Project Report
26575
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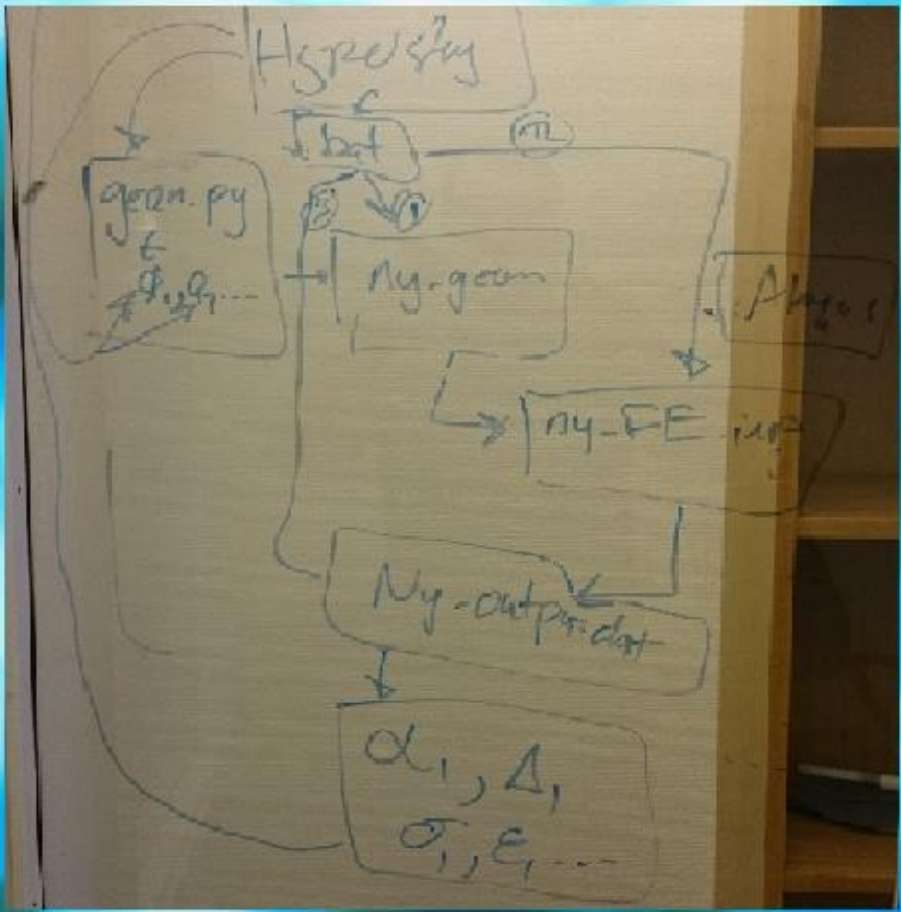

Optimization of product properties

Three practical cases

2018-06-01

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Preface

This project, Digital pilot för optimering av produktegenskaper – diarienummer 2017-01542, is sponsored by VINNOVA as part of their founding program “Digitalisering av svensk industri – Nya piloter våren 2017”. The project has a predecessor named “Datorstödd struktur och material optimering” also sponsored by VINNOVA within the founding program SIP Lighter. Both projects were managed by Swerea IVF AB in close cooperation with the industrial partners.

Participants in this project were:

Research organizations:

Swerea IVF AB

Swerea Sicomp AB

Industrial partners:

GKN Aerospace Sweden AB

Lamera AB

Husqvarna Aktiebolag

EnginSoft Nordic AB

Altair Engineering AB

The duration of the project was from 2017-03-01 to 2018-03-15.

Acknowledgements

Except for the authors substantial and valuable work in this project were done by Peter Ottosson at Swerea IVF AB, Mohammad Rouhi at Swerea Sicomp AB and Pär-Ola Jansell at Altair Engineering AB. We also would like to thank our industrial partners for their support in this project.

Content

Summary

The work in the project were divided into three practical cases. One for each industrial participant. One of these are confidential. The other two are:

- Simulation of the use of sandwich metal
- Optimization of an aircraft engine part

These two are described in this report and the results from the confidential case is described in general terms.

The overall results are:

- Digital optimization and simulation were tested and proven feasible.
- Optimization and simulation tools are powerful and accurate if used correctly.
- Special skills are required to handle these simulation software. Suitable education is a Master of Science degree or doctoral degree with specialization in optimization and simulation.
- Parameters that can be improved by using the CAE tools used in this project are:
  - Lead time in business situations
  - Physical properties such as:
    - Weight
    - Stiffness
    - Shape
- Detailed calculations can be done on carbon fiber reinforced epoxy structures.

The results indicate that CAE/Digital tools within different application areas clearly can support the dialogue with a client in supplying accurate facts about the products in a shorter time compared to the previous set up with absent of the Digital tools. Therefore, the use of the CAE tools clearly strengthens the competitiveness of Swedish enterprises in a global market.

A short video sequence has been prepared where participants in the project describe the advantages of the project and what the project has contributed to their daily based business activities. Furthermore, a PowerPoint presentation is available as a collection of the project outcome. Both the video and the presentation material can be used as digital documents in seminars or other dissemination activities to share the project results and knowledge.

Introduction

In product development today, computer simulation models is used because they typically:
- Reduce development time
- Increased knowledge about products being developed
- Decrease development costs

Most products on the market are optimized in some respect, but often by manual efforts. Even though this is a great start, there are good reasons why dedicated process automation and optimization tools are now becoming popular. The systematic design optimization approach allows engineers to:
- Explore huge design spaces
- Improve collaboration efficiency with colleagues, suppliers and customers
- Find better designs and making better decisions

In this project we have used both topology optimization applied to structural components and the general parametric approach based on design variables. Parametric optimization allows engineers in the same design task to include results from different engineering disciplines like structural analysis, computational fluid dynamics together with manufacturing considerations and product cost analysis. This unique characteristic positions the parametric approach on the same level of importance as financial and customer relations software in the company. As demonstrated in this project, it is also equally useful to support the needs of a single engineer.

