PLATO-N

SIXTH FRAMEWORK PROGRAMME

FP–6 STREP 30717 PLATO–N (Aeronautics and Space)

PLATO–N

A PLAtform for Topology Optimisation incorporating Novel, Large-Scale, Free-Material Optimisation and Mixed Integer Programming Methods

Final Publishable Activity Report

Start date of project: **October 1, 2006**
Duration: **39 Months**

Project coordinator name: **Mathias Stolpe**
Project coordinator organization name: **DTU**

Executive Summary

PLATO-N

SIXTH FRAMEWORK PROGRAMME

Project acronym: PLATO-N **Proposal/Contract no.:** 30717
Project full title: A PLAtform for Topology Optimisation incorporating Novel, Large-Scale, Free Material Optimisation and Mixed Integer Programming Methods

Project objectives:

Developing safe and minimum weight structures is the driving factor in aircraft structural design. The heavier the airframe, the more fuel per passenger is required, or the shorter the range achieved.. Commonly, weight reduction programs have to be launched deep into the *detailed design phase*, and are characterized by local, manual modifications to the design, applying more expensive materials, or adjustments to the manufacturing process, for example to achieve reduced minimum gauges.

Improved overall arrangement of materials provides the largest potential for saving structural weight in airframe design. Tools for topology optimisation support these early, important decisions by suggesting optimal material distributions. Current commercial design and decision-support tools do not allow the full potential of composite materials to be exploited in airfame design This requires new tools that are targeted at the specific requirements within aerospace structural design.

PLATO-N will enable the operational integration of optimisation assistance as a standard procedure in the conceptual design process for the European aerospace industry. PLATO-N will be validated against real case studies and will be implemented as a suite of software, integrated in a common environment, and its improvement in performance will be benchmarked against state-of-the art commercial products. PLATO-N aims to overcome the limitations of current state-of-the-art topology optimisation tools in order to enable integration of optimisation assistance into the conceptual design process of the European aerospace industry.

In terms of research goals the following strategic decisions that have been:

- The platform should be flexible with respect to the inclusion of new optimization algorithms and visualization tools, and it should provide a range of tools and modelling approaches geared to aeronautical needs.
- The large-scale optimization algorithms should employ some form of algorithm based on a development of dedicated first-order methods.
- The method should be extended to plate and shell problems and should be able to handle multiple objectives such as stiffness, vibration, and buckling problems.
- An algorithm should be developed in order to handle local stress constraints.
- Benchmark examples should be generated using mixed-integer convex models.
- The results should be interpreted and visualized in a manner consistent with aerospace needs, e.g., shell structures using laminate lay-ups.
- The platform should be tested on examples of industrial origin.

Project partners and coordinator contact details:

Partners

1. Technical University of Denmark (CO-ORDINATOR), Denmark
2. Technion – Israel Institute of Technology, Israel
3. University of Birmingham, UK
4. Friedrich-Alexander Universität Erlangen-Nürnberg, Germany
5. Universität Bayreuth, Germany
6. Altair Engineering, Ltd., UK
7. RISC Software GmbH, Austria
8. EADS Deutschland GmbH, Germany
9. Airbus UK, Ltd., UK
10. Eurocopter Deutschland GmbH, Germany

Contacts

The PLATO-N project is coordinated by the Technical University of Denmark (DTU):

Department of Mathematics
Building 303S, Matematiktorvet
DK-2800 Kgs. Lyngby, Denmark
Phone: +45 45 25 30 31, Fax: +45 45 88 13 99

Project coordinator: Professor Martin P. Bendsøe, DTU
Project Administrator: M.Sc. Ellen Juel Nielsen, DTU
Dissemination Manager: Associate Professor Mathias Stolpe, DTU
Exploitation Manager: Professor Dr. G. Leugering, Universität Erlangen-Nürnberg, Germany

Work performed

The work of the second reporting period has been concentrated on the following:

1. To establish and implement the basic structure of the software platform PLATO-N.
2. To generate a library of benchmark examples of academic as well as industrial origin collected in the public domain PLATO-lib.
3. To develop and implement algorithms for mathematical models that takes into account multi-disciplinary constraints within Free Material Optimisation.
4. To develop the modelling and implementation for shell and plate settings.
5. To continue with the development the fundamental theory, algorithms, and computational tests of very efficient novel, first-order methods for large-scale, convex optimisation and incorporate these into semi-definite programs.
6. To develop and implement the visualization tools
7. To monitor the adherence to the system specification and the project status in relation to the Use-Case definition and its adaptation in the systems specification.
8. To develop and implement a novel branch-and-cut method for topology optimization with discrete design variables.

Re.2. During testing of the PLATO-N platform in year 3, the library will be supplemented with results obtained with the methods developed in the project.

Re. 3 Methods for handling vibration constraints have been finalized and models for creating benchmark examples using mixed-integer programming have been established (this is to generate globally optimal solutions). Compared to the original project plan more focus is given to the so-called nested format (due to computational efficiency), and at the same time more progress than expected has been made in relation to dealing with stress constraints.

Re. 5. Novel first-order large scale, convex optimization methods have been developed and methods for convex approximations have also been developed. The new and unplanned results on using matrix-type convex and separable approximations for vibration and buckling problems have been implemented; this lead to even more efficient algorithms than envisaged at the beginning of the project.

Re .6. A range of visualization tools has been generated, including a technique for showing laminate realizations. The latter have also lead to new algorithms, an un-planned spin-off.

Re. 7. This work has lead to some clarifications of the system specification as seen in relation to the Use-Case definition.

Expected results

The main innovations and products at the end of the project period of three years are

1. PLATO: A generic software platform for topology optimisation, specific for aeronautics applications. This will be a significant advance on the current state of the art.
2. PLATOlib.: A sample case library which can be used as a benchmarking library for the topology optimisation community, including challenging applications derived from real world industrial design problems.
3. PLATO-N: A software system integrating the implementations of algorithms and methods developed in the project. This software system will have higher performance than any current commercial systems.

Benefits of the multidisciplinary research approach are expected at all levels:-

- The research community will profit from the "technology pull" applied by the aeronautic industry.
- It will improve awareness of entities outside the research community to the potential of topology optimisation..
- PLATO-N greatly extends the scope of topology optimisation and expands both its applicability and acceptance in the European aerospace industry. It provides means for shortening development times and reinforce competitiveness.
- the European aeronautic industry will be more capable of responding to the growing demand of the European society for a more effective and sustainable air transport system by being able to design and manufacture conventional and novel aircraft configurations at reduced cost, with reduced operating costs, and reduced environmental impact.

Using and dissemination of knowledge

Dissemination:

The results of the project will be made publicly available through:

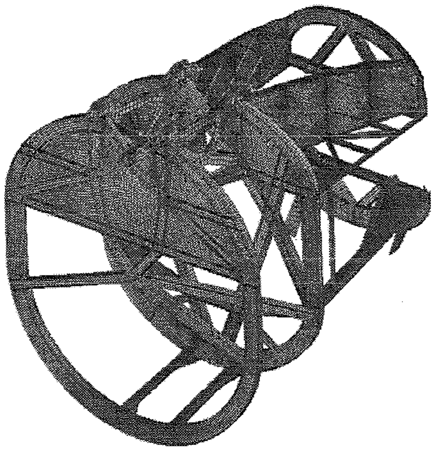
- A release of a limited version of PLATO-N as a public domain software (no source code)
- The project homepage www.plato-n.org
- Public reports, available from www.plato-n.org
- Publications in international journals
- Articles in popular magazines
- Workshops and conference for academic researchers and researchers and users from industry.

Use

The project will generate a software platform, which will enable research partners to integrate and test their new methods on real industrial problems and to validate the reduction in design time and costs achievable.

PLATO-N greatly extends the scope of topology optimisation and expands both its applicability and acceptance in the European aerospace industry. The features and possibilities provided with PLATO-N will enable industry to develop novel minimum weight concepts for composite and metal aircraft components like load introduction features (e.g. brackets for tail-plane to fuselage attachments) as well highly loaded, complex frames door support structures, floors, bulkheads and so on. The potential applications cover a huge range of components up to complete fuselage- and wing-sections, landing gears and other significant structural aircraft components. It provides means for shortening development times, improving the quality of products by offering minimum weight solutions, enabling design of novel, unconventional configurations, and, therefore, reinforce the competitiveness of the European airframe manufacturers on the global market.

The European aeronautic industry will be more capable of responding to the growing demand of the European society for a **more effective and sustainable air transport system**. by being able to design and manufacture conventional and novel aircraft configurations at reduced cost, with reduced operating costs, and reduced environmental impact.
PLATO-N will be used for research by the universities



A design study for the Airbus A350 – topology optimization was used to obtain the lower, right hand design, with a predicted weight saving between 15 to 20% purely due to the new design concept/topology. Also, a reduced stress level is achieved.

Publishable results

Reports
All the reports are available for download on the PLATO-N website www.plato-n.org.

