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Parameterization and Multiobjective Optimization

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PARAMETERIZATION AND MULTIOBJECTIVE OPTIMIZATION
Parameterisering og multiobjektiv optimalisering

Modeling and multiobjective optimization is one of the main tasks in the EC project SupLight. In SupLight two industrial cases are selected for design/parameterization and optimization based on a fully integrated multiobjective optimization loop. These are one control arm from Raufoss Technology (RT) and an aircraft door connection arm from Hellenic Aerospace Industry (HAI).

The main goal is to document the process as well as benchmarking how single- and multiobjective design optimization can be applied and implemented to improve products.

The following tasks must be completed:

1. Find an optimal strategy for model parameterization of the aircraft door connection arm in NX based on the following criteria:
    a. Identify product requirements and optimization criteria for the door connection arm
    b. Design flexibility for robust design perturbations(selection of design variables and optimal modeling strategy for the largest impact on optimization criteria and design requirements)
    c. A minimum number of design variables (short simulation times)
    d. Smart selection of linked design expressions (minimum number of user inputs)
2. Parameterize the component and perform manual or automatic optimization to verify if the above criteria are met.

3. Perform multiobjective design optimization based on Mode Frontier and NX of the aircraft door connection arm:
    a. Study optimization theory and identify the best algorithms for the optimization considering the given requirements (from point 1a)
    b. Implement the multiobjective optimization loop in Mode Frontier for the component
    c. Perform design optimization and evaluate the results wrt. ease of use and final product requirements

The thesis should include the signed problem text, and be written as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is appreciated.

Three weeks after start of the thesis work, an A3 sheet illustrating the work is to be handed in. A template for this presentation is available on the IPM's web site under the menu "Masteroppgave" (http://www.ntnu.no/ipm/masteroppgave). This sheet should be updated one week before the Master's thesis is submitted.

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Preface

This master thesis, written within the field of implementation of design optimization, is a culumination of the work to obtain a Master of Science for the Department of Engineering Design and Materials at the Norwegian University of Science and Technology.

The project has been performed in close collaboration with fellow student Espen Nilsen. Together with him, the attached A3 sheets have been produced.

The intention of this report is to present a practical approach to optimization.

Supervisor Prof. Terje Rølvåg has been one of the contributors in this project from the very start. He handed over some of the documentation and model files in order to form the baseline.

Exploring this field of engineering has been very interesting, but still challenging, since most of the documentation is written from a theoretical perspective.

Adam Thorp at Esteco Nordic AB has been a great help, and provided us with necessary data to perform an optimization with modeFRONTIER, as well as general support. I will also thank fellow student Steffen Johnsen for a great collaboration in this project. Many interesting discussions have been essential to the outcome of this work. Last but not least, I will like to thank my family and my girlfriend. They have always been supportive and encouraging, though they have no idea of what I am doing.

Carl Hougsrud Skaar

Abstract

One of the core ideas in this thesis is to determine how single- and multiobjective design optimization can be applied and implemented to improve products. The background for this thesis is an EC research project named SuPLight. The purposes is to develop a practical approach by introducing an aircraft component from Hellenic Aerospace Industry. The objective is to reduce the weight/mass of this component by 10 %, without sacrificing stiffness in the load direction. This proved to be impossible with such stringent conditions. However, it was possible to reduce the mass by 6.26 %, and still maintain the same stiffness.

In Chapter 1, the reader is introduced to design optimization and the main objective of this thesis. Chapter 2 covers the base line for the aircraft component. Further, it will be presented how the model should be prepared in order to capture design intent, a so called parameterization. This is covered in Chapter 3. In Chapter 4, a demonstration is presented of how a sensitivity analysis can be performed. A sensitivity analysis helps the validation of the design parameters before performing an single-objective optimization in Chapter 5. In addition to the single-objective optimization, the multiobjective approach will be thoroughly considered in Chapter 6. Beside the thesis, a set of detailed descriptions realted to the use of the software in A3 format, have been made. These can also be found in the appendices.

Sammendrag

En av de sentrale ideene med denne oppgaven er å finne ut hvordan singel- og multiobjectiv design optimalisering kan brukes og implementeres. Bakgrunnen for denne oppgaven er et EU-forskningsprosjekt kalt SuPLight. Formålene er å utvikle en praktisk tilnærming ved å innføre en flykomponent fra Hellenic Aerospace Industry. Målet er å redusere vekten/massen av denne komponent med 10%, uten å gå på bekostning av stivhet i lastretningen. Dette viste seg å ikke være mulig, med så stremge krav. Imidlertid var det mulig å redusere massen med 6.26%.