Regardless the expected complexity, the preferred startup of an optimization task include definition of:
1. Results which measure the performance of a design candidate
2. Simulation models providing the results
3. Design variables which affect the results of interest

A design variable may be a length, a radius, number of holes, choice of material or similar and the volume defined by all design variables together create your "design space". The combination of simulation models, automatic evaluations controlled by smart algorithms has opened the door for a change in design methodology.

Consider the situation where an engineer do manual design iterations based on a simulation model, each iteration provide very little system information and keep the engineer busy with repetitive tasks thinking about which design variable to change and how much. Using the automatic process the engineer would execute a design question like "provided you may change design variable 1 (like a radius) between 3 and 8 in step of 0.1, design variable 2 ... ; please find the design candidates with the highest performance, lowest production cost and all the best compromises in between". The engineer is now released from the repetitive tasks and may focus on the value creating evaluation of results, understanding system performance and deciding which of the best compromises to select.

As long as engineers have existed, engineers intuitively have searched for the optimal design. Finally, our computer aided engineering (CAE) tools are ready to support them and allow companies to capture competitive advantages in the process.

Application cases within the DOPP project

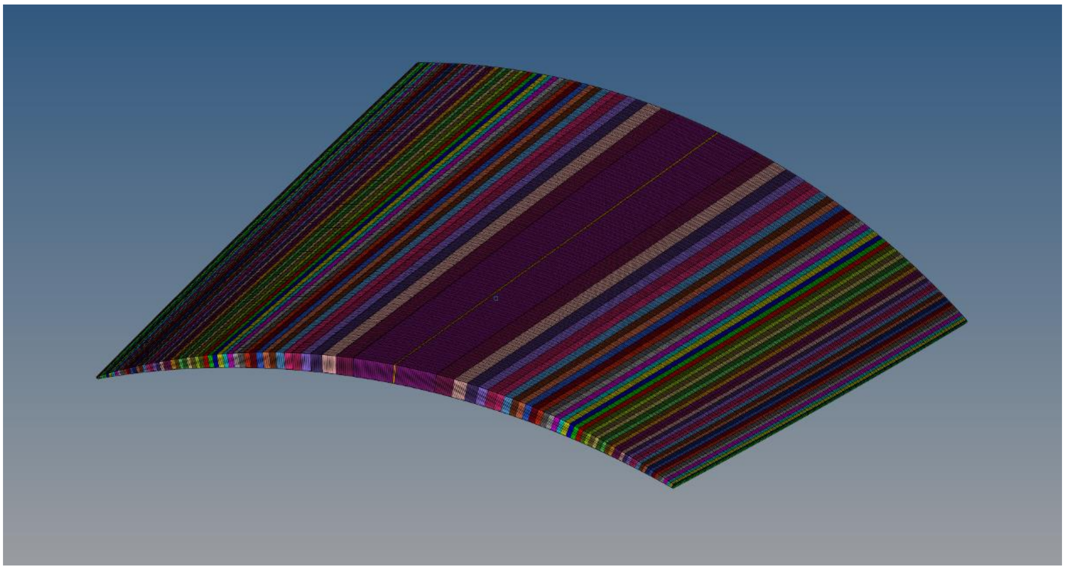
This project contained three practical cases where simulation and optimization tools were applied. In this report are two of these cases described. The third case is partly confidential and is for this reason only partly described.

Optimization of a compressor blade of an aircraft engine

In this chapter a brief description is made of how a system of digital tools is set up to optimize the structure and layout of a carbon fiber reinforced plastic (CFRP) compressor blade.

Problem description

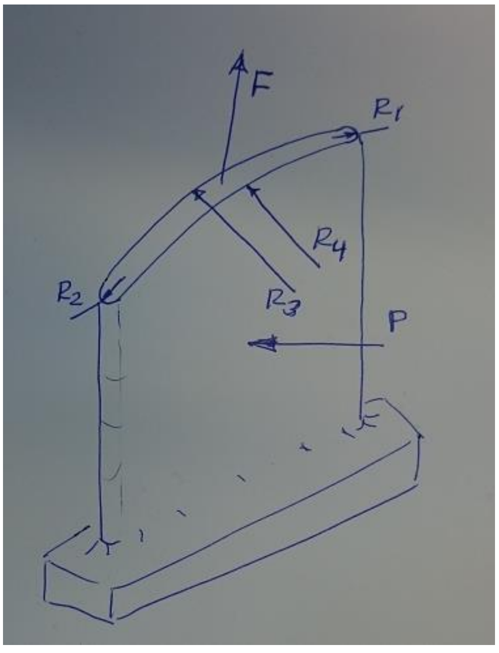
The blades outer shape is designed to optimize aerodynamic performance using advanced CFD (Computational Fluid Dynamics) simulations. This kind of blade is traditionally made from titanium alloys, and represents the lowest weight solution using conventional aerospace metals capable of withstanding the loading conditions. In a constant effort to save weight, alternative materials are investigated. One such promising material is CFRP (Carbon Fiber Reinforced Plastics). As CFRP is approximately 40% of the density of titanium, a CFRP solution would represent a significant weight savings for the same volume. The assumption is that a CFRP bladed will be lighter and still sufficiently stiff and strong to withstand load to an acceptable extent. The outer shape of the blade cannot be changed, without impact on aerodynamic properties, but the internal structure of the blade can be varied. The geometry of the blade is built up using layers of carbon fiber, presumably in a matrix of epoxy, however the parameterization implemented in the model allows easy adjustment to the material properties to evaluate alternative fiber or matrix materials. By parameterizing ply thicknesses and the direction of the fibers in each ply, numerical algorithms can be used to vary the internal structure to find optimal configurations with the best mechanical performance for a given set of materials.



Picture 1. The blade is made up of plies of uni-directional (UD) carbon fiber. Each color in the picture above represents a section of the blade with a different number of plies within the stack.