Title: **PLATO-N Use Case Definition**
Abstract: At the beginning of EU-FP6's research project PLATO-N ('a PLAtform for Topology Optimisation incorporating Novel large-scale, free material optimisation and mixed integer programming methods') the industrial partners prepared a use case definition which comprises the industrial requirements that should be considered in the project. Using the, in aircraft industries commonly employed, design process as a basis, the engineer's tasks are described and his needs are derived. Single design criteria out of a huge amount of aircraft requirements are selected, prioritised and, from an industrial point of view, tailored to the scope of the project.
Keywords: PLATO-N, software platform, large scale, topology optimisation, aircraft industry, industrial requirements, design process, optimisation process, free material optimisation, mixed integer programming, visualisation
Author: Markus J.D. Wagner
Address: EADS
Defence & Security
Military Air Systems
Dept. MEG64
Rechliner Straße
D-85077 Manching, Germany
E-mail: Markus.JD.Wagner@eads.com
Author: Lars Krog
Address: Airbus UK,
Composite Research Centre –
20A1, Bristol,
BS99 7AR, UK
E-mail Lars.Krog@Airbus.com
Date: March 26, 2007

Title: **Specification of Aircraft Topology Optimization System, PLATO-N**
Abstract: This document details the software specification requirements for PLATO-N in accordance with deliverable D4 of Annex I of the project description of work. Details are provided on what is required of the PLATO-N software system to satisfy performance, function, and industry needs. These needs have been discussed and agreed through consultation within the PLATO-N consortium. Assumptions and risks associated with the development of the software system are also documented. Details on the PLATO-N system configuration, dependencies, formulations, organisation and usage are also documented.
The contributions from all partners within the PLATO-N consortium are acknowledged.
Keywords: PLATO-N, free material optimization, finite element, topology optimisation, large-scale convex optimization, sequential convex programming, aerospace
Author: Richard Boyd
Address: Altair Engineering Ltd
Imperial House
Holly Walk
Royal Leamington Spa, CV32 4JG
United Kingdom
E-mail: richard.boyd@uk.altair.com
Date: June 26, 2007

Title: **Large Scale Methods for Convex FMO-Type Problems**
Abstract: In this report we review several first order methods suited for problems arising from large-scale free material optimization (FMO) problems. Our focus is on the Non-Euclidean Restricted Level (NERML) and on the reduced gradient methods. Both algorithms have demonstrated encouraging empirical results in preliminary numerical testing. Finally, we

describe the CONERML method, which is a variation of the NERML method capable of dealing with constraints.
Keywords: First-order methods, large-scale convex optimization, bundle methods, free-material problems
Authors: Amir Beck, Aharon Ben-Tal and Luba Tetruashvili
Address: William Davidson Faculty of Industrial Engineering and Management
Technion – Israel Institute of Technology
Technion City
32000, Haifa
Israel
E-mail: becka@ie.technion.ac.il
Date: September 15, 2007

Title: **Sequential Convex Programming Methods for Free Material Optimization**
Abstract: We consider a numerical method for constrained nonlinear programming, that is widely used in mechanical engineering and that is known under the name SCP for sequential convex programming. The algorithm consists of solving a sequence of convex and separable subproblems, where an augmented Lagrangian merit function is used for guaranteeing convergence. Originally, SCP methods were developed in structural mechanical optimization, and are particularly applied to solve topology optimization problems. A new challenge for SCP methods is the solution of free material optimization (FMO) problems which contain additional semidefinite variables and even nonlinear semi-definite matrix constraints. A few formulations are investigated in more details and possible solution approaches are outlined.
Keywords: Nonlinear Programming, sequential convex programming, method of moving asymptotes, free material optimization, semi-definite programming, interior point methods
Author: Sonja Ertel
Address: Department of Computer Science
University of Bayreuth
D-95440 Bayreuth, Germany
E-mail: sonja.ertel@uni-bayreuth.de

Author: Klaus Schittkowski
Address: Department of Computer Science
University of Bayreuth
D-95440 Bayreuth, Germany
E-mail: klaus.schittkowski@uni-bayreuth.de
Author: Christian Zillober
Address: Department of Mathematics
University of Würzburg
D-97074 Würzburg, Germany
E-mail: christian.zillober@uni-wuerzburg.de
Date: July 23, 2007

Title: **Efficient Algorithms for Visualising FMO Results**
Abstract: In this report we discuss the possibilities of FMO data visualisation, providing an inventory of the techniques to be supported by the FMS visualisation component of the PLATO-N software system. Furthermore we discuss the currently identified computationally critical subtasks that might pose performance problems, and we suggest solutions to cope with them in the form of efficient data representation techniques and algorithms, as well as in terms of software design.
Keywords: scientific visualisation, evenly spaced streamlines, skeletonization, pipeline visualisation architecture
Author: Gábor Bodnár
Address: RISC Software GmbH
Softwarepark 35
A-4232 Hagenberg, Austria
E-mail: gabor.bodnar@risc-software.at

Date: June 22, 2007

Title: **Convex approximations for complex non-convex constraints**
Abstract: We consider three algorithmic approaches to deal with displacement and/or stress constraints in free material optimization (FMO) models. The first approach is a simple sequential linear programming (SLP) approach and we describe how to adopt it to FMO-type problems with semidefinite constraints. We then provide another approximation scheme based on [1] to a general form of nonconvex constraints that includes (among other) stress or displacement constraints. At each iteration the constraint function is approximated by another overestimate function and thus the approximated solution is guaranteed to be feasible. Finally, we briefly review a sequential convex semidefinite programming method recently developed by Stingl, Kocvara and Leugering.
Authors: A. Beck, A. Ben-Tal and L. Tetruashvili
Address: William Davidson Faculty of Industrial Engineering and Management
Technion – Israel Institute of Technology
Technion City
32000, Haifa
Israel
E-mail: becka@ie.technion.ac.il
Date: October 13, 2007

Title: **Free Material Optimization with Control of the fundamental Eigenfrequency**
Abstract: The goal of this paper is to formulate and solve free material optimization problems with constraints on the minimal eigenfrequency of a structure. A natural formulation of this problem as linear semidefinite program turns out to be numerically intractable. As alternative, we propose a new approach, which is based on a nonlinear semidefinite low-rank approximation of the semidefinite dual. Throughout this article, an algorithm is introduced and convergence properties are investigated. The article is concluded by numerical experiments proving the effectiveness of the new approach.
Keywords: structural optimization, material optimization, semidefinite programming, nonlinear programming

Author: Michael Stingl
Address: Institute of Applied Mathematics
University of Erlangen
Martensstr. 3
91058 Erlangen, Germany
E-mail: stingl@am.uni-erlangen.de
Author: Michal Kočvara
Address: School of Mathematics
University of Birmingham
Edgbaston
Birmingham B15 2TT, United Kingdom
E-mail: kocvara@maths.bham.ac.uk
Author: G. Leugering
Address: Institute of Applied Mathematics
University of Erlangen
Martensstr. 3
91058 Erlangen, Germany
E-mail: Guenter.Leugering@am.uni-erlangen.de
Date: September 27, 2007

Title: **Lower bounding problems for stress constrained discrete structural topology optimization problems**
Abstract: The multiple load structural topology design problem is modelled as a minimization of the weight of the structure subject to equilibrium constraints and restrictions on the local stresses and nodal displacements. The problem involves a large number of discrete design variables and is modelled as a non-convex mixed 0–1 program. For this problem, several convex and

mildly non-convex continuous relaxations are presented. Reformulations of these relaxations, obtained by using duality results from semi-definite and second order cone programming, are also presented. The reformulated problems are suitable for implementation in a nonlinear branch and bound framework for solving the considered class of problems to global optimality.

Key words: Topology optimization, Stress constraints, Relaxations, Global optimization
Author: Mathias Stolpe
Address: Department of Mathematics
Technical University of Denmark
Matematiktorvet, Building 303S
DK-2800 Lyngby, Denmark
E-mail: M.Stolpe@mat.dtu.dk
Author: Roman Stainko
Address: Department of Mathematics
Technical University of Denmark
Matematiktorvet, Building 303S
DK-2800 Lyngby, Denmark
E-mail: R.Stainko@mat.dtu.dk
Author: Michal Kočvara
Address: School of Mathematics
University of Birmingham
Edgbaston
Birmingham B15 2TT, United Kingdom
E-mail: kocvara@maths.bham.ac.uk
Date: September 28, 2007

Title: **FMO Models with Displacement Constraints**
Abstract: Free material design deals with the question of finding the lightest structure subject to one or more given loads when both the distribution of material and the material itself can be freely varied. We additionally consider constraints on displacements of the optimal structure.
Author: Michal Kočvara
Address: School of Mathematics
University of Birmingham
Edgbaston
Birmingham B15 2TT, United Kingdom
E-mail: kocvara@maths.bham.ac.uk
Author: Michael Stingl
Address: Institute of Applied Mathematics
University of Erlangen
Martensstr. 3
91058 Erlangen, Germany
E-mail: stingl@am.uni-erlangen.de
Date: April 9, 2008

Title: **Sequential Convex Programming for Free Material Optimization with Displacement and Stress Constraints**
Abstract: We consider free material optimization (FMO) problems, which are defined in form of semidefinite programs. The objective is to compute the stiffest structure subject to given loads. Constraints are bounds for compliances, displacements or stresses. Optimization variables are the entries of element material matrices in two or three dimensions. FMO problems are solved by a sequential convex programming algorithm, which is frequently applied in mechanical structural design optimization. The idea is to construct convex and separable subproblems, which are either solved by an interior point method or by an external solver, which is able to treat positive semidefinite variables. In the case of isotropic materials, additional linear constraints guarantee positive definite material matrices. For anisotropic materials, we propose to optimize over Cholesky factors of the elasticity matrices. Some preliminary numerical results are presented for these two situations. Finally

we discuss the integration of two semidefinite subproblem solvers called PENNON and CONERML and the possibility to add stress and displacement constraints.

Keywords: nonlinear programming; sequential convex programming; method of moving asymptotes; free material optimization; semidefinite programming; displacement constraints; stress constraints; SCPIP; PENNON; CONERML

Author: Sonja Ertel
Address: Department of Computer Science
University of Bayreuth
D-95440 Bayreuth, Germany
E-mail: sonja.ertel@uni-bayreuth.de
Author: Klaus Schittkowski
Address: Department of Computer Science
University of Bayreuth
D-95440 Bayreuth, Germany
E-mail: klaus.schittkowski@uni-bayreuth.de
Author: Christian Zillober
Address: Department of Mathematics
University of Würzburg
D-97074 Würzburg, Germany
E-mail: christian.zillober@uni-wuerzburg.de
Date: March, 2008

Title: Methods for Computer Aided Interpretation of FMO Results

Abstract: It is a challenging task to interpret FMO-materials by investigating their properties and eventually trying to substitute them with suitable existing materials. In this report we discuss possibilities how computer algorithms can help engineers in this process. There are various approaches to the problem, for instance visualization, material property discovery or automatic substitution of FMO-materials with real ones. From each of these branches we discuss selected methods, their applicability to FMO results interpretation and their combinability, if applicable.