I kapittel 1, blir leseren introdusert for design optimalisering og hovedformålet med denne avhandlingen. Kapittel 2 dekker analysegrunnlaget for flykomponenten . Videre, vil det bli presentert hvordan modellen må forbereden for å være i stand til å kunne endre form. Dette kalles parametrisering og er dekket i kapittel 3. I kapittel 4blir det demonstrert hvordan en sensitivitetsanalyse kan utføres. En sensitivitetsanalyse hjelper validering av design parametere før singel-objecktiv optimalisering blir utført i kapittel 5. I tillegg til single-objektiv optimalisering, vil multiobjective tilnærming bli grundig vurdert i kapittel 6. Foruten avhandlingen, har et sett med detaljerte beskrivelser relatert til bruken av programvaren, blitt vedlagt i A3 format. Disse kan også bli funnet i vedlegget.

Contents

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Nomenclature

ABS	Absolute coordinate system
ARSM	Adaptive Response Surface Method
CAE	Computer Aided Engineering
DOE	Design Of Experiment
EC	European Commission
ES	Evolution Strategies
FEA	Finite Element Analysis
FEM	Finite Element Method
GA	Genetic Algorithm
GUI	Graphical User Interface
HAI	Hellenic Aerospace Industry
MCDM	Multi Criteria Decision Making
MOGA	Multi-Objective Genetic Algorithm
MOGT	Multi-Objective Game Theory
MOSA	Multi-Objective Simulated Annealing
RSM	Multi-Objective Genetic Algorithm
SA	Simulated Annealing

SM	Synchronous Modelling
SQP	Sequential Quadratic Programming
STL	Stereolithography
WCS	Work coordinate system

Chapter 1

Introduction

1.1 Background

SuPLight is a multidisciplinary EC research project that involves participants from the industry as well as academic environments. The project will be a multidisciplinary research project combining metallurgy, continuum mechanics, structural mechanics, optimization algorithms, tolerance analysis and life cycle analysis. This multidisciplinary perspective represents a challenge, but is also necessary to yield result that exceed today's knowledge on the topic. SuPLight stands for Sustainable and efficient production of light weight solutions. As the world‘s energy needs get higher every day, one needs to find sustainable solutions that reduces today's energy consumption. Production of virgin aluminum is very energy consuming and more extensive use of recycled aluminum in addition to lightweight optimized solutions can reduce overall energy consumption. The main objective of the SuPLight project is to provide sustainable lightweight industry solutions based on wrought alloy aluminum. Some of the sub goals included:

- Gain a 50 % increased weight/performance ratio through optimization.
- More than 75 % post consumer recycled wrought aluminum alloy is to be used.
- New methodologies and tools for holistic Eco-design of products, processes and manufacturing

The SuPLight project aims to develop new methods and concepts that can be used by the industry. [5, 6]

As a contribution to the overall project, this thesis will seek to find out how it is possible to simplify the design optimization process by use of computer software fitted for this purpose.

1.2 Design Optimization

The field of Computer Aided Engineering(CAE) has grown rapidly the last decades and has become essential in the engineering field. A wide range of different design and analysis tools help to streamline the product development process. During the structural design process in various fields of engineering, the best decisions are made with respect to different aspects like stiffness, strength, construct ability and aesthetic property.

In structural optimization, use of different sets of data representing a mathematical model describes the behavior of a structure. Different control parameters are tuned by a set of design variables to find a situation in which the structure meets a given property [7]. It is common to divide structural optimization into the following three types:

- Sizing optimization involves different size parameters of the structure that is to be optimized. It is common to relate this kind of optimization to a problem where you have a truss containing beams, and you change the thickness of each beam. [8]
- Shape optimization is where you optimize a structure by changing conture or form without changing topology (introducing new holes). Shape optimization has an interdisciplinary character, meaning it can be used on a wide arrange of problems. This kind of optimization is more complex than the sizing optimization. It involves mathematical disciplines as partial differential equations, approximations of these and theory of nonlinear mathematical programming. In terms of three dimensional models and finite element methods, advanced software is required. [9, 8]
- Topology optimization optimizes the topology by, for example, making holes in the component. The algorithm changes the density of elements, controlling the stiffness contribution from that particular element. The result from the optimization must be interpreted and smoothed by the engineer, as output geometries are highly organic shapes that must be

processed before production. Today, gradient-based algorithms are mostly implemented in commercial software, however new algorithms are continuously developed. For a more detailed description, see [10]

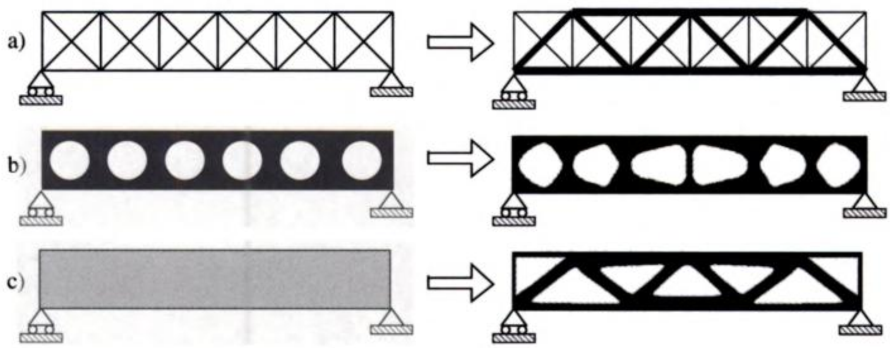


Figure 1.1: a) Sizing optimization, b) Shape Optimization, c) topology optimization [1]

As we can see, there is clearly a correlation between sizing and shape optimization, and several different definitions exists. In terms of this project, controlling various geometry parameters will be referred to as *geometry optimization*. This is in agreement with the terminology used in the CAE software.