Load case

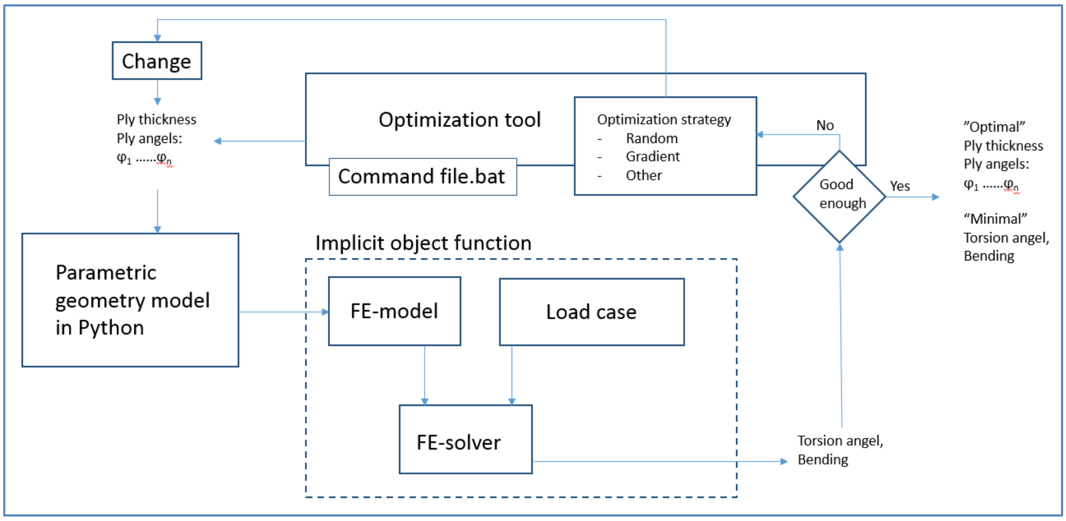
The load case considered in this work is a radial force, F, due to centrifugal effect from the rotation of the compressor and a distributed force, P, due to the compression on the pressure side of the compressor blade.



Picture 2. The load case of the compressor blade

Optimization of the internal structure of the blade
The shape of the blade is described numerically with four circles, corresponding to the inner and outer radius of the blade (pressure and suction side respectively), and a leading and trailing edge radius, a vertical height of the blade, and a degree of twist. The internal structure is created using a Python script. The geometric volume of the blade is filled with plies of carbon fiber to the maximum extent allowed by the layer thickness for a given configuration. Within the script, the fiber alignment, i.e. ply angle, is made to be an independent variable that can be altered within a design loop to rapidly evaluate numerous configurations. See picture 3.

The python script generates input data for the FE solver Abacus, to perform a structural analysis of the blade, and to calculate the torsion angel of the blade due to the load case described above, the bending displacement of the blade tip, as well as the stress state within the part.



Picture 3. The principle setup of the calculation system used.

The question asked now is how the internal structure shall be changed to improve the mechanical properties of the blade. A design engineer can of course change the internal configuration by feeding the Python script with new input data, however improved results would be dependent on skill, experience, and to a certain degree, luck. If lucky the result will be an improvement, but given the number of variables in the problem (upwards of 60 different ply angles for a given ply thickness) the result can also be a reduction of the designs performance. The nature of the dependency between input data and output is not easily understood, and final designs dependent on significant user input are not likely to be consistent between users. An indefatigable and unbiased helper is needed that can make consistent and accurate assessments on how to change the input for the next iteration based on the output from the previous iteration. This helper is, in this case, an optimization software tool. The optimization tool selects input data, based on a mathematical based strategy for design improvement, and sends it to the calculation system to investigate the impact on the output data. The optimization tool can from its investigations create response models that can be used with optimizations methods to find an optimal combination of design parameters, in this case ply thickness, number of plies and the ply angles, by repeating the process until a good enough result (defined by convergence criteria of the designer) is obtained.

Application of the results

The system created in this work can serve as a tool that can be used to find optimal design of the compressor blade within the capability of the designed model. This system can be used by GKN in their dialogue with their customers to give accurate answers in a business situation where lead time and reliability in given offers are extremely important to gain competitive advantages on a global market.

In parallel with the development of the calculation system for the compressor blade GKN has developed an integrated system where similar models covering the design of other parts (than the compressor blade) of an aircraft engine. This system of integrated models makes up a complex system where design parameters of an aircraft engine can be varied and the impact on other parameters can be seen. This is described more thoroughly in the following chapter.

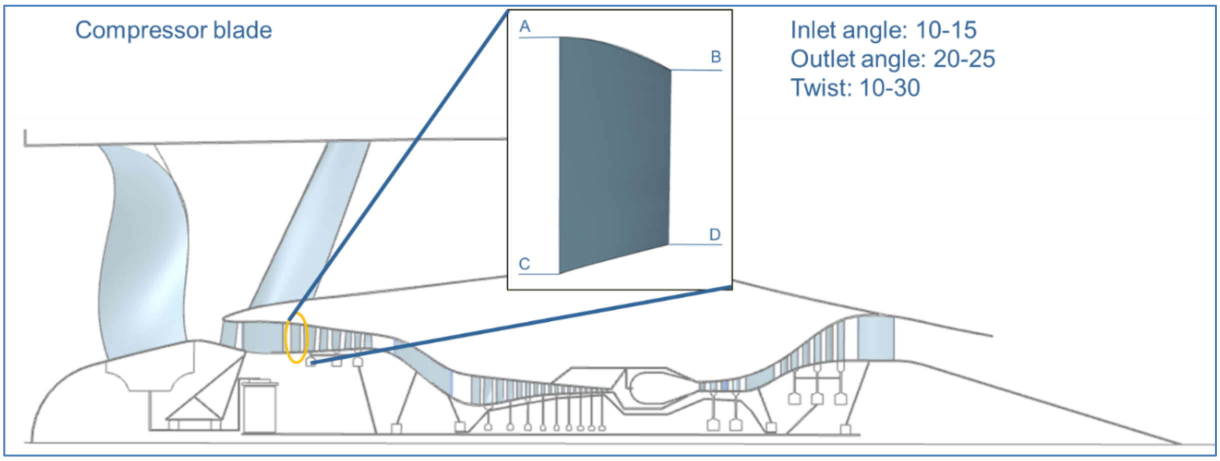
Multidisciplinary Set based design & optimization

The GKN use case describes a simplified scenario in product development where a component supplier interacts with a whole engine model architect and multidisciplinary Set based design is used to reduce development lead time and enable a more optimized solution.