Keywords: scientific visualization, free material optimisation, elastic material classification, laminate realizations of materials

Author: Gábor Bodnár
Address: RISC Software GmbH
Softwarepark 35
A-4232 Hagenberg, Austria
E-mail: gabor.bodnar@risc-software.at
Author: Peter Stadelmeyer
Address: RISC Software GmbH
Softwarepark 35
A-4232 Hagenberg, Austria
E-mail: peter.stadelmeyer@risc-software.at
Author: Michael Bogomolny
Address: Department of Mathematics
Technical University of Denmark
Matematiktorvet, Building 303S
DK-2800 Lyngby, Denmark
E-mail: m.bogomolny@mat.dtu.dk
Date: April 17, 2008

Title: Free Material Optimization for Plates and Shells: the Single Load Case

Abstract: In this article, we present the Free Material Optimization (FMO) problem for plates and shells based on Naghdi's shell model. In FMO – a branch of structural optimization – we search for the ultimately best material properties in a given design domain loaded by a set of given forces. The optimization variable is the full material tensor at each point of the design domain. We give a basic formulation of the problem and prove existence of an optimal solution. Lagrange duality theory allows to identify the basic problem as the dual of an infinite-dimensional convex nonlinear semidefinite program. After discretization by the

finite element method the latter problem can be solved using a nonlinear SDP code. The article is concluded by several numerical studies.

Keywords: Free Material Optimization, Structural Optimization, Shells, Continuum Mechanics, Elasticity

Author: Stefanie Gaile
Address: Institute of Applied Mathematics II
Department of Mathematics
University of Erlangen-Nürnberg
Martensstr. 3
91058 Erlangen, Germany
E-mail: stefanie.gaile@am.uni-erlangen.de

PLATO-N

SIXTH FRAMEWORK PROGRAMME

FP–6 STREP 30717 PLATO–N (Aeronautics and Space)

PLATO–N

A PLAtform for Topology Optimisation incorporating Novel, Large-Scale, Free-Material Optimisation and Mixed Integer Programming Methods

PLATO–N Use Case Definition

PLATO–N Public Report PU–R–1–2007

March 26, 2007

Authors:

Markus Wagner

Lars Krog

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)

Dissemination level: Public

PLATO-N

Use Case Definition

(Deliverable D2)

Compiled by

Markus J.D. Wagner
Markus.JD.Wagner@eads.com
EADS Military Air Systems
Williy-Messerschmitt-Straße
85521 Ottobrunn
Germany

Lars Krog
Lars.krog@airbus.com
Airbus UK
Building O9H-D
Filton
Bristol BS99 7AR
United Kingdom

Keywords:

PLATO-N, software platform, large scale, topology optimisation, aircraft industry, industrial requirements, design process, optimisation process, free material optimisation, mixed integer progamming, visualisation

Abstract:

At the beginning of EU-FP6's research project PLATO-N ('a PLAtform for Topology Optimisation incorporating Novel large-scale, free material optimisation and mixed integer programming methods') the industrial partners prepared a use case definition which comprises the industrial requirements that should be considered in the project.
Using the, in aircraft industries commonly employed, design process as a basis, the engineer's tasks are descibed and his needs are derived. Single design criteria out of a huge amount of aircraft requirements are selected, prioritised and, from an industrial point of view, tailored to the scope of the project.

26th of March 2007

Content:

1 Introduction

PLATO-N is an acronym that stands for "a PLAtform for Topology Optimisation incorporating Novel large-scale, free material optimisation and mixed integer programming methods".

Work package 2.1 of the PLATO-N project gives the industrial partners the opportunity to define their specific needs, to describe development processes in order to make the industrial needs transparent to all partners. The further work packages are based on the deliverable of WP2.1 namely the Use Case Definition. All industrial partners, here EADS-MAS (Military Air Systems), AUK (Airbus UK) and ECD (Eurocopter), have agreed on its content. Cause things may change during project progress it might be necessary to revise it. But close consultation with the industrial advisory board is obligatory.

A generic industrial development process is described in chapter two. Certainly only the main steps are given. However, it should be sufficient for a general understanding. Chapter three comprises the individual use cases. They include detailed information about industry's needs, as far as the conceptual design phase is concerned. These requirements are asked to be implemented in the platform. Eventually the engineers would like to utilise the given spectrum in industrial applications.

2 Industrial Scenario

This chapter comprises descriptions of typical air vehicle structures and their according development process. The latter focuses on decisions made at different process stages. A separate section highlights how topology optimisation may be used to assist developing solutions within these different stages of the design process. The chapter is concluded by a view on how topology optimisation technology may be used to shorten the development process providing early views on optimum structural solutions throughout the air vehicle design process.

2.1 Structural Overview

Figure 2.1-1 gives an overview of major aircrafts components that have to be optimised through the design phases of an aircraft design cycle, starting at conceptual design and ending with detailed design. The different design phases are described further in Section 2.2.

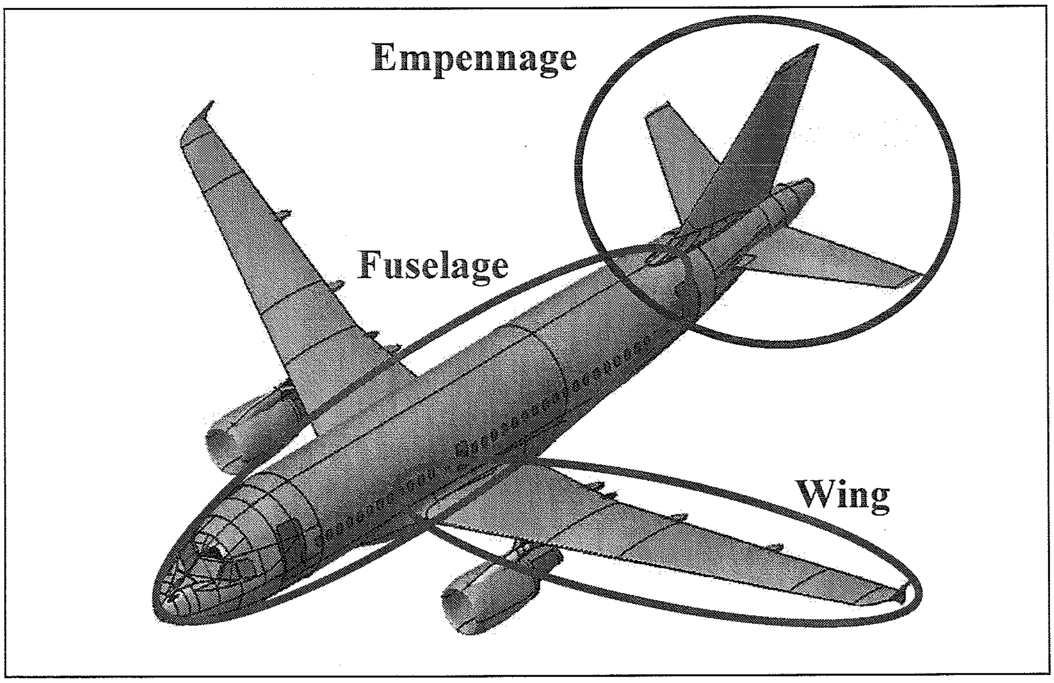


Figure 2.1-1 Major aircraft components

As an example showing the typical breakdown of an aircraft component into subcomponents Figure 2.1.2 shows the components comprising a conventional commercial aircraft wing structure. The wing structure is build from four main subcomponents: skins, stringers, spars and ribs and in addition includes a large number of subcomponents making up the leading and trailing edge structures and also subcomponents providing support for both engines and landing gear structure. Materials used in a commercial aircraft wing structure include a mixture of carbon fibre reinforced plastic, aluminium and titanium. Many of the subcomponents in the structure are designed as integrally stiffened thin walled structures, with a wall thickness ranging from 1 – 30 mm.

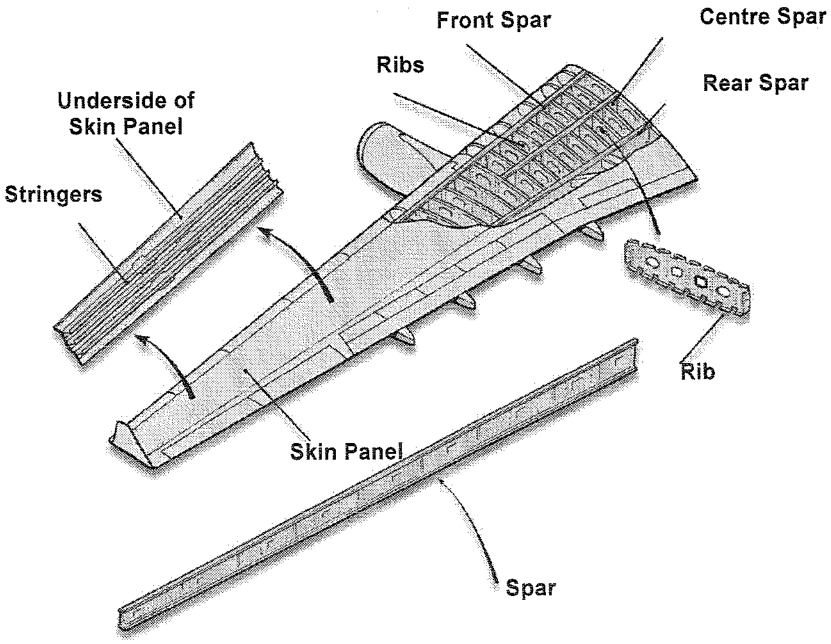


Figure 2.1-2: Components comprising a conventional aircraft wing structure.

The configuration optimisation of the major components shown in Figure 2.1.1 is typically a task of conceptual design. Each major component consists of lots of subcomponents, which have to be designed and optimised either during the concept design phase or during preliminary design phase. Finally smaller parts like fittings, brackets, couplings etc. can even be optimised in the detailed design phase.

2.2 Design Cycle

The design process followed during an air vehicle development program is typically broken into three distinct phases, with specific topics being address at different stages. Figure 2.2-1 illustrates the design process break down. Work performed during each phase is further described in subsections throughout this section.

