameters are needed to describe the material behavior, in particular for the intra-ply behavior.

Trends

Kinematic and mechanical approaches provide tools which can simulate the composite forming process with acceptable computational efforts. A limitation is certainly the need for material properties over the full temperature range in the process, which

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\(^{5}\)http://www.aniform.com

\(^{6}\)http://www.esi-group.com
calls for an excessive experimental effort. Another challenge is the modeling of interlaminar shear and tool/ply friction for which pressure, temperature, deformation rate, fabric structure and orientation are recognized as governing parameters. The underlying mechanisms, however, are subject to further research [72].

According to the literature, the use of draping models should not only allow for a more detailed assessment of the draped fabric, but also for an optimization of the draping strategy, see Guillermin [73]. Examples of possible areas of optimization are maximum intra-ply shear deformations, fiber orientations, positions of darts and splices, and location of the point of initial contact during draping. The optimization of the forming of woven composites was performed by Skordos et al. [74], who used a truss model to simulate the draping of a hemisphere and compared it with experiments. The same model was used to reduce wrinkling in the subsequent optimization of the holding force along the edge of the fabric. A genetic optimization algorithm was used for this purpose.

In Paper D, Guillermin’s idea to optimize for best draping was implemented and exemplified by means of a case study. Thus, the result of a draping strategy was examined with objectives such as material consumption, total cut length prior to draping, resulting fiber angles and material shear, see Figure 5.3. For this purpose, the commercial draping tool Composite Modeler was used.

![Figure 5.3: Structural and economical impact of the draping strategy in terms of resulting fiber angles, material consumption, cut length and drapability.](image-url)
5.2 Composite Modeler

Composite Modeler is a kinematic draping tool developed by Simulayt Inc. and forms an add-on to ABAQUS/CAE. It maps unidirectional and woven composites onto a previously modeled shell surface and stores the draped lamina information in sections. Input parameters are shown in Figure 5.4 and contain:

Material type  The type of the material (weave or tape) has a distinct influence on the shear mechanism (i.e. scissoring or sliding mechanisms).

Seed point and seed curves  The seed point is the location of the initial contact between a draped ply and the underlying mold or ply stack. A seed curve constrains warp or weft directions along one or two paths on the surface.

Reference angle  The reference angle is the angle between the 1-axis of the ply and a reference coordinate system.

Extension type  The extension type governs the draping kinematics. Three extension types are available in Composite Modeler:

  - Geodesic  The first extension yarn lies in a geodesic direction nearest the principal axis.
  - Energy  The draping proceeds from a seed point minimizing shear strain deformation energy.
  - Maximum  The draping proceeds from a seed point minimizing the maximum shear.

Other parameters  Other parameters cover the maximum shear angle during the draping of the fabric (also known as shear locking angle), warp/weft angles and warp/weft ratios. In addition, the thickness and angle tolerances for the generation of the ABAQUS sections can be defined.

Figure 5.4: Definition of seed point, reference coordinate system, reference angle $\phi$, nominal fiber direction, draped fiber direction and fiber angle deviation at control points.
Use of Composite Modeler

The procedure of using ABAQUS/CAE and Composite Modeler is the following: mesh the part, call the draping plug-in, define layup, material and draping properties (such as seed point location and reference angle), export the flat pattern, and map the simulated composite properties back onto ABAQUS sections. During the draping calculation, a PJN mesh as shown in Figure 5.1 is applied to the shell surface, and the internal data points (such as fiber angles and thicknesses) are averaged to section properties. A recently integrated feature allows access to the output data not only on the screen, but also by means of a text file (.vfp). The data comprise:

**Resulting fiber angles** Stored in ABAQUS section definitions, shown on the screen as a ply stack plot and saved in the .vfp file, the latter containing the internal PJN data points.

**Fabric shear** Shown on the screen and written to the .vfp file. Colors depict areas where the maximum fabric shear is reached and risk for wrinkling occurs (see Figure 5.5).

![Figure 5.5: Screen shot of the fabric shear modeled in Composite Modeler. The area with risk for wrinkling is emphasized with dashes.](image)

**Ply thickness** The ply thickness is stored as part of the ABAQUS sections. In addition, the internal data points of the PJN model are saved to the .vfp file.

**Flat pattern** The shape of the ply when undraped, see Figure 5.3. This shape is saved as a drawing exchange format (.dxf) file which can be post-processed by means of scripts in order to obtain ply area, scrap ratio and perimeter of the cut, see Lang [75].
6 Cost Optimization Framework

The result of this thesis is a multiobjective optimization framework for aircraft structures that incorporates cost and weight aspects into the objective function. The framework is designed modularly in order to capture a variety of structures, materials, processes and constraints.