1.3 Software

In this thesis, there are essentially two software packages which have been used. The first one is NX 8.5, which is advanced Computer Aided Design (CAD) and Computer Aided Engineering (CAE) software package developed by Siemens. This software is mainly being used for design (direct solid/surface modeling) and engineering analysis (static, dynamic, thermal using FEM). Intergrated in NX is the CAE software is called NX Advanced Simulations which includes a set of optimization tools[4]:

- **Geometry Optimization:** Modifies the dimensions of the geometry features or sketches, expression values, etc. This is used to achieve a design objective such as minimizing weight.

- **Topology Optimization:** Uses the Tosca topology optimization solver to adjust the material densities of the elements in your mesh to achieve a design objective such as minimizing weight. The result is an optimized STL or bulk data file that you can use as a guide for creating a new part.

- **Shape Optimization:** Uses the Tosca shape optimization solver to displace nodes in your mesh with the objective of reducing localized stresses or maximizing specific natural frequencies in your final design. The result is an optimized STL or bulk data file that you can use as a guide to make adjustments to your design.

- **NX Nastran SOL 200 Design Optimization:** Modifies physical and material properties and mesh associated data to achieve a design objective.

In this thesis we will only use the geometry optimization. This optimization tool contains two different optimization types:

1. Altair HyperOpt

2. Global Sensitivity

Only the former will actually try to optimize the model and make changes in the geometry.

Global Sensitivity evaluates the sensitivity of the design objective for each selected design variables By using this tool, it is possible to evaluate the design variables which have the most impact on model responses. *Global Sensitivity* is also a great way of investigating the design space.

The second software package being used is modeFRONTIER 4, a multidisciplinary and multiobjective software allowing easy coupling between different CAE tools. This software extracts results from NX (or almost any other CAE tool for that matter). It is a more advanced software than the geometry optimizers in NX by offering more options regarding how the software should meet the optima. modeFRONTIER has build-in support for a range of softwares. [11]

1.4 Main Objective

The main objective of this thesis is to document the process on how NX and modeFRONTIER can be used to perform geometry optimization. In addition to this, benchmarking the software based on the results and ease of use will be considered. A typical scenario will be to decrease weight without affecting the durability. In other words; how is it possible to automatically tune various design variables in order to reduce weight?