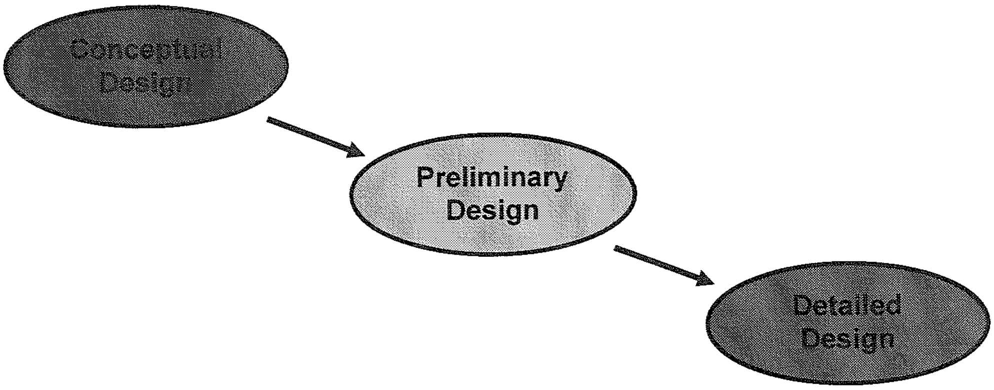


Figure 2.2-1: Air vehicle design process break down into three design phases

2.2.1 Conceptual Design Phase

During conceptual design the aim is to provide a first refinement of the aircraft definition, considering aerodynamic performance and structural architecture. Examples of decisions being made during conceptual design, include

- Aerodynamic profile / plan-form definition
- Structural break down for manufacturing
- Rough material selection (metal / composite)
- Structural architecture, considering the integration of major components
- Structural layout definition in terms of for example rib/stringer/frame pitches

2.2.2 Preliminary Design Phase

During preliminary design the aim is to provide a further refinement of the structural design, in terms of both material selection and first sizing. During preliminary design, loads for sizing may be typically based on scaling of loads from previous aircraft. Preliminary design provides a further refinement of the structural design in terms of for example

- Material down selection (e.g. type of composite, laminate composition)
- Configuration definition for long lead item subcomponents
- Aero-elastic tailoring of a composite solution (driving e.g. ply orientations)
- Component architecture studies (shear web vs. truss structures)
- Preliminary sizing of structures to develop robust stiffness estimates / loads models

2.2.3 Detailed Design Phase

Finally the detailed design phase comprises the sizing of all components for minimum weight meeting all design criteria. In this phase of the design process, the loads are well established based on stiffness estimates made during preliminary sizing. At this stage we consider e.g.

- Sizing optimisation for subcomponents
- Stacking sequence / orientation optimisation for composite subcomponents
- Design for Manufacturing
- Design to Cost

2.3 Design Requirements

During development of air vehicle structures many conflicting requirements have to be met, including both, on the one hand performance and cost requirements, defined by the customer, and on the other the structural requirements, defined by the official certification regulations. Customer requirements may be seen to define the main targets in the air vehicle development program, driving definition of performance and cost critical parameters like for example plan-form and material choice, while the certification regulation requirements define for example aerodynamic and structural requirements that must be met during detailed design. During the air vehicle development work is often split according to skill area. As an example work in aerodynamics and structures may typically be seen to focus on performance and weight, respectively.

Aerodynamics:
Minimise: Fuel burn
Considering: Aerodynamics, Aero elastics, Dynamics and Weight

Structures/Manufacturing:
Minimise: Weight / Cost
Considering: Strength, Stability, Fatigue, Damage Tolerance and Reparability

Still the overall goal is to design a high performance and low cost solution that meets all certification regulation requirements. The following list selects a few of the topics that must be addressed during conceptual, preliminary and detailed design

1) Performance requirements
    - Aero elastics
    - Aerodynamics
    - Dynamics
    - Displacements

2) Fundamental failure modes
    - Static strength
    - Stability
    - Aero elastics

3) Life cycle demands
    - Fatigue
    - Damage Tolerance
    - Manufacturing
    - Lightening Protection
    - Electro- / Thermal- conductivity
    - Reparability

Each single one of the topics above mentioned may comprise several design criteria, which are again highly dependent on material choice, structural concept and design details. As an example the stability criteria for metal and composite components and for shear web and truss components are not necessarily the same. Metal structures may be allowed to post-buckle before limit load while thicker composite structures may be required to be non-buckling until ultimate load. Likewise a shear web structure may be allowed to post buckle, while a truss structure may be required to remain stable at all load levels. Rapidly the requirements become very complex, with design requirements being depending on material choice, structural concept and even dimensions. Clearly not all design requirements can/should be considered at the level of early conceptual design.

The air- vehicle design process is further complicated by the fact that air vehicle structures are highly redundant structures. Internal loads in the structure therefore generally depend on both the global stiffness of the structure, affecting for example aerodynamics, and on the relative stiffness of internal load paths in the structure. Some of these effects are non-linear deflection effects and must be analysed using appropriate methods. Often component sizing is performed under the assumption of constant loads, with load updates between sizing loops. However, examples exist in which it is necessary to incorporate the load changes as integral part of the analysis process. Such examples include:

- Aero elastic applications where the loads will vary in both magnitude and direction as a function of displacements. As an example a wing will deflect during flight and thus change its angle-of-attack and pressure distribution ($\underline{\underline{K}}*\underline{u} = \underline{p}-\underline{\underline{S}}*\underline{u}$ where $\underline{\underline{S}}$ is an unsymmetrical matrix representing the aerodynamic influence).

- Designing a pressure bulk head the loads are design dependent (pressure acts always perpendicular to the surface). If the pressure distribution is constant – say the passenger compartment pressure – the loads will vary in direction only.
- Varying the shape of a wing airfoil the pressure distribution is not constant anymore. Thus the loading changes design dependent in magnitude and direction.

2.4 Optimisation in the Design Process

Descriptions provided so far have not addressed how optimisation technology and especially topology optimisation technology fits into the design process for an air vehicle structure. The aims of using optimisation technology are both to reduce development time scales and to develop more efficient designs. Topology optimisation technology is specially aimed towards concept design, providing tools to guide the development of optimum structural architectures, including for both components and subassemblies.

According to the design cycle description provided in Section 2.2, different use of topology optimisation at different stages of the design process could be imagined.

1) Conceptual Design:
- Topology optimisation of larger sub-assemblies as architecture problems, for example in order to determine an optimum integration of a landing gear with a wing or fuselage structure.
- Free material optimisation to determine the optimum property layout for a composite structure in order to guide for example an optimum break down of a structure for manufacturing.

2) Preliminary Design:
- In component optimisation, conventional topology optimisation methods could be used to determine optimum truss type configurations, while free material optimisation along with conventional sizing/topology optimisation methods could be used to optimise stiffened composite shear web structures.
- Free material optimisation methods could be used to tailor composite material properties for an entire wing or fuselage skin to achieve optimum local strength/buckling performance and also global stiffness performance.

3) Detailed Design:
- At this point conceptual optimisation should have been completed for most major components. Still topology optimisation methods could play a role. Conventional topology optimisation methods could for example be used for optimisation of small brackets etc.

Clearly major benefits in terms of development time reductions and weight and performance improvements are delivered during concept design and preliminary design.

2.5 Aim

The overall aim is to bring the first two phases (conceptual and preliminary design) closer together. The more requirements of the preliminary design are considered during the concept phase the less modifications have to be redesigned which might be at this stage very time consuming, very expensive and certainly heavier in weight. In addition the confidence in the structural concept will increase.

Within the PLATO-N – project this means to create a weight minimised structural concept considering as many requirements of the preliminary design phase as possible. The mass itself should be available as a direct result of the optimisation process. For subsequent tasks the concept needs to be described in a full running NASTRAN- FE- model and its according geometric representation (CAD).

However, the question now is, how to tailor the amount and complexity of requirements to the PLATO-N project potentials in a realistic manner.

For future projects the platform should be developed in a modular manner and to be easily extended with e.g. new algorithms, element types, constraints, visualisation/interpretation methods or, in general, further features.

3 Use Case Definition

This chapter comprises several generic use cases. Each of the described use case has been selected to cover a specific set of applications and/or optimisation issues.

3.1 Small Examples for Validation and General Understanding

As described in WP8 all partners will use their own sample cases and contribute to the PLATOlib (test example library). Although the industrial partners will generate real life applications for testing they are on top very interested in academic sample cases, for which analytical or at least numerically obtained (generally accepted as proven) solutions are available. Thus, for the user's convenience, these well known results of the academic test cases have to be reconstructed, visualised, interpreted and compared. Possible examples are Michell- structures in general, the L-shape and the 2-, 3- and 10- bar- truss, respectively.

3.2 Subcomponent Optimisation

One of the potential applications of topology optimisation methods identified in Section 2.4 considers optimisation of subcomponents that are part of a larger sub-assembly like a wing, fuselage or empennage structure.

Topology optimisation of components is typically performed during preliminary design, when trade studies to find the optimum structural configuration are still possible. Candidate subcomponents to be optimised at this stage of the design process, includes:

- Fuselage fames
- Fuselage floor support beams
- Wing and tail plane ribs
- Wing leading edge ribs
- Wing trailing edge structures like aileron and spoiler brackets

To speed up development times and improve performance the topology optimisation should upfront include as many of the design criteria as possible. Compared to today's process of performing component topology optimisation, see Figure 3.2-1, this would also avoid unnecessary looping between Steps I and II.