In early phases of product development projects, the design is often scaled from a previous product and the requirements are estimated based on preliminary 1 or 2 dimensional Whole Engine Models (WEM). The WEM architect distributes load requirements and interface positions from the whole engine model down one level for component design. Based on the initial requirements and interface data, the component is designed in a more detailed 3D model. The manufacturing process is defined, aero dynamical and mechanical characteristics including weight are analyzed and feed back to the engine architect that updates the whole engine model. This results in updated load requirements and interface positions to be feed down to update the component design. This is a time consuming process and generates a large number of iterations during a product development project. It is difficult for the WEM architect to fully understand the impact of changes, which often lead to undesirable domino effects and new updates.

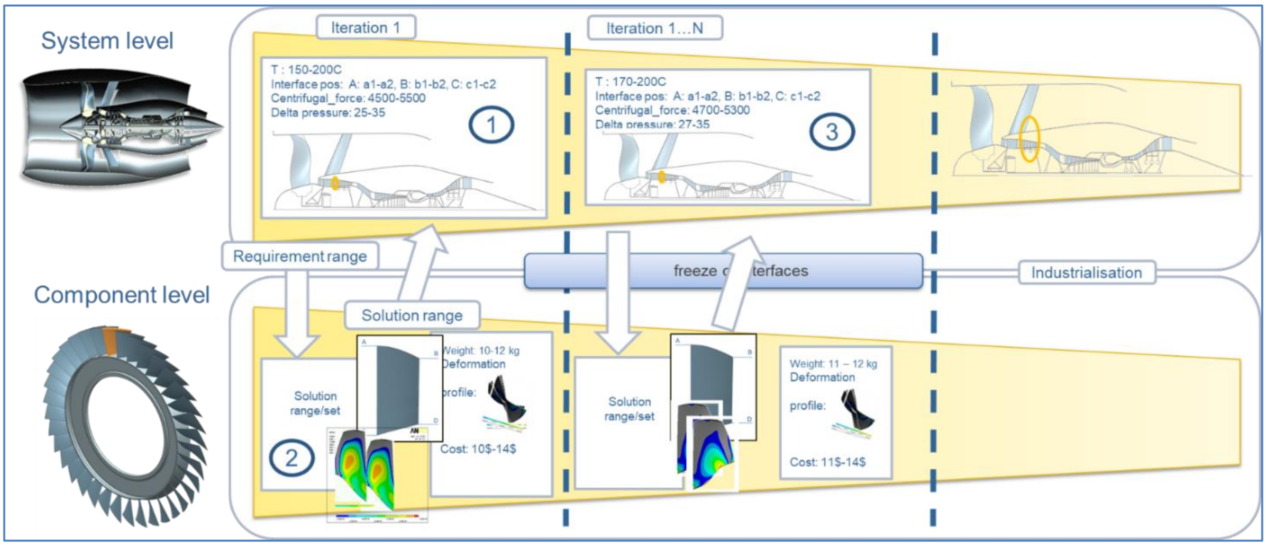
The approach described here demonstrate briefly the use of multidisciplinary set based design with the aim to reduce the number of whole engine model iterations and at the same time obtain a more optimized solution.

In the GKN use case, a compressor blade is design and optimized towards tip displacement, max twist and cost with the purpose to demonstrate the set based multidisciplinary optimization approach, including topology optimization described in separate chapter. The Picture below shows the compressor blade as part of the whole engine model.



Picture 4. The Compressor blade design as part of the whole engine model.

In the GKN example, Mode Frontier is used for modeling the process and generating several designs based on a set of requirements. The set of requirements are here geometrical variation of interface positions A, B, C and D (see Picture 4), ranges of mechanical loads and temperatures.
Instead of designing for a single point in the range of requirements, a set of solutions are designed that satisfies the set of requirements. This results in several optimized solutions using topology optimization that corresponds to the range of requirements. The approach requires a large number of optimization tasks and analysis to provide a spectra of solutions for the design space. The Picture below illustrates the flow of requirement and solutions as ranges (set) between system level & component level. The set based approach provide a better understanding of how the different requirement parameters such as interface position and mechanical loads effect the component and enables a more “robust” design concept, avoiding to choose a single concept that might not meet changes in the requirement later in the product development process. By providing a response surface model instead of a single design, the engine architect have a better understanding of how changes in the requirements effect the mechanical and aero dynamical characteristics of the component and can avoid updates of interfaces that are known to be unfeasible from a component design perspective.



Picture 5. Illustrating the flow of requirement and solutions as ranges (set) between system level & component level in contrast to a point based approach.

The steps are as follows:

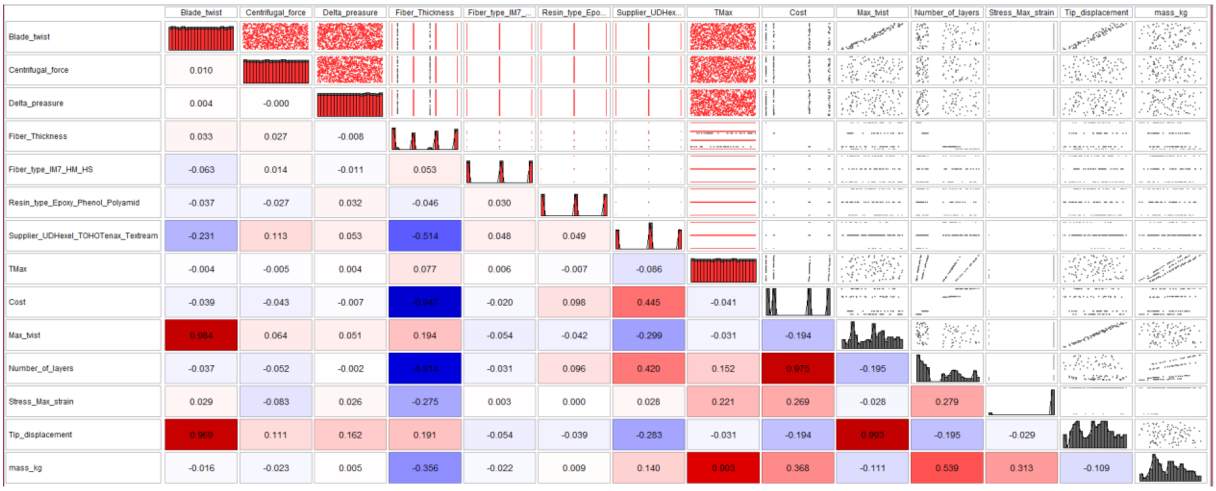
1) The interface between whole engine model and the compressor blade is calculated as a range for each parameter. In Picture 5 the temperature is defined as a range between 150-200 degrees, where the "baseline" temperature is 170 degrees. The inlet outer radius (Parameter A) is defined as a range between the values a1 – a2. The outlet outer diameter (Parameter B) is defined as range between b1 – b2 and so on.
2) A set of solutions of the compressor blade is produced. For each set of parameters is one optimal solution of the compressor blade created. The combinatory effect due to the large number of parameter values generate a large number of compressor blade variants. The solution space of the compressor blade is feed up to the whole engine model/ architect and the consequence including cost model/ trade of curves becomes visible in the whole engine model
3) Due to more matured design and better understanding of the whole engine system makes it possible to narrow and decrease the span for each parameter. The design space is narrowed and also effecting the number of possible solutions of the compressor blade

The next step is equal to number 2, however the design space feed up to the whole engine model is narrowed one more step and the these iterations continue until we have a narrowed design solution and a base line is selected to be e.g. included in an offer.

As an effect of working with set of designs instead of single design points, a large amount of data is generated. Mode Frontier is used to create response surface models and analyzing the data.

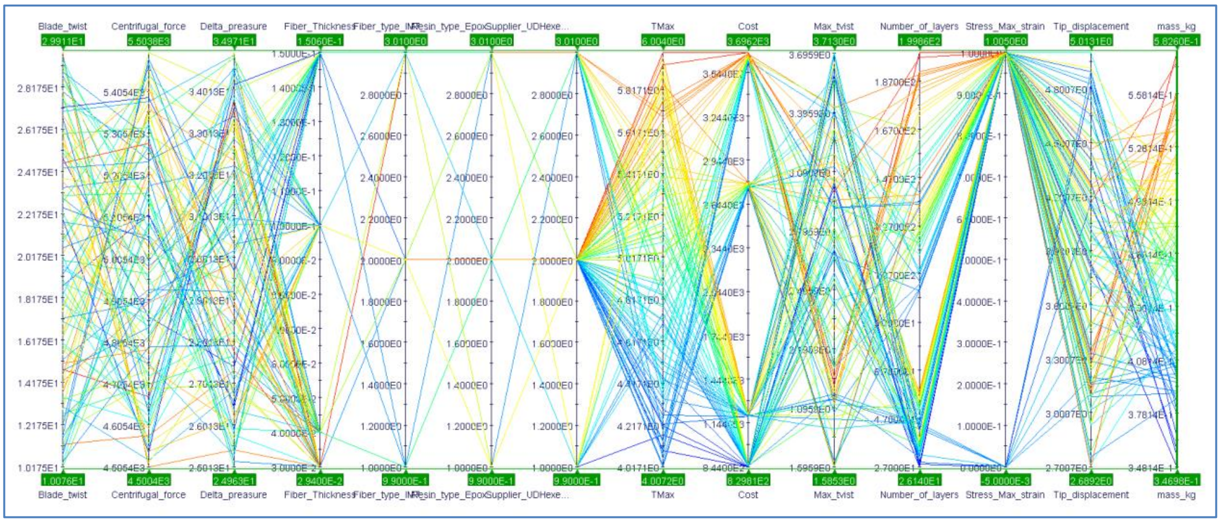
This is accomplished using design of experience and response surface methodology to interpolate and represent design “in between” calculated design points.

Picture 6 shows a matrix chart that shows the Pearson cross-correlation coefficients, the corresponding scatter plot and discrete PDF charts for the selected variables.
The lower part of the diagram provides information on the Pearson cross-correlation coefficients for the included parameters. If the correlation number is close to 0, the correlation is negligible. If the correlation is strong and positive, the cell is highlighted with a red color. The cell is highlighted with a blue color if the correlation is strong but negative, meaning that a positive change in one parameter has a negative effect on the opposite. E.g. Increased fiber thickness will reduce the cost.
B the Pearson cross-correlation coefficients, the discrete Probability Density Function (PDF) charts, that provides information about the quality of the parameter distribution.
The scatter matrix above the PDF charts plots the value of the parameters as a dot in a two axis plot. This gives a quick view of how the parameter values are distributed and if there are any trends in the data.