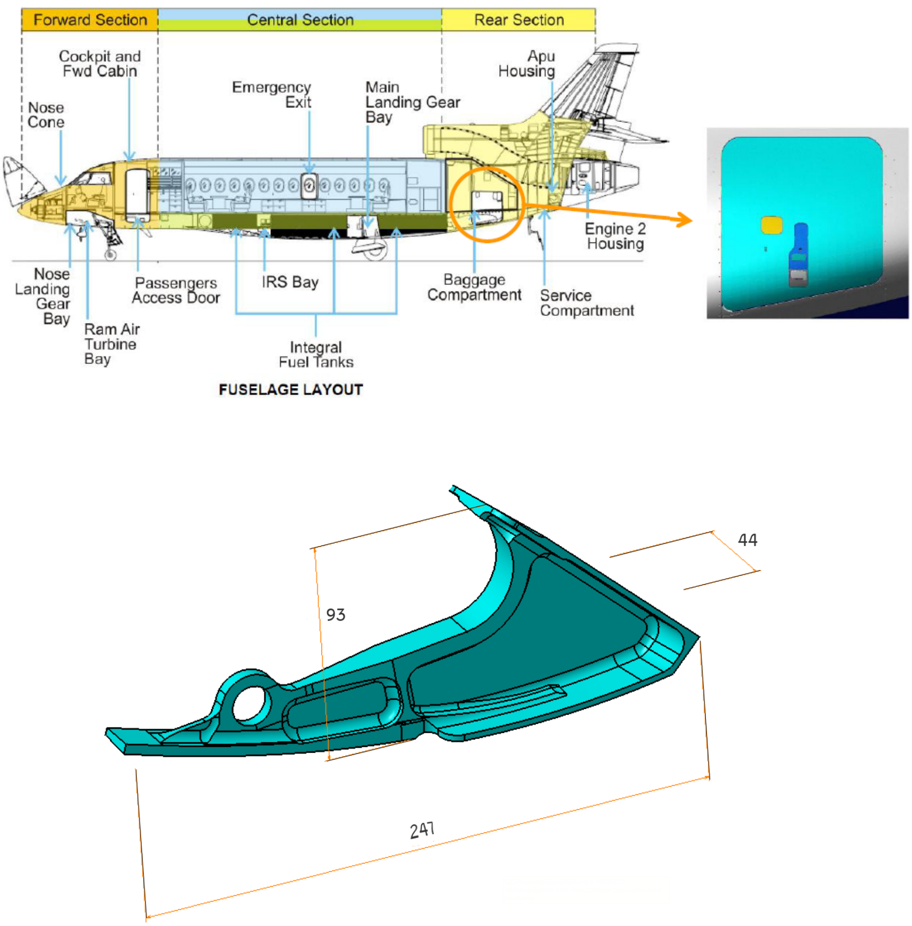


Figure 1.2: Original part from HAI

A case study is conducted in terms of an aircraft door connection arm from

Hellenic Aerospace Industry (HAI). Such door connection arm is located at the baggage door and are subjected to alternating loads (Figure 1.2). First we will try to do this with the optimization tool in NX, and compare this with the results from modeFRONTIER.

1.5 Scope of Work

In order to perform an ideal geometry optimization, the approach mapped in Figure 1.3 has been used.

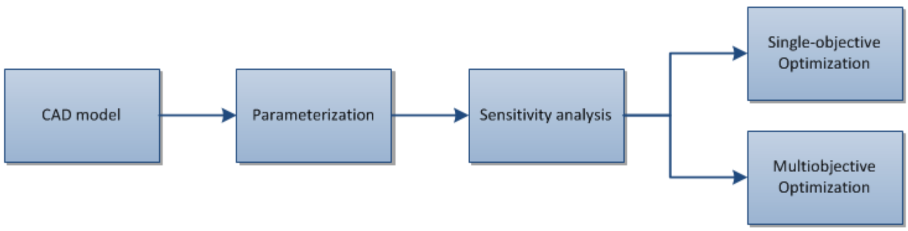


Figure 1.3: Overall workflow

The CAD model needs to be parameterized in order to capture design intents . To evaluate the parameterization, a sensitivity analysis will be performed using *Global Sensitivity*. The model is then ready to be optimized. In this case, it can either be done by a single-objective or a multiobjective analysis. All these steps will be described step by step throughout this thesis. Each chapter will contain a summary and a discussion. In addition to the specific case study, a general guide is given in the appendices D, E, F.

1.6 Limitation

- Only the multiobjective approch will be tested in modeFRONTIER.
- Production methods and tolerances will neither be discussed or brought into considuration.

Chapter 2

Base Line

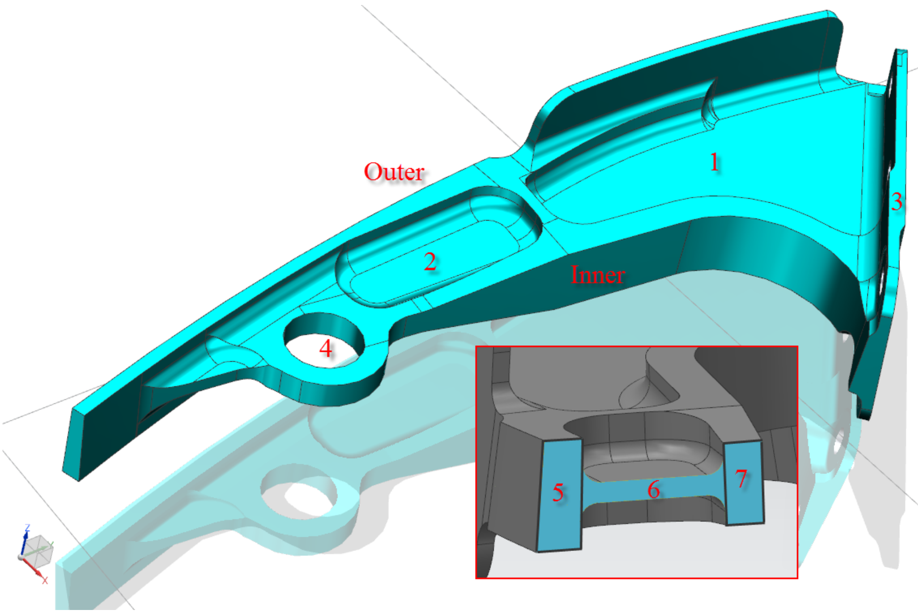


Figure 2.1: Terminology of areas

The intention of this chapter is to identify product requirements and optimization criteria on an initial stage. The base line should form a point of reference for the final model. A clarification of the terminology used when refering to certain areas on the part, is shown in Figure 2.1:

1. Large Cavity
2. Small Cavity
3. Bracket
4. Hole
5. Outer flange
6. Web
7. Inner flange

2.1 Material Data

The material to be used during the analysis is Aluminum 7075 T7351. This is a wrought alloy which is commonly used in the aircraft industries.