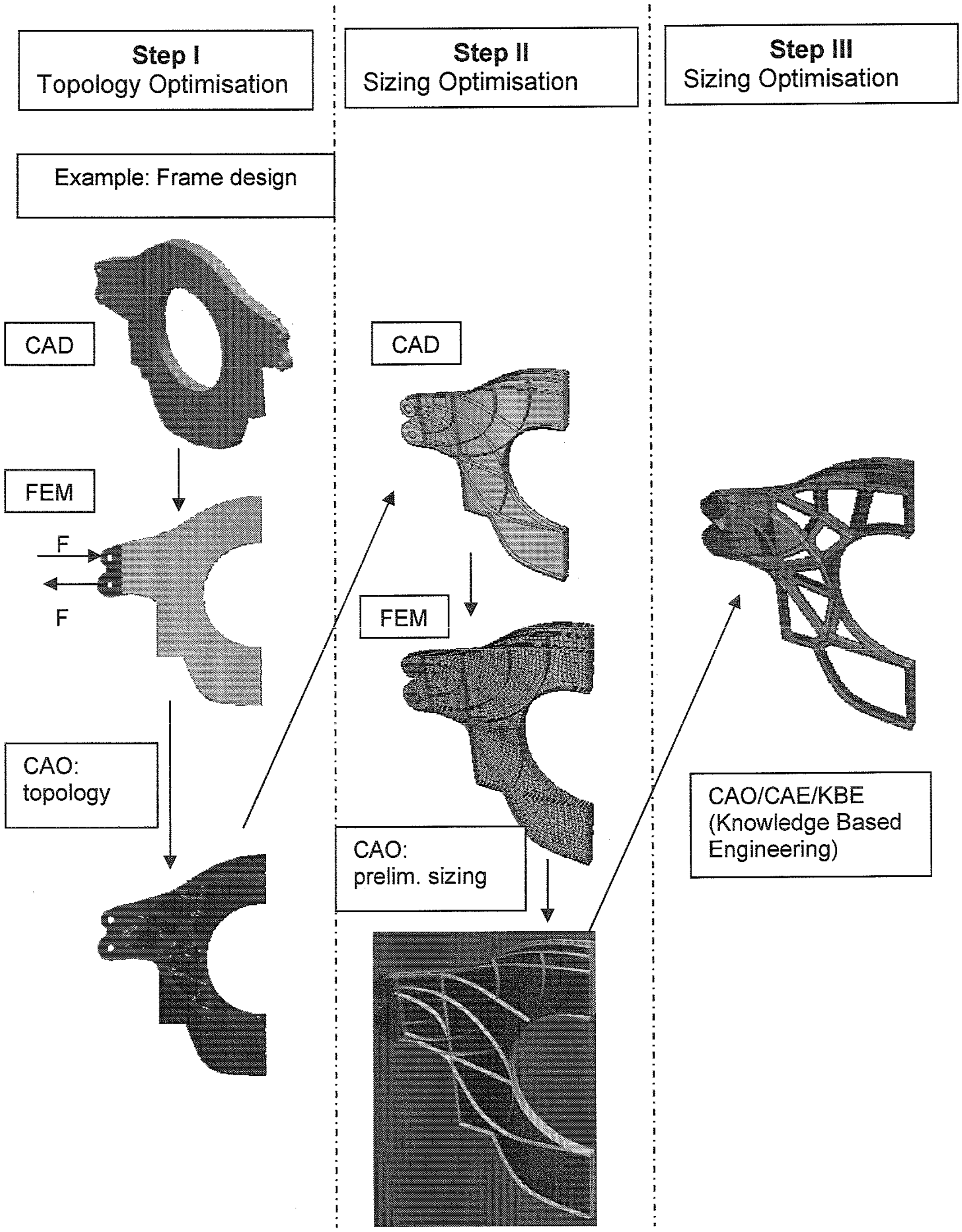


Figure 3.2-1 Conventional topology optimisation design process.

Compared to larger architecture studies, component studies are smaller in terms of overall size but require more complexity in terms of both design detail and analysis accuracy. Figure 3.2-2 illustrates a conventional shear web metal rib design. The stiffened shear web design in Figure 3.2-2 is machined to a minimum thickness of 1-5 mm and may be required to satisfy a multitude of requirements, including for example: buckling requirements, stress and strain requirements and also deflection requirements for lateral fuel pressure cases. Clearly capturing this level of detail is a challenge for topology optimisation.

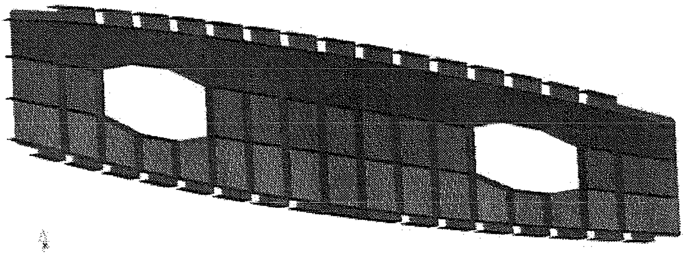


Figure 3.2-2: Conventional shear web design for metal wing box rib.

Figure 3.2-3 shows an attempt to optimise the wing box rib in Figure 3.2-2 using current topology optimisation technology. The compliance based topology optimisation problem formulation used to generate the design in Figure 3.2-2 suggests a truss design as the optimum solution.

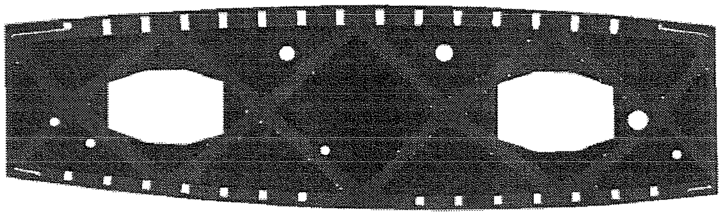


Figure 3.2-3: Topology Optimisation Result for Wing Box Rib

The suggested design in Figure 3.2-3 leaves a number of questions unanswered that can not be easily answered with current topology optimisation technology. For example

a) What would be the optimum design had the topology optimisation been performed using engineering design criteria like buckling, stress or strain?
b) What would be the optimum design had the optimisation been allowed to form shear web designs by not penalising intermediate densities?
c) What would be the optimum design had the optimisation been allowed to use composite materials.

The rib example presented above presents a number of interesting complexities and has therefore been chosen as a use case for air vehicle component optimisation. Although this use case may seem to be very specific, it is aimed to cover a large number of problems seen generally in subcomponent optimisation. The use case description provided in the following sections considers a topology optimisation process form initial model generation through to deliverables of a new design.

3.2.1 General Procedure

A component topology optimisation study is started by generation of analysis and optimisation models. The analysis and optimisation models are typically generated either by refinement of existing FE models or by FE-meshing from CAD-model data. This task is typically performed using an FE pre-processor like for example Altair's HyperMesh.

In cases where a good reference design exist this design is often modelled and analysed. Performing a baseline analysis is a good way to establish an understanding of key design drivers for the component being optimised, but is also when the component is part of a larger structure a key element in establishing reliable components loads for the optimisation.

To establish reliable interface loads for use in a component topology optimisation study the component is typically modelled within a larger global FE model for analysis of internal load flows. An example is given in Figure 3.2-4, which shows the rib in Figure 3.2.2 modelled within a global wing finite element model. Clearly for this purpose the more accurate the stiffness of the component is the more accurate will be the calculated interface loads.

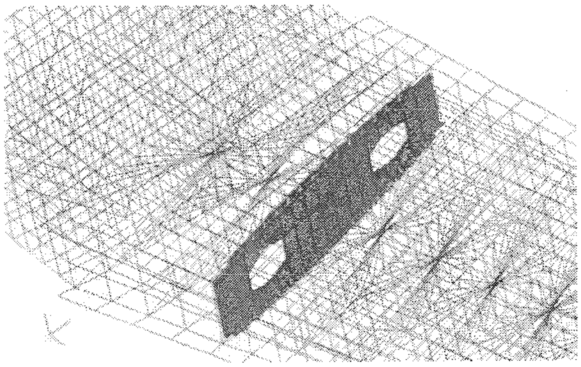


Figure 3.2-4: Baseline rib design in global FE model for internal loads analysis

For validation purposes component interface loads are next applied directly to the local component finite element model with appropriate boundary conditions being applied to model the build-in support offered by the main structure. This step is intended both to validate the extracted interface loads and also the support conditions applied to the local sub-model.

Next to perform topology optimisation; a local design space model is constructed. The construction of this model as either a solid model or a shell model may depend on which kind of structure is expected and also on how the structure is loaded. The constructed topology optimisation model is next subjected to a combination of global interface loads and locally applied loads. The optimisation problem formulation is decided and topology optimisation is performed, typically using varying settings for penalisation of intermediate material densities, and for minimum member size and using varying constraints for manufacturing.

The obtained result is interpreted into a concept design, taking into account manufacturing and functional requirements that could not be accounted for in the optimisation, and this design is then sized using for example finite element based sizing and shape optimisation.

Finally after sizing of the new concept design, the design should inserted into the global FE model for calculate updated interface loads. The loop could then start again as we would have to evaluate how the topology optimisation result and the sizing would change as a result of updated design loads. This here described process is illustrated in Figure 3.2.5.

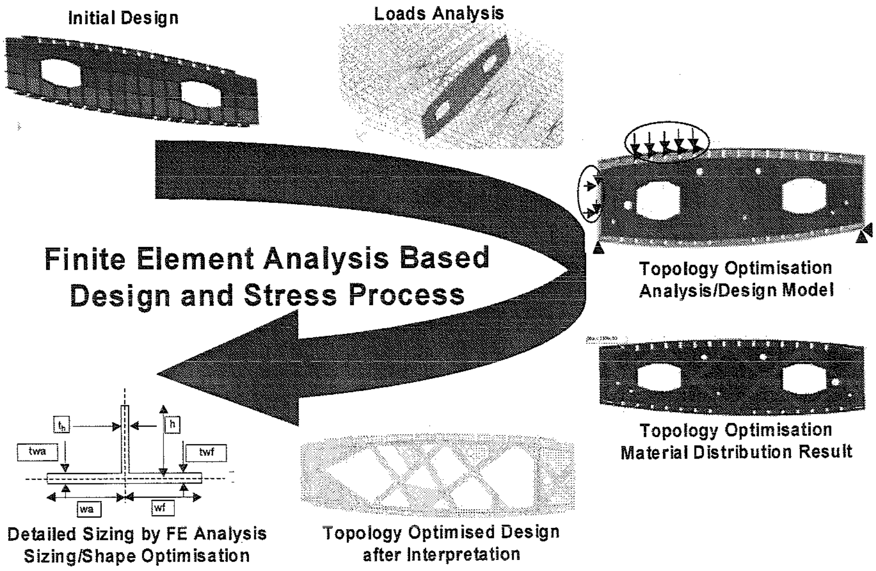


Figure 3.2-5: Finite element analysis based design and stress process

3.2.2 FE- Modelling

Support of a full NASTRAN capability is clearly not required for component optimisation. Still the FE-models could be complex, containing a mixture of element types. To model load introduction and support conditions accurately, the following element types must be available in PLATO-N for modelling of both metal and composite structures:

Solid Elements: CHEXA, CPENTA, CTETRA
Shell elements: CQUAD, CTRIA
Bar / Beam Elements: CROD, CBAR, CBEAM
Rigid Elements: RBE2, RBE3

For definition of load and boundary conditions it must be possible to specify both nodal loads and deflections and distributed loads (pressure). In addition the NASTRAN case control deck enables the combination of several sets of BC-entries providing the possibility of linear superposition of loads and an accurate definition of each single load case (SUBCASE-entry).