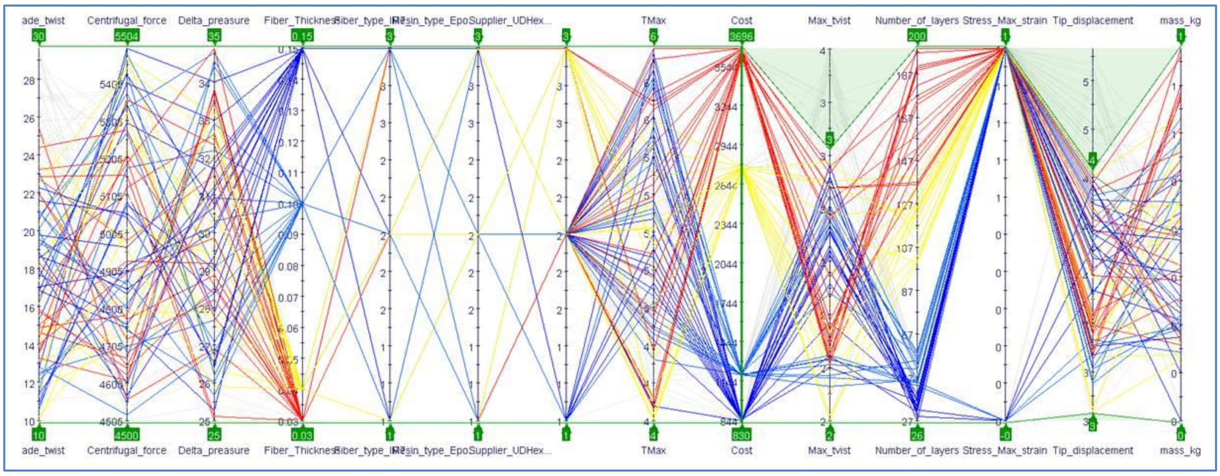
Picture 6. Illustrating the matrix chart that shows the Pearson cross-correlation coefficients, the corresponding scatter plot and discrete PDF charts for the selected variables.

A parallel diagram as shown in Picture 7 is a multi-dimensional diagram that can be used to visualize the complex relation between design parameter alternatives and performance criteria’s such as tip displacement, max twist and also cost as a consequence of fabrication alternatives. The parallel diagram is an interactive tool that can be used to instantly see the effect of narrowing a parameter range and to filter different solutions. Each line in in the parallel diagram represents a solution of one design. The coloring of the lines can be set to match a specific parameter.



Picture 7. A parallel diagram that visualize the complex relation between multiple parameters.

In Picture 7 the coloring is set to represent the values of the mass parameter values in a Red, Green, Blue (RGB) scale. Red solutions are high values and blue solutions are the lower values. Yellow and green are in between. A user can narrow the span of one parameter and see the impact on others.

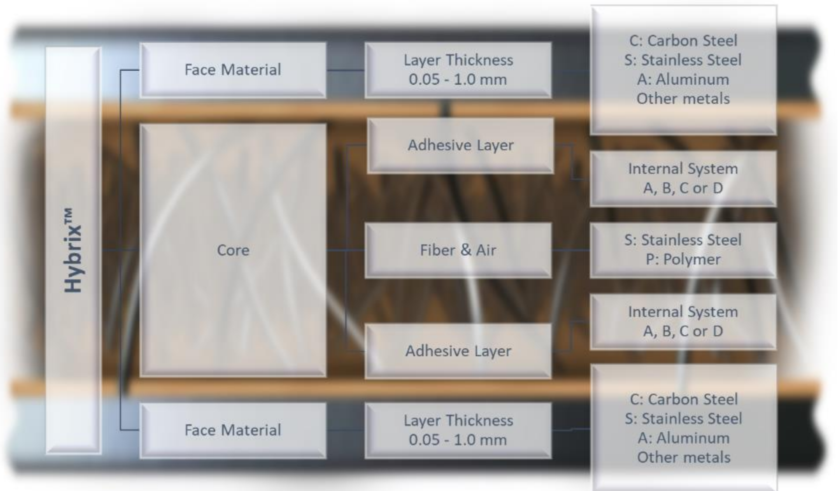


Picture 8

In Picture 8 the coloring is set to represent the values of the cost. Expensive solutions are red and less costly are blue. Here, the range of max twist and tip displacement is narrowed and the consequence on other solutions is shown. Solutions that are not within the solution space are grayed out. This is in particular visible on high values of blade twist that are geed in the upper left corner of the diagram. This type of interactive tool enable the designer to try and elaborate different options before decide on a particular approach.

Using digital tools for material configuration of Hybrix™

This application case is about using digital tools to investigate the possibility to use sandwich metal Hybrix™ in different applications and configurations.



Picture 9. Hybrix™ material with different configurations

Problem description
Lamera AB is producing multilayer materials under a common brand name Hybrix™. The material is constituted of two outer sheet layers and a core that is a mixture of adhesive and millions of microscopic polymer fibers that bind the thin metal surfaces together. Hybrix™ is hollow and contains air.

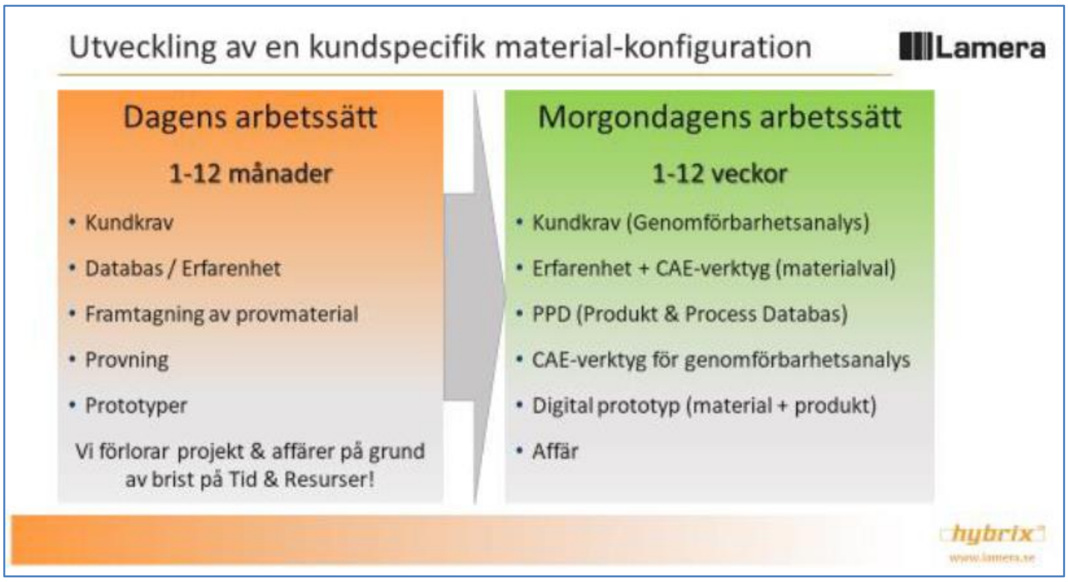
The addressed material is a highly specialized lightweight material for various applications where both formability and stiffness are two essential elements for the product final performance and functionality. Hybrix™ is 50% lighter (in average) than equal solids with the same rigidity and stiffness. Using an advanced material as Hybrix™ leads to endless opportunities when designing lightweight products.