Table 2.1: Main material properties for Aluminum 7075 T7351

	Value	**Unit**
Density	$2,81$	$\frac{Kg}{dm^3}$
Ultimate Tensile Strength	505	MPa
Yield Tensile Strength	435	MPa
Fatigue Strength $5 * 10^8, R = -1$	150	MPa
E-modulus	72	GPa
Poisson's Ratio	$0,33$	
Shear Modulus	$26,9$	GPa

2.2 Load Case

The load case defined by HAI exposes the component to axial tension applied inside of a bearing hole. From a previously project concerning fatigue testing of the component, the constraints have been defined within a jig (Figure 2.2).

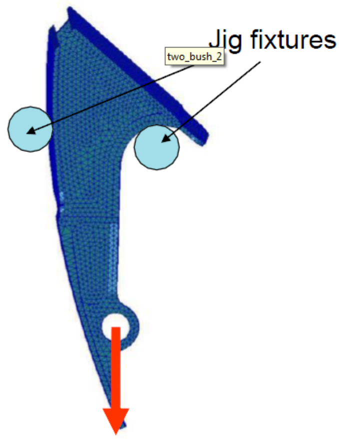


Figure 2.2: Original test load direction and constraint

The component is subjected to a tensile-tensile load of 2.5 kN. This means that the minimum load equals zero, while the maximum load equals 2.5 kN. To keep the focus directed towards the optimization, rather than determine cycles until fatigue, a static load of 2.5 kN will be applied. An overall goal for the optimization, is to reduce the weight by 10 % without affecting the stiffnes. The stiffness is expressed by displacment. Less stiffness involves more displacement. In addition, yield strength should not be exceeded.

2.3 Coordinate systems

Before moving on with the static analysis, the coordinate system needs to be reoriented. This gives a more proper representation of the displacements.

Two of the most important coordinate systems are [4]:

- Absolute coordinate system (ABS): represents origo. Only its orientation can be seen.
- Work coordinate system (WCS): main coordinate system which can be reoriented and is visible in the work environment

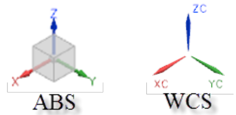


Figure 2.3: Coordinate systems

Only one of each of these coordinate systems exists for a model. On the original hinge model, the ABS together with WCS appears outside the model. This is inconvenient in terms of measuring displacements. For this reason the WCS is moved to the center of the hole.

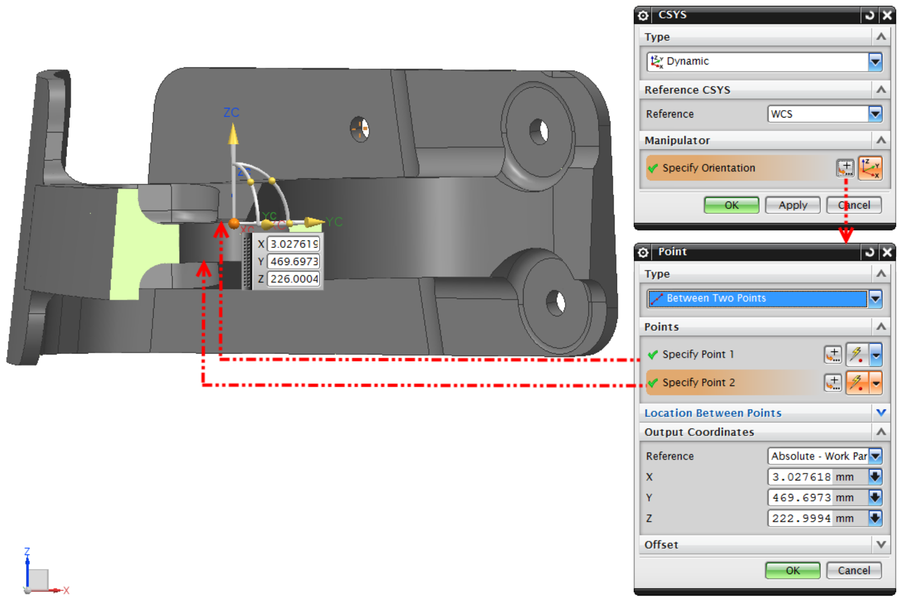


Figure 2.4: Placing the WCS

To move the WCS, choose Format → WCS → Orient. The edge around the hole is selected to position the WCS. By selecting one point on the upper and lower edge of the hole, the WCS is places into the middle of the web, see 2.4.