In addition the use of super elements should be allowed to allow a condensation of surround structure into just an elastic super-element stiffness and load boundary condition.

A specific problem is related to buckling analysis of sub-components. For such applications it is important that boundary conditions are correctly represented, and it is not always sufficient to model just the subcomponent being optimised, when for buckling modes exist that involves both the subcomponent and also the surround structure. In such situation it may be necessary to model also a part of the surround structure.

3.2.3 Problem Complexity

Aero space structures are generally designed as large thin walled components. A wing box rib like the one shown in Figure 3.2-2 may have a wall thickness in the order from 1 - 5 mm and may be machined from a solid block of material with dimensions 4000x500x80mm.

Conventional topology optimisation methods do not capture the fine detail of such stiffened structures. The topology optimisation result shown in Figure 3.2-3, may have an element size of the order 25mm and therefore a minimum member size of the order of 100mm. Ultimately the result in Figure 3.2-3 may be interpreted into a design with a thin-walled cross section to ensure that the design has sufficient out-of-plane bending capacity to prevent buckling.

One of the goals of PLATO-N is to be able to address very large-scale optimisation problems in order to be able to capture the fine detail of aerospace structures. Therefore ideally FMO should be able to determine both the optimum composite properties of a shear web rib, like the one shown in Figure 3.2-2, and also the optimum stiffener arrangement for this structure. If modelling with solids topology optimisation models would clearly be extremely large.

In addition to large problem size typically topology optimisation problems may be required to consider in the order of 10-20 load cases and in special cases up to 40-50 cases.

Model sizes of this order of magnitude are clearly unpractical when considering problems that involve calculation of buckling Eigen-values using finite element analysis.

3.2.4 User's Deliverables

The deliverable of a component topology optimisation study consist in an optimisation solution interpreted into a new design concept for detailed sizing by e.g. finite element based optimisation methods. To assist the interpretation of topology optimisation results into design solutions, PLATO-N must be supported by strong post-processing tools to visualise and explore topology optimisation results. In terms of FMO PLATO-N tools are clearly required to allow visualisation of for example stiffness properties, including principal stiffness directions, but tools may also be required to realise 2D FMO results into laminate stacking sequences.

3.2.5 Resources

Distributed computing is not established in air vehicle industries to such an extent as in the automotive industry. Topology optimisation runs are today run mainly on Unix clusters build from 4 CPU machines. Pre- and Post-processing may be performed either on Unix or PC's.

3.2.6 Objective & Constraints (FMO)

Topology optimisation of components should ideally be performed by minimising weight, considering relevant structural strength, buckling and stiffness criteria and taking into account manufacturing constraints. Having a correct problem formulation should in principle allow us to use topology optimisation, including FMO methods, for prediction of weight. However, considering the very general formulations used in topology optimisation and FMO this may not actually be achievable. In terms of FMO it is at present not fully clear how constraints should be formulated to ensure correct and meaning full designs once the FMO solution is converted into for example a laminate solution satisfying manufacturing rules. What is clear is the need for constraints to control strength, stability and stiffness of the solution and furthermore the need for constraints to push the solution towards a manufacturable design.

3.2.6.1 Objective Function

The objective function in air-vehicle component design is clearly weight or an equivalent measure like for example volume of material.

3.2.6.2 Constraints

Constraints to be considered during component design should clearly include both structural constraints and constraints for manufacturability. The selection of structural design criteria to be used in topology optimisation of statically loaded components, should include

1. **Compliance/Deflection Constraints**
   In terms of structural constraints for static design, currently topology optimisation is limited largely to consider compliance and deflection criteria. Currently most topology optimisation work is performed using these criteria either as objective functions or as constraints. These criteria must therefore be present within PLATO-N.

2. **Stress/Strain Constraints**
   Basic strength failure criteria will have to be defined, considering both stress and strain formulations. Typically for metal structures a preferred method could be to use the von-Mises-Henkey stress formulation, whilst for composite an equivalent strain failure criteria must be defined. Composites strain failure criteria are typically formulated at a ply level and it is not clear how such criteria can be formulated for FMO applications.

3. **Stability Constraints**
   Thin walled and slender aerospace components are naturally prone to instability, and this key criterion should therefore be available within PLATO-N. In component design it is important to control both local and global instabilities. Typically shear web designs are allowed to post-buckle locally at a given load level, whilst global buckling is avoided. It may therefore be necessary to track local / global modes and optimise with different requirements for local / global modes. Another problem related to stability constraints is the need to sometimes model part of the surround structure to obtain correct boundary conditions for modes which extends into the surround structure. In such situation special filtering techniques may have to be developed to allow determination of which modes are local modes to be controlled by the optimiser and which modes are pure surround structure modes not to be controlled.

It is believed that the above set of constraints will cover most topology optimisation component applications. In addition to these structural constraints, constraints should be available to limit the FMO search for solutions to certain classes of laminates. For example we could imagine limiting the solution search to the class of symmetric laminates, hence avoiding problems with cure distortions in manufacturing.
It may be possible to formulate such laminate constraints by requesting certain terms of the elastic tensor to be zero. Finally, it would be desirable if manufacturability constraints could be available to control the smoothness of the developed solutions, both in terms of thickness variations and in terms of variations of anisotropy.

3.2.7 Robust Design

The robustness of topology optimisation solution with respect to especially load variations is a significant concern. Topology optimisation should for maximum benefit be used early in the design process where loads are very uncertain. Ideally this uncertainty should be considered during topology optimisation. In classical topology optimisation this could drive the decision between a truss design and a shear web design while in free material optimisation this could drive the decision between a very specialised highly anisotropic solution and a less specialised more isotropic solution. It is clearly important to ensure that optimum designs being chosen during concept design are also at least "near" optimum solutions during detailed design.

3.3 Major Component Optimisation

This use case deals with optimisation of major aircraft components such as shown in Figure 2.1-1. For this kind of problem the question is, having a design space limited by the outer (aerodynamic) loft and the inner usable space (passengers, cargo, fuel, systems etc.), where to distribute material to achieve a weight minimal structure satisfying all necessary requirements. In more practical terms this means e.g. to quantify the stringer- / frame- / rib-pitch which is an essential conceptual decision since these structural elements act as a reinforcement of the skin in terms of retaining the overall cross section and in terms of buckling field support.

The following subchapters describe in detail the optimisation process from an engineer's point of view, beginning at the project start meaning the engineer's input via the engineer's activities up to the program expectations i.e. the engineer's deliverables.

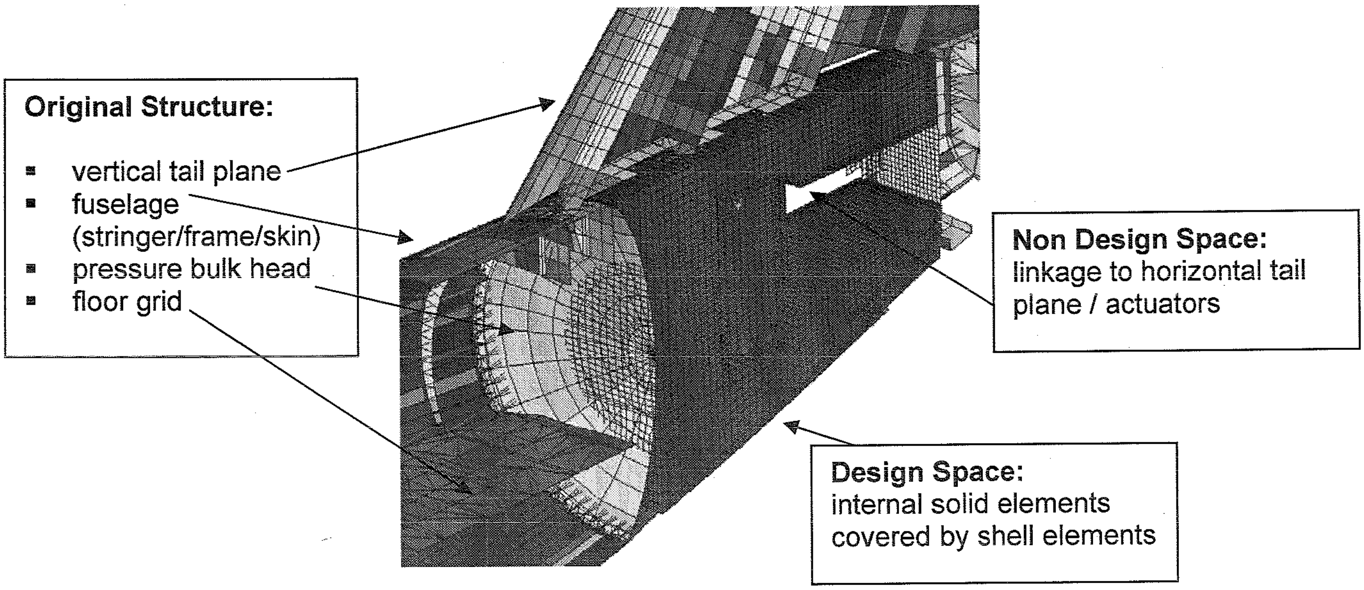
3.3.1 General Procedure

On a basis of an FE- or CAD-model the analysis model and the optimisation model have to be generated. Thus a strong pre processor is necessary offering lots of features concerning geometry clean-up, (batch-/re-) meshing and visualisation, e.g. Altair's HyperMesh.
Standardised data I/O-file formats (FE: NASTRAN / Geometry: IGES) should be used to avoid unnecessary translators in case of data exchange with other CAE/CAD-tools. The data management between pre-processor, solver and post-processor should be handled in a modern man-machine-interface (MMI) manner (full automatic or graphically supported).
As a result a well understood structural concept is requested, which is ready to be handed over to the preliminary design phase. This means a detailed report for general understanding, geometric data for CAD- issues and FE- data for CAE- purposes have to be available. It is surely a post processing issue to support the user to interpret the result and to convert it for subsequent tasks.