The direct operating cost $DOC$ (Equation (4.2)) was used as the basis and simplified to the objective function seen below. Thus, only design-driving cost aspects were considered to be part of the objective function. The optimization problem was formulated as

$$\begin{align*}
\text{min} & \quad DOC \text{ of an aircraft component} \\
\text{subject to} & \quad \text{prescribed load case} \\
& \quad \bar{x}_i < x_i < \bar{x}_i, \quad i = 1 \ldots n,
\end{align*}$$

with the direct operating cost given as the weighted sum

$$DOC = \alpha_1 C_{\text{man}} + \alpha_2 C_{\text{ndt,prod}} + N\alpha_3 C_{\text{ndt,serv}} + pW.$$  \hfill (6.2)

$C_{\text{man}}$ is the manufacturing cost, $C_{\text{ndt,prod}}$ and $C_{\text{ndt,serv}}$ are non-destructive testing costs for in-production and in-service inspection, $p$ is a weight penalty (in €/kg) and $W$ is the weight of the structure. The parameters $\alpha_i$ incorporate calibration factors due to depreciation, overhead cost and other cost adjustments, and $N$ is the estimated number of regular inspections during the lifetime of the aircraft. The final framework is illustrated in Figure 6.1.

In Curran’s and Kassapoglou’s work (see Section 3.3), closed-form solutions provided the basis for the structural calculation. Here, it was proposed that an FE tool (e.g. ABAQUS) would calculate the structural performance of the component. Thus, the problem was independent from any limitations, such as geometries, material models and boundary conditions. In addition, the setup was reduced to the generation of the FE model and its parametrization. A major drawback, however, was the computational effort that was necessary in order to generate the structural feedback.

The calculation of the structural constraints emerged to be the limiting factor and a gradient-based method was chosen. The method of moving asymptotes (MMA) was developed by Svanberg and first published in 1987, see [76–78]. This solver
obtained the results from the different analysis blocks, i.e. SEER-MFG (for the calculation of the manufacturing cost), ABAQUS/CAE, Composite Modeler and the NDT model. Based on that feedback, the objective function, the constraints and the update of the variables were computed.

The approach of a weight penalty $p$ was introduced in the work done by Kelly and Wang [37], Wang et al. [38] and Curran et al. [39]. The quantification of $p$, however, is not trivial. The literature proposes values between €45/kg and €380/kg, whereas own estimations, based on the fuel consumption of an A330 and today’s fuel price, resulted in a weight penalty of approximately €2000/kg. A definite value for $p$ could not be given, as it depended on the viewpoint of the designer, the application and the operational profile. Instead, it was concentrated on the effect of different settings of the weight penalty $p$ on the design. This was done as follows:

**Paper A**

A skin/stringer panel was optimized using a simplified version of the objective function formed by the equation $DOC = C_{man} + pW$. The weight penalty $p$ was varied between 0 and $\infty$, thus capturing the whole spectrum between pure cost optimization and pure weight optimization. The optimization was done for three material configurations: an all-metal, a mixed and an all-composite configuration. The optimal design solution was highly dependent on the weight penalty, and it was shown that the ideal choice of the design solution was neither low-cost nor low-weight but rather a combination thereof.
Paper B

A skin/stringer panel was optimized using the objective function given in Equation (6.2). Further, the design strength of each laminate was adjusted according to the parameters of non-destructive testing. One of the parameters, the scan pitch, was a representative value for the guaranteed laminate quality. It was shown that – similar to the results of Paper A – the optimum laminate quality was again dependent on the weight penalty. The designs of the investigated skin/stringer panels were mainly governed by fulfilling the buckling constraint. As a consequence, the design strength could be lowered by adjusting the scan pitch of the ultrasonic testing, reducing the cost of NDT by 35-54% and the component’s direct operating cost by 4-14%.

Paper C

The results of Paper A and Paper B showed that the actual cost could even be lower than the estimations using prescribed process parameters. Thus, the sub-optimization of machining and other process parameters was necessary in order to estimate the lowest manufacturing cost in each iteration. A framework for the sub-optimization of machining parameters was proposed, minimizing the manufacturing cost in each iteration by the adaptation of manufacturing parameters. The framework extension was added to the existing implementation and tested on the center wing box rear spar of an airliner. Three optimizations were performed, and a low cost, a low weight and an intermediate design solution were found. The difference between the low cost and the low weight solutions was 4.4% in manufacturing cost and 9.7% in weight. Based on these optimizations, the effect of the parameter adaptation module was analyzed.