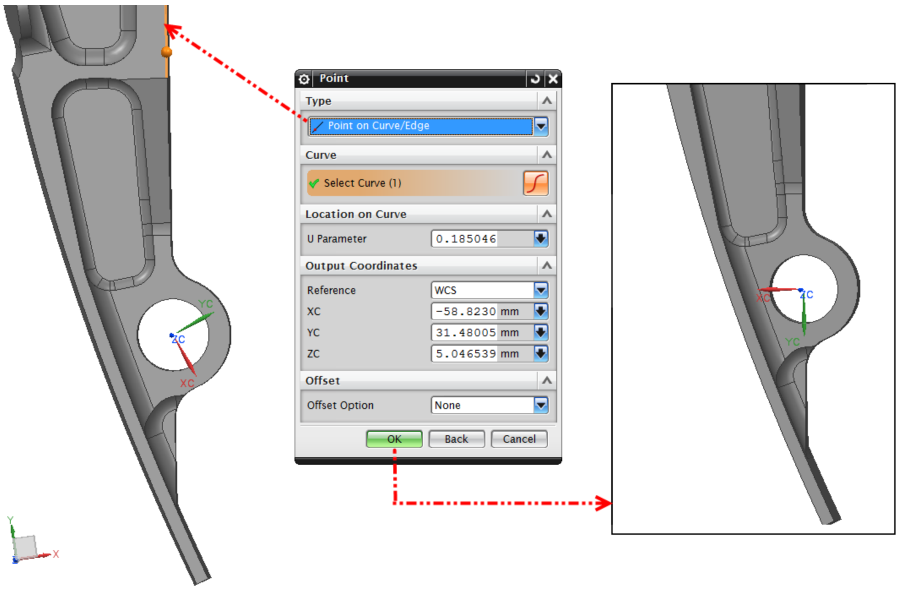


Figure 2.5: Orientation of the y-direction

The WCS is oriented with the y-direction parallel to the positive load direction so that the reaction displacement directs in the positive x-direction. This is performed by selecting Format → WCS → Change YC-direction (Figure 2.5).

2.4 Simulation

A static structural analysis was performed on the model using NX Advanced Simulation. All analyses will be performed using the NX NASTRAN solver.

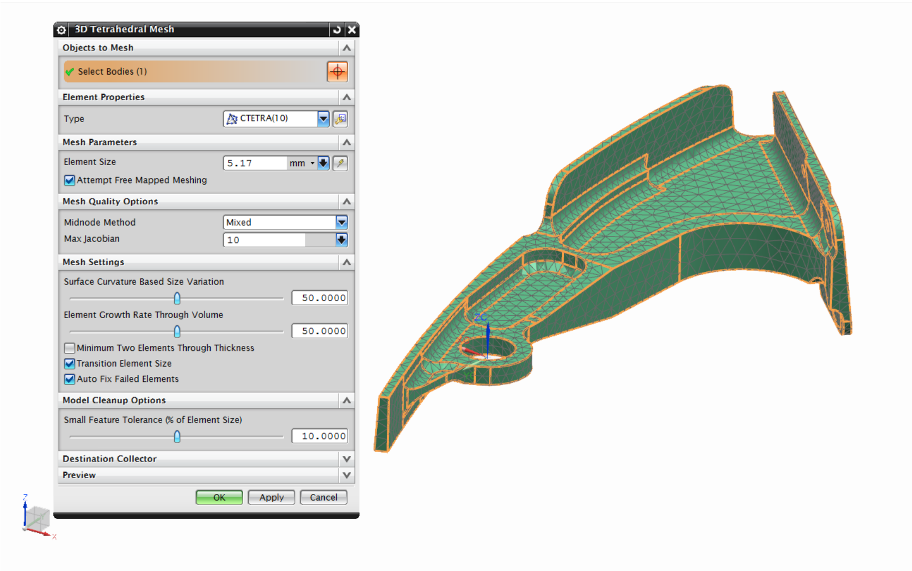


Figure 2.6: Meshed solid body

The element model was generated (meshing) using elements CTETRA(10). Automatic element size gave an element size of 5.17 mm (Figure 2.6)

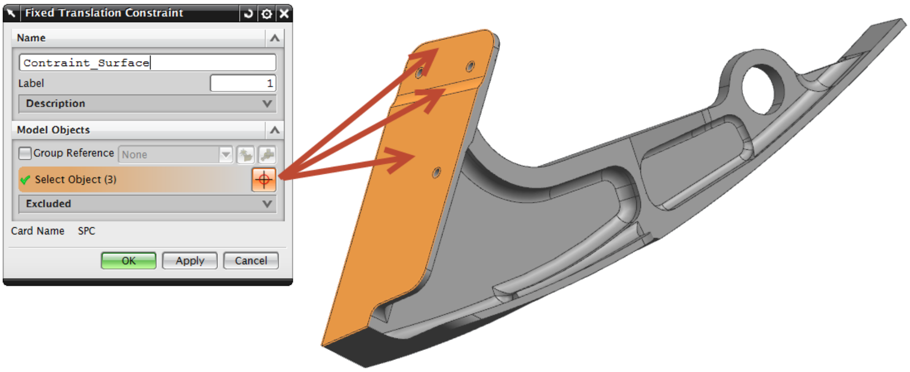


Figure 2.7: Constraints

Representing the constraint within a jig will complicate this problem. This involves introducing contact analysis, which takes a lot of time. It is more likely that the connection arm is constrained by the bracket. In this case, the constraints were defined as simple as possible to reduce computational time and achieve a more accurate result. Fixed constraint were therefore applied to the bracket (Figure 2.7). The bracket consists of three faces, where all three were selected.