3.3.2 FE- Modelling

Certainly the full NASTRAN functionality is not required, however, the FE-model might be rather complex (see Figure 3.3-1). Thus several element and property types are mandatory (in NASTRAN – language):

- CHEXA
- CPENTA
- CTETRA
- CQUAD with membrane-, plate- and shell- properties (PSHELL / PCOMP)
- CTRIA with membrane-, plate- and shell- properties (PSHELL / PCOMP)
- CROD/CBAR
- CELAS (spring elements)
- Rigid elements like RBAR, RBE2 and as a special kind the RBE3
- General element like an external stiffness/mass matrix (KAAX/MAAX) e.g. representing an elastic support incl. its according set of load vectors (PAX)



Original Structure:

- vertical tail plane
- fuselage (stringer/frame/skin)
- pressure bulk head
- floor grid

Non Design Space: linkage to horizontal tail plane / actuators

Design Space: internal solid elements covered by shell elements

Figure 3.3-1 Complex FE- Model

In general the definition of the (load case dependent) boundary conditions contains two different possibilities:

- nodal defined BCs (FORCE, MOMENT, SPC (fixed or enforced displacements))
- distributed BCs affecting more than one node (PLOAD (as pressure), MPC)

The NASTRAN case control deck enables the combination of several sets of BC-entries providing the possibility of linear superposition of loads and an accurate definition of each single load case (SUBCASE-entry). Special attention has to be paid to the potentially load case dependent MPCs, since the commonly used method to consider them results in more than one global stiffness matrix and thus in very high computational efforts. However, the usage of load case dependent MPCs makes it possible to analyse different configurations of e.g. doors (opened/closed) or flaps/slats (fully, partially or not extracted).

3.3.3 Problem Complexity

Since the project deals with large scale optimisation algorithms, the model size is expected to comprise 10^6 degree of freedom (DOF) and about the same amount of variables in a multi-load case scenario (up to 20 load cases). However, to reduce the complexity it is necessary to use a kind of substructure technique meaning either a full super-element analysis or at least the definition of a sub domain as design space or as a substructure for Eigen value analysis (dynamics / stability). Another powerful method to reduce complexity could be to start with a course mesh and refine it automatically with the progress of the optimisation iterations. Cause of the large scale it is mandatory firstly to use robust and stable algorithms and secondly to provide a restart- possibility.

3.3.4 User's Deliverables

In general the project's need is to generate a structural concept which should be easy to understand with a correct mass information. For interpretation, presentation and reporting the user has to visualise the results. For further investigations he has to provide the designers with geometric data and the stress and/or the optimisation department with a complete and running (NASTRAN-) FE-model, both extracted from the optimisation result. The FE- model itself shall not contain any 3D- elements (slender structures). Thus a reduction (skeletonisation) to the 1D- and 2D- domain is necessary. FMO deals with generic anisotropic materials which properties have to be interpreted and mapped into a reasonable stacking sequence of a given unidirectional layer material. Certainly it is technically possible to use an anisotropic constitutive law within the FE- simulation but physically this is not sufficient, since finally the concept should end up in a manufacturable air vehicle.

3.3.5 Resources

Computer:

Nowadays distributed computing is not established in air vehicle industries to such an extent as in the automotive industry. Thus stand-alone PCs (single- and dual- processor) and small - not to say tiny - clusters are available. However, in future one can imagine that clusters will be built up to achieve more computational power supporting more parallel processing. In addition the transfer to 64- bit technology at least in the Linux environment is in progress and certainly will be finished in a few years. For smaller applications a Windows version should be available as well.

Time / personnel:

Once the problem has been set up by a single engineer meaning the necessary input data has been generated in a reasonable time the optimisation jobs will be performed. Often there are parameters to be varied resulting in a whole optimisation study. Thus one job should not last more than at most one night to have the results available on a next day basis. This requires certainly very stable algorithms.

3.3.6 Objective & Constraints (FMO)

For a good performance of an air vehicle it is most essential to minimise the take off weight and especially the pure structural weight whilst the payload remains constant. On the other hand the structure has to withstand the aerodynamic/inertia loads. Thus the optimisation problem may be defined from a engineering point of view like minimise weight subject to several constraint preventing any failure of the structure. In a mathematical sense the problem might be reformulated carefully, as far as the new formulation is equivalent or dual. However, the weight is an important information of the optimised design.

3.3.6.1 Objective Function

Naturally it is reasonable to use the global aim of a problem as objective function. In this case this would be the weight of a (sub-)structure. However, if it is possible to find an equivalent formulation to it, recovering the weight afterwards, it is sufficient.

3.3.6.2 Constraints

All potentially occurring failure modes have to be covered in the final design. On top there are additional demands to be satisfied e.g. manufacturing-wise or performance-wise. Focusing on classical lightweight structures the most important issues are static strength and stability needs. Concerning dynamics the stiffness- and mass- distribution is essential, which influences the (aero elastic) performance as well. Since the stiffness-distribution affects the global structural behaviour, special attention has to be paid on it.
For sure the list of desirable constraints is too long to be covered within PLATO-N, thus they are prioritised and selected carefully:

1. Stress constraints: Basically a failure criteria has to be defined. FMO deals with scaled values for stiffness thus it is natural to use scaled stress allowables as well, however the equivalent applied stress should allow for somehow considering the different levels of tensile and shear allowable stress. Preferred method is to calculate the von-Mises-Henkey stress. For discrete lay-up optimisation real allowables have to be used layer-wise. Often only allowable strains are available, thus a strain based criteria is more practicable.
2. Stability constraints: Slender structures like in aerospace applications are naturally prone to instability. For reduction of the Eigen value analysis complexity it is desirable to define substructures for which the stability analysis should be performed. On the other hand the concern is more on the global buckling behaviour than on local modes, which affect only few elements. Of course the design has to withstand all loads with respect to stability (all load case dependent Eigen values greater than one).
3. Dynamic constraints: Sometimes it is necessary to raise the natural frequency to a higher level or to avoid a specific frequency range.
4. Displacement constraints: In general they allow for defining stiffness requirements. Complex displacement constraints may restrict the structure to deflect only up to a specified extend e.g. the global wing torsional movement. In a certain sense one can map aero elastic issues into a generalised displacement constraint but this is never a real substitution of aero elastic design criteria.
5. Aero elastic constraints: Although they might be out of the scope of PLATO-N, they are listed here to highlight their particular importance. On the one hand there is the opportunity to adjust the loads for e.g. the cruise flight condition gaining a lighter structure and less fuel consumption (less drag). On the other hand there are performance requirements like control surface effectiveness to be satisfied and failure modes like (static) divergence or (unsteady) flutter to be avoided.

3.3.7 Selection of Design Freedom

Certainly FMO will provide a result having ultimate design freedom. This information is desirable to have an idea of the best design. However, to tailor the final design to real world applications (manufacturing-wise), some restrictions should additionally be possible to select:

1. To avoid element-wise micro-mechanisms the material should adhere to a physical continuum. This means specific entries in the material tensor are positive (diagonal terms) whilst others are negative (transverse contraction terms) and the matrix has to be diagonal dominant. ($(0 \leq \nu_{ij} \leq 1)$; theoretically ν_{ij} might be in the range of $(-1 \leq \nu_{ij} \leq 1)$, but physically $(-1 \leq \nu_{ij} \leq 0)$ means a mechanism, in this context element-wise)
2. In general orthotropic materials can be manufactured. Orthotropic and/or isotropic properties can be achieved by manipulating the constitutive law a-priori or during the

optimisation iterations (more complex). The latter might find a better design since the design freedom is reduced gradually.

Nevertheless it is useful to deal with the ultimate design freedom, since all additional restrictions end up in a non-optimal design.

3.3.8 Combined Optimisation

In general an air vehicle structure consists of two different classes, an outer cover defining the aerodynamic surface and an inner support structure.

Outer cover:

Certainly the outer cover/loft has to exist and shall not vanish during the course of topology optimisation. Therefore the problem formulation, like the variable thickness sheet (VTS) approach, has to allow a lower gauge for the thickness of 2D- elements.

Inner support structure:

The inner support reinforces the outer cover. There might be void areas due to systems or any other (non- load- carrying) devices excluded from the design space. Usually the internal space is filled up with 3D- elements in a first approach. If more detailed load path information is desired, a second approach, interpreting the results of the first investigation, refines the areas of elements exceeding a given 'density'- threshold and possibly reverts them into the 2D – domain. This means, that a FMO- formulation is necessary which allows both, 2D- and 3D- elements to be optimised simultaneously.

Combined structure:

Regarding both structural classes together, it is necessary to use the FMO- and the VTS- formulation simultaneously. Of course this separation has to be supplied by the user in the input deck, where he has to divide the total design space into two sub domains and control both of them.

3.3.9 Robust Design

During the concept design phase many parameters, even customer specifications, are still not fixed, and may vary in a certain range. Since mathematical programming results in single (local) optima satisfying exactly the given problem, small variations in the problem are not considered. In reality small variations of parameters may result in a possibly different structural design. To cover these uncertainties e.g. in the loading, which might be a rough estimation in the concept phase, robustness becomes particularly important. The aim is, that small imperfections on the parameters conditions do not affect the gained topological concept significantly.