Paper D

The optimization framework was enhanced by a kinematic draping simulation which allowed the fiber angles to be simulated more realistically. First, a draping knowledge database was generated in which combinations of seed points and reference angles were evaluated in terms of fiber angle deviation, scrap, ultrasonic cuts and material shear. Second, the solver picked the best sets of plies during the subsequent optimization. The methodology was tested by means of a curved C-spar which was designed using plain weave and unidirectional prepreg. It was shown how different objectives during the generation of the draping database led to different design solutions. No non-destructive testing cost was included in this work.

Paper E

The total optimization framework as shown in Figure 6.1 was applied to the design of a curved C-spar. The case study included five material systems: aircraft grade aluminum, two non-crimp fabrics and two types of prepreg. The results were
compared in relation to each other and it was shown that (depending on the estimated fuel burn share of the component) a different material system was favorable when optimizing for operating cost. In addition, several what-if scenarios were examined in which changes in labor rates, material costs and production quantities were studied.
7 Conclusion

The proposed optimization framework is an approach to include more of the total life-cycle of the aircraft into the design process than done today. Depending on the viewpoint of the designer, cost and weight are traded differently. Thus, a simplified form of the direct operating cost is used to evaluate the merit of a design solution. A weight penalty is assigned to balance the cost and weight objectives. In combination with the proposed NDT and draping tools, the literature’s cost/weight optimization concepts are brought forward towards a more holistic view of cost-efficient design.

In each of the case studies, different design solutions were favorable in dependency of the value of the weight penalty. Thus, the fiber angle distribution, the thicknesses and the stringer configuration changed. It was shown that the engineer should not perform cost or weight optimization alone, but rather a combination thereof.

The cost and the structural model generated good estimates and provided sufficient sensitivity for the shape and size optimization. Under the condition that the component was modeled with appropriate elements, a fast convergence rate was achieved. A drawback of the current form of the framework, however, was the time needed to parameterize the models. More work would be necessary to bridge the gap from a CAD model to an applicable optimization setup.
8 Future Work

A lot of aspects in the design of aircraft structures were implemented in this work. Nevertheless, there are four fields where future work is proposed.

First, more work is needed to capture the total life-cycle of an airliner already in its design process. Little primary structure made of composite material is flying today, as both the A350 and Boeing’s 787 are still in prototype stages. Therefore, little experience of ageing carbon fiber wings and fuselages exists, and to foresee the number and thoroughness of inspections is delicate. An enhanced maintenance model, repairability and end-of-life aspects could be integrated into the objective function.

Second, it is suggested to enhance the framework by probabilistic design methods. The structural performance, for example, should be robust to manufacturing tolerances, such as angle or thickness deviations, porosities or irregularities in the material properties. Thus, the use of a reliability-based optimization framework would enable the design of robust structures.

Third, the NDT cost and the NDT strength reduction models could be improved. The difference between in-production and in-service testing could be more elaborate by applying different scanning techniques and overhead adjustments. Another suggestion is the application of the strength reduction as function of the stacking sequence, material properties and manufacturing technique. In addition, a stiffness reduction due to porosity might be included in the structural model. Beyond that, the inspection interval could be adapted to the stress level and the structural function of each feature. A probabilistic damage model could be included to capture the possibility of failure and repair for each structural member.

Finally, one could work on developments for the optimization of the draping strategy. In the current state, a restricted set of seed points is included for the generation of the draping knowledge database. One could imagine enhancements of the methodology where all points of the component’s surface are considered. The use of a response surface method could provide that functionality.
Bibliography


Division of work between authors

**Paper A**
Kaufmann was responsible for the implementation and the numerical experiments. The analysis of the results was performed jointly by the authors. The paper was written by Kaufmann with support from Zenkert.

**Paper B**
Mattei proposed the cost model. The implementation, the experiments and the analysis of the results were performed by Kaufmann. The paper was written by Kaufmann with support from Zenkert.

**Paper C**
Czumanski implemented the framework under Kaufmann’s supervision. Kaufmann and Czumanski jointly carried out the case study. The paper was written by Kaufmann with support from Czumanski and Zenkert.

**Paper D**
Kaufmann carried out the implementation of the framework, the numerical experiments and the analysis of the results. The paper was written by Kaufmann with support from Zenkert and Åkermo.

**Paper E**
Kaufmann carried out the numerical experiments and the analysis of the results. The paper was written by Kaufmann with support from Zenkert and Åkermo.
Part II

Appended papers