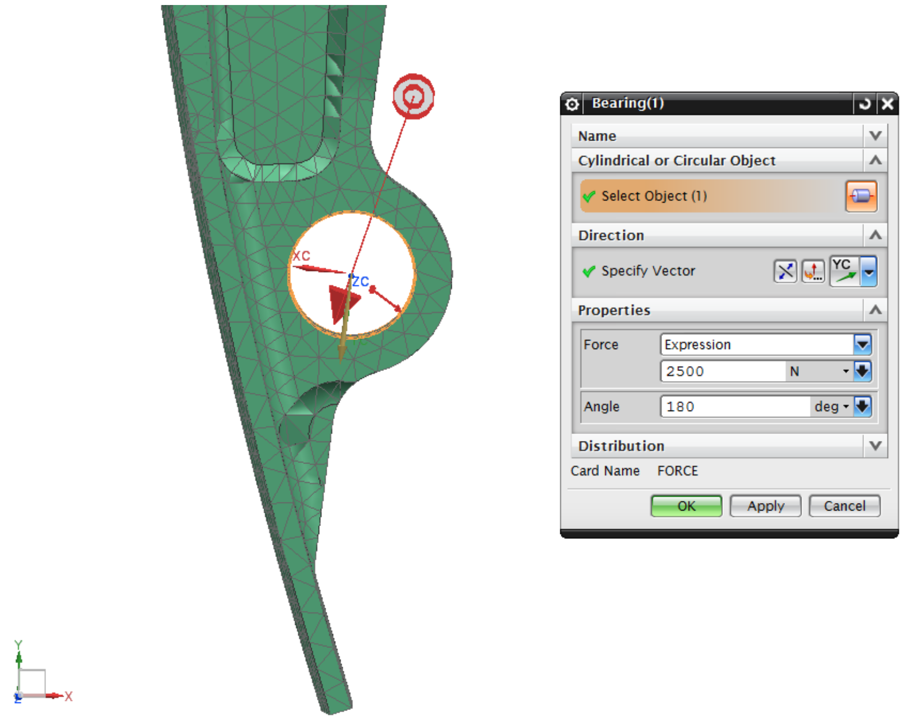


Figure 2.8: Applied bearing load

The load type *Bearing* was used with the load applied on the surface inside the hole (Figure 2.8). The load directions was set to YC, which indicates that the load should acts in the WCS y-direction.

2.5 Baseline Simulation Results

The results from the simulations shows stress concentrations inside the hole and at the contours at the inner side of the component, close to the hole (Figure 2.9, 2.10)