3.3.10 Stacking Sequence (Mixed Integer Programming)

For subsequent tasks like engineering and design it is not sufficient to extract 2D- material tensors. Furthermore a discrete composite lay-up (PCOMP/MAT8) is required. This can be obtained in two different ways:

1) Without FMO

In this case the overall problem, minimise weight subject to several constraints, has to be solved within the mixed integer programming framework. This approach leads to a complexity which might be beyond the limits of branch and bound algorithms to be computed in a reasonable time. However, it is possible and for sure useful for validation of round up-FMO results within a range of academic test examples.

2) Using FMO results

Once the FMO has converged, its results comprise a specific material tensor for each single element. Now, the aim is to find a stacking sequence which matches the material law element-wise. Therefore it should be possible to use the mixed integer programming for determining the composite lay-up element-wise with a small number of variables. Since the FMO- job has considered the global constraints, it is now possible to introduce local element-wise constraints, e.g. manufacturing, for the lay-up itself. Once the material law is met with the optimised stacking sequence the global constraints are satisfied as well.
Obviously this is a typical post processing issue, which should be initiated by the GUI of the post processor.

3.3.11 Result Interpretation

Some efforts have been made so far, to simplify the FMO- results (see 3.3.7 and 3.3.10). However, it is desirable to get an idea how the ultimate freedom design acts and how it looks like. Therefore it is essential to support the user in the visualisation and interpretation.

First of all after pre processing the user needs to understand the input model itself. Of course the user builds it up, however, for explanations and presentations it is necessary to provide all input data in pictures or better in animations. The issues for that are:

- The defined elements belong to three different unique domains (fixed elements, VTS-design space and FMO- design space) and should be coloured accordingly.
- The load case dependent boundary conditions have to be display individually.
- Special elements like the rigid elements should be coloured differently.
- Interface grid points of condensed stiffness matrices should be highlighted.
- Re-use of element-sets defined during pre processing.

During the optimisation process the following data from the consecutive iterations should be stored and visualised either as a transient animation/chart representing the optimisation history or as a steady state animation/chart comprising only one single (e.g. the final) iteration:

- Trace and single entries of the material matrix
- Main material directions (not necessarily orthogonal) and their according stiffness values
- Material classification
- Displacements
- Individual terms of the objective function and their according weights.

At least for the steady state animation it should possible to display the load case dependent boundary conditions and deformations to verify the structure's reaction on the loads.

Since complex models in the 3D- domains have to be interpreted it is essential to implement several features in the post processor:

- Zoom
- Rotate
- Translate
- Iso-domains incl. values above/below the iso-value
- Clipping
- Streamlines of vector data (e.g. main material axis)

The usage of iso-value- animations may result in a non-connected structure. Thus it is desirable to interact by defining a potentially smaller local iso-value at a specific region.

Figure 3.3-2 depicts an iso- value plot of elements of equal and higher densities than a chosen threshold. FE- clean-up algorithms are necessary to interpolate the elements geometry to gain firstly a smooth surface and secondly a skeletonised design (e.g. map a 3D-beam into a 1D-beam). An automatically generated interpretation, where to put 1D- and where to put 2D- structural elements (truss vs. shear web), might be useful, however, manual interaction is required as well.

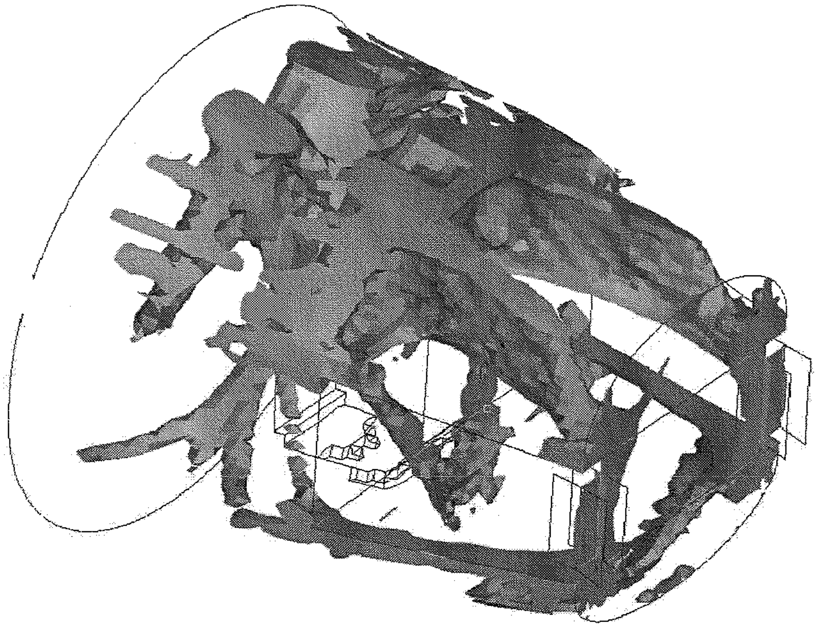


Figure 3.3-2 Result of a compliance optimisation

Finally the post processor should support a variety of export functions:

- Screenshot-like pictures in jpeg- and postscript- format
- displayed (iso-)design in a compact (binary) format
- Geometry of the displayed (iso-)design: surfaces and solids in IGES- and STL- format
- Finite element model of the displayed (iso-)design including their properties even after skeletonisation

Note: After mapping 3D- elements into 1D- or 2D- elements their according properties as well as their material definition might not be available at this stage. Since this data is required for subsequent simulations, it is mandatory to create the necessary information automatically at least with default entries. User interaction then is required to adjust the values manually. Once the FE- model is set up correctly the post processor should be able to start the re-analysis.

For interpretation and presentation tasks it is desirable to have a viewer available which provides very limited functionalities of the full post processor just to visualise exported designs. Thus a designer or a stress engineer has the possibility to have a detailed look at the results without the necessity to learn anything about the usage of the (additional) post processor. This concept has been successfully pursued by Altair with their freeware HyperViewPlayer, which is gladly used in industry.

4 Generic Process of FMO- Studies

This chapter comprises a bullet-style description of typical actions to be performed by the engineers throughout a single cycle of an optimisation study. The responsible department and, if applicable, the software application is specified in brackets:

Generation of the Analysis- Model (pre processing: e.g. HyperMesh)

- Definition of geometry (Design/Aerodynamics)
- Meshing/Modelling (Stress/ Optimisation)
- Definition of boundary conditions ((Aero-)Dynamics, Loads, Mass ...)
- Application of loads & support (Stress/ Optimisation)
- Definition of analysis type: Static, Dynamic, Buckling, Aero elastic ... (all disciplines)
- Quality evaluation and assessment of the FE- model wrt all types of analysis (all disciplines)

Generation of the Design- Model

- Definition of the design space (Design/ Optimisation: pre processing)
- Preparation of element sets (i.e. grouping several elements to one set) in pre processor (Optimisation: pre processing)
- Export of the sets in FE- deck (Optimisation: pre processing)
- Assignment of variable type to the sets (2D FMO, 3D FMO, 2D VTS) (Optimisation: FMO studio)
- Definition of lower and upper boundary for VTS- variables (gauges) (Optimisation: FMO studio)

Generation of the Criteria- Model (Constraints)

- Preparation of element sets as (regionally defined) response domains (Optimisation: pre processing)
- Export of the sets in FE- deck (Optimisation: pre processing)
- Assignment of element sets to the constraints (stresses, frequencies, buckling loads, global and/or regional compliance, volume, robustness) including the lower and/or upper boundary as values (Optimisation: FMO studio)
- Definition of displacement constraint: Node ID, DOF, value or linear combinations (Optimisation: FMO studio)
- Definition of control parameters (e.g. number of computed Eigen values) possibly exported in separate file (Optimisation: FMO studio)

Definition of the Objective Function

- Selection of the appropriate objective function (Optimisation: FMO studio)

Execution of the Optimisation Studies

- Selection of the optimisation solver (Optimisation: FMO studio)
- Control of the entire calculations ((re-)starting, monitoring) (Optimisation: FMO studio)
- Tuning of optimisation parameters (Optimisation: FMO studio)
- Adjustment of the FE- model (e.g. introduction of missing cross sectional data of bars) (Optimisation: pre processing)
- Consideration of different optimisation solvers (cascading) (Optimisation: FMO studio)

- Gradual increase of the studies' complexity in terms of extending the design space and/or the criteria model (scheduling) (Optimisation: pre processing, FMO studio)

Result Exploitation (post processing: FMO studio via HDF5 and/or HyperWorks via OP2)

- Graphical visualisation of all obtainable results in an appropriate manner
- Recovery of geometric surfaces
- Support of the transfer of the topological results into structural elements (skeletonisation)
- Recovery of laminate stacking sequences of shell elements meeting the FMO-resulting material properties
- Reporting

5 Summary

From an industrial point of view, Plato-N is a promising project in which industrial needs are directly considered by the academic partners in developing new methods and algorithms. Thus, this top-down research work can be used in industrial application afterwards.

Looking at a generic design process, several use cases are derived. They comprise the full range of work, that has to be performed by the engineer. After the input generation he will perform the optimisation studies using scheduling- and cascading- techniques. Finally he will interpret the achieved results and provide a detailed structural concept in terms of a geometric parameterisation for both, subsequent CAD and CAE tasks.

The main issues for the project are:

- Complex FE- model representation
- Different design sub domains with according aims
- Consideration of multiple design criteria: strength, instability, stiffness requirements & robustness
- Stable solver & optimisation algorithms for very large scale applications
- Pre- & post- processor easy to handle with sophisticated features for input generation and result exploration
- Clearly arranged platform architecture enabling a successive extension in the future

Certainly the user's demands concentrate on pre- and post- processing, whilst the specific optimisation features are user-wise only a small, but possibly essential flag of the algorithms in the background. Concerning the academia the development and implementation of the algorithms may be of more interest than the graphical user interface. But the engineer will not go into coding details, he would like to work with a GUI. Therefore the academic partners are requested to provide a software package, which is easy to handle and accurately described in comprehensible manuals.