The sandwich material is a very thin (0.5 - 3.5 mm) metal micro-sandwich that is strong, formable and lightweight with a total weight between 1.0 - 8.5 kg/m^2 (depending on the configuration). The unique micro-sandwich design also provides good insulation and dampening properties. Being able to use everything from stainless steel to copper to aluminum makes Hybrix™ a very formable material, unlike conventional lightweight sandwich materials.

When applying sandwich metal in a design it is desirable to investigate the result of different forming operations and how well the design when using sandwich metal can withstand different load cases. By using appropriate tools this can be studied in a digital environment.

Typically stamping is one common process in sheet metal forming. If the stamping operation can be simulated by using digital tools it is possible to predict any further problems that are likely to appear during production.

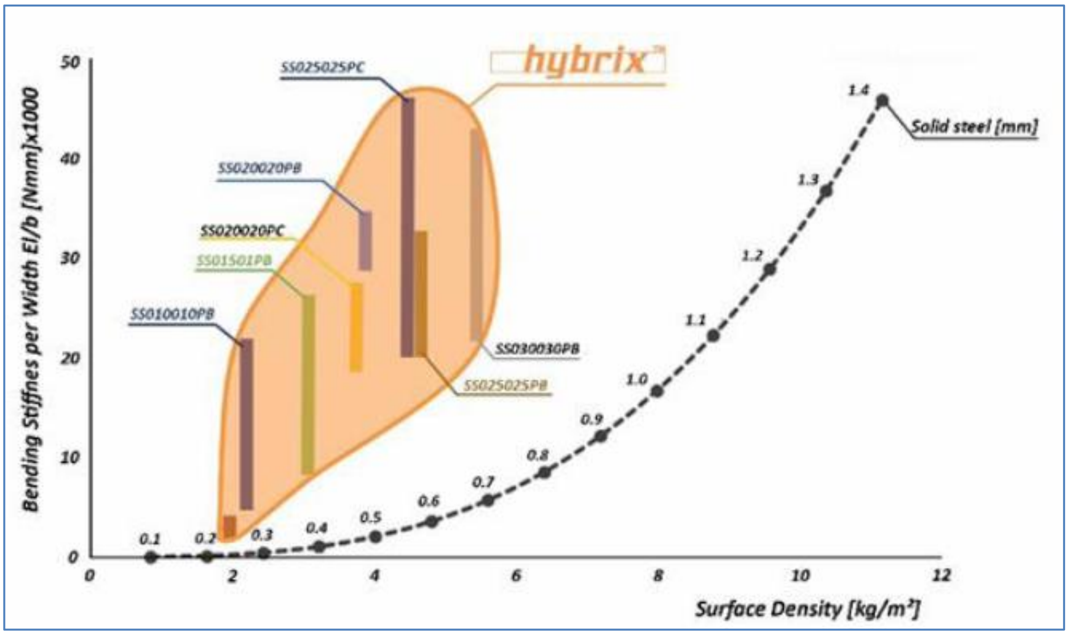
The major challenge in this application case is to shorten the lead time in a business situation when replying on a request for proposal with an offer where sandwich metal is used. The lead time was previously 1-12 month and is now 1-12 weeks due to the use of digital tools.



Picture 10. One objective for Lamera is to shorten the lead time to offer a customer specific material configuration from 1-12 month to 1-12 weeks

Digital tools

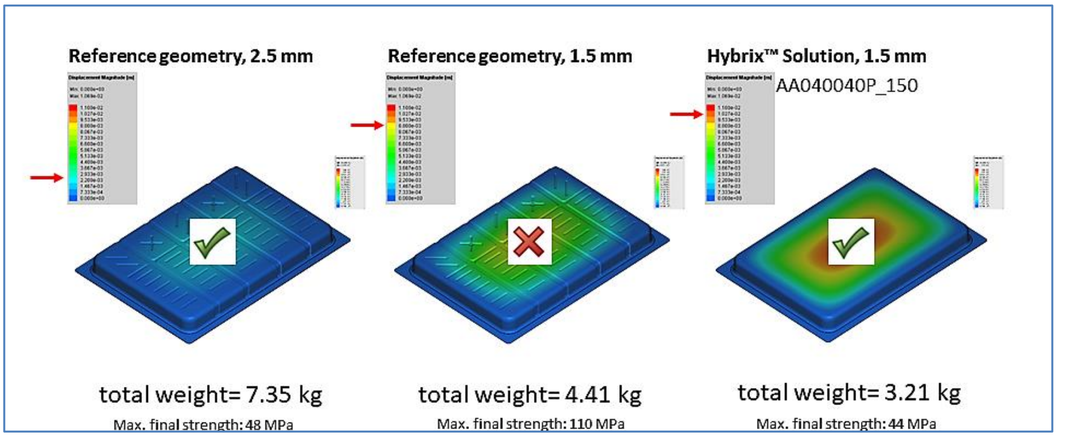
Using advanced digital tools, e.g. for material configuration and stamping operation, are creating huge amount of possibilities for the company for a successful product launch and introducing the material for a non-tested application area.



Picture 11. In the graph above are solid steel compared to a sandwich metal material regarding bending stiffness.

Picture 11 illustrates how the Lamera manufacturing technology improves the multi-layer material bending stiffness property vs. surface density (weight reduction) both for solid respective Hybrix™ materials with different configurations. Using in-house digital tools has enabled Lamera to reproduce stiffness maps by developing meta-models driven by known experimental data and FE-simulations.

When one is looking at actual components and comparing solid steel with Hybrix™ material it is easy to realize the differences in weight and stiffness by using digital tools for simulation of forming operation and the impact of certain load cases.



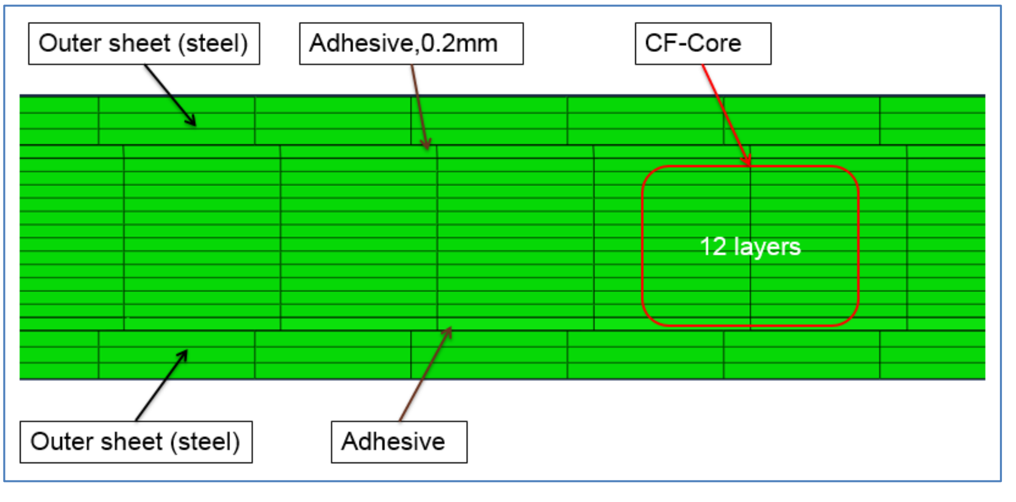
Picture 12. The results from FE-simulation analyses show the difference between material performance for a pre-defined load case for different material selections i.e., a common sheet material with different thicknesses and a Hybrix™ solution.

The information in picture 11 and picture 12 is valuable information when assessing the capability of a certain material combination. Digital tools can give us this information in reasonable time frame in a business situation.

Achievements
Lamera has in this work improved their capability to give accurate and fast replies on request for proposals. This capability is due to a knowledge built up regarding how to use digital tools. Lamera has reached its target on a maximum lead time of 12 weeks, for designing offers of new material combination to its customers.

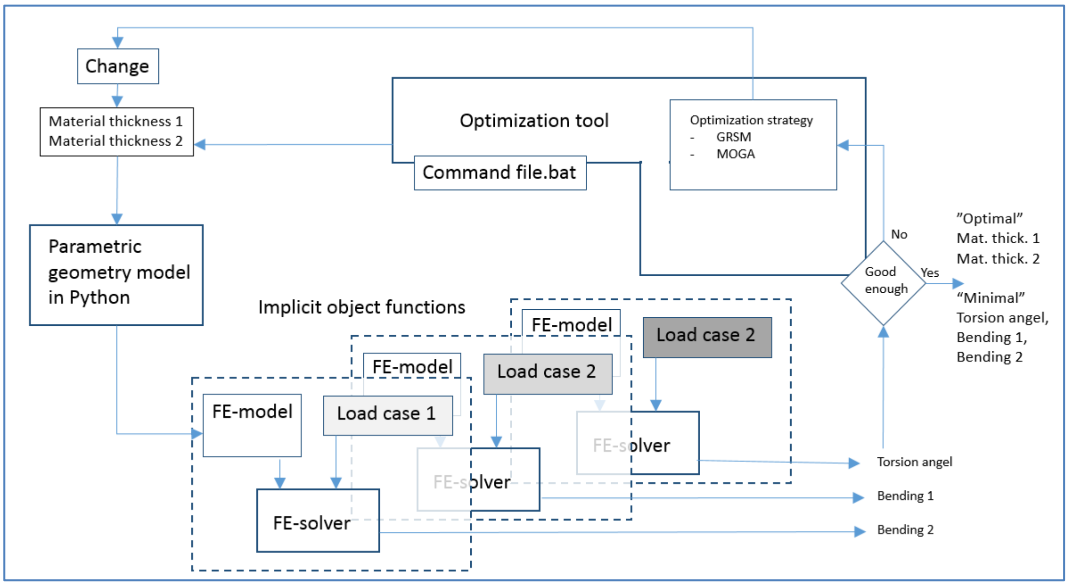
Multi objective optimization

The third application case, from Husqvarna, in this work is confidential but some information can be shared. The case involves an optimization of a laminate design. See picture 13.



Picture 13. The principal layout of the laminate design. GF is short for Carbon Fiber in a polymer matrix.

The application case involves three load cases, two bending and one torsion. Each load case is calculated separate by the FE-lover (see picture 14) and treated as a multi objective optimization case by the optimization tool. This is a difference compared to the optimization work of the compressor blade (above). The objectives subject to optimization are the torsion angle and the two bending displacements. The parameters varied are two material thicknesses in the laminate. The layout of the system is shown in picture 14.



Picture 14. The layout of the system for multi objective optimization.

The results from this case provides valuable insights of the laminate design. The experience from using these tools has served as a starting point for Husqvarna in it's strive to introduce optimization tools in different products areas.

Discussion

Here are reliability and generality commented.

Reliability of the results

The work in the project is done in real industrial cases. The results and the procedures of each practical case is validated by both researchers and industrial representatives. There has been information exchange between the application cases. Industrial experts and researchers have had opportunities to comment and question circumstances in each practical case. Digital tools used are well established on the market. These facts strengthen the reliability of the results from the work done.

Generality of the results

The practical cases of the project are from three different industrial segments. This fact promotes the generality of the results. One drawback could be that the same optimization tools has been used in two of the cases.

Conclusion

From the results described above we can conclude the following:

- Digital optimization tools are mature for wider use in industry
- Information on digital optimization tools should be spread to potential users in industry
- Dissemination activities requires expert knowledge about optimization and simulation
- Optimization tools can support industrial firms in critical business situations