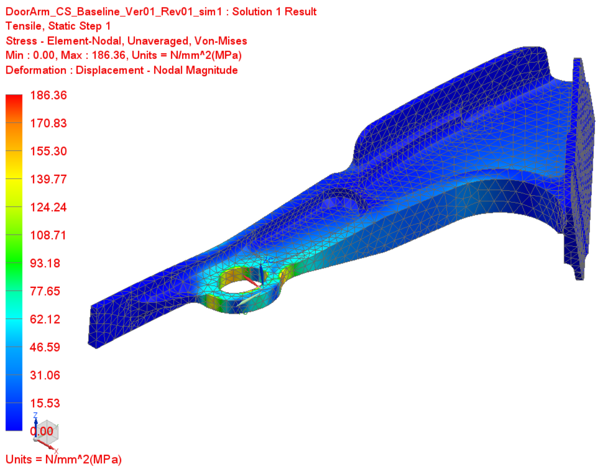


Figure 2.9: Stress plot

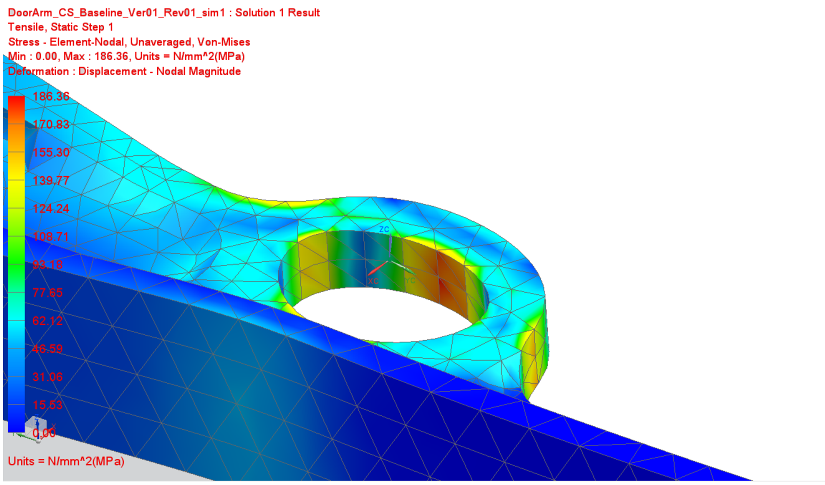


Figure 2.10: Local stress plot of the hole

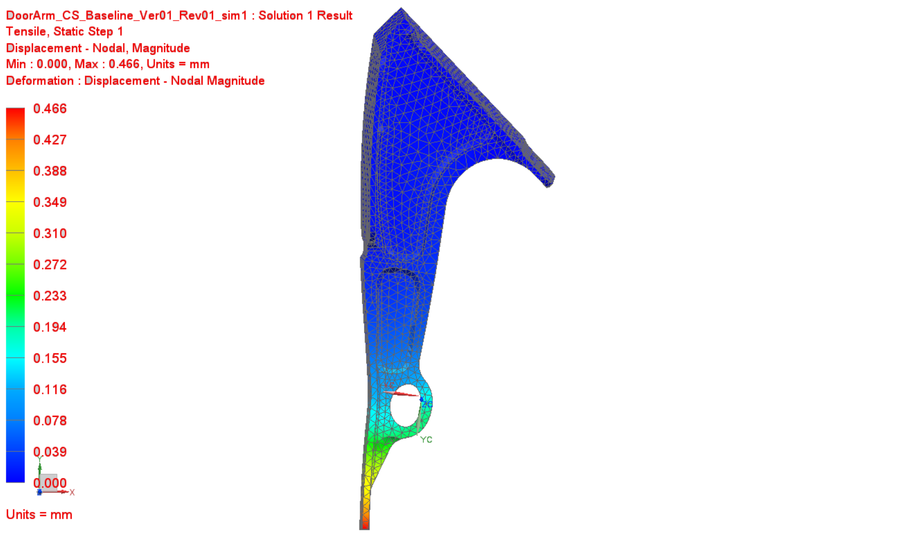


Figure 2.11: Magnitude of displacement

The displacements in x-direction, y-direction and the magnitude of displacement are based on the WCS. A plot showing the deformation when the component is subjected to load, is depicted in Figure 2.11.

Table 2.2: Baseline results

	Mass	**Displacement (x-direction)**	**Displacement (y-direction)**	**Displacement Magnitude**	**Von Mises Stress (Elemental-Nodal)**
Max	202 g	0.443 mm	0.159 mm	0.466 mm	186.36 MPa
Min		-0.009 mm	0.000 mm	0.000 mm	0 MPa

As can be seen in Table 2.2, the component experiences the largest displacement in x-direction, though the load is directed towards y-direction.

From now on, when displacement is mentioned, it will refer to the magnitude of displacement.

2.6 Summary

The component has been simulated with the material properties which were provided by HAI. This analysis gives an idea of what kind of stresses and displacements the componenet are subjected to. Because of the angled bracket, the component will be subjected to bending, as well as axial tension. The stiffness in the bending direction is less than the axial stiffness. This results in large displacement directed towards the x-direction. This results in greater tension in the inner flange than the outer flange.

2.7 Discussion

The constraint type used in this case differs from the one defined by HAI. While HAI in earlier fatigue analysis has chosen to use a jig constraint, fixed constraints were used in this case. There is reason to believe that this gives a more realistic representation for the global aspect. The jig constraint is most likely chosen to eliminate sources of error during a fatigue analysis, since the area around the hole is of greatest concern in terms of stresses.

Chapter 3

Parameterization

In order to perform an automatic geometry optimization process, the model needs to be parameterized to capture design intents. This involves controlling the design so that the optimization goal can be reached. In order to achieve a proper geometry optimization, the parameterization is important. As stated in [12], an ideal geometry parametrization should:

1. Be able to generate a large variety of physically realistic shapes with as few design variables as possible
2. Be robust meaning that a random perturbation of the design variable should still provide a realistic design
3. Be generic to be applied to a large variety of shape optimization problems and able to be integrated or coupled with any existing CAD system
4. Provide design parameters that can easily be handled by an engineer in order to define design variable bounds
5. Provide an easy optimization problem by minimizing the skewness and improving the conditioning of the design space

In this chapter, a detailed review on how the model is parameterized by use of NX is presented. In addition, the reason for the selected parameters will be discussed.

3.1 Design Limitations

Since the component should fit into the same position on the aircraft, HAI defined the following design limitations shown on the illustration.(3.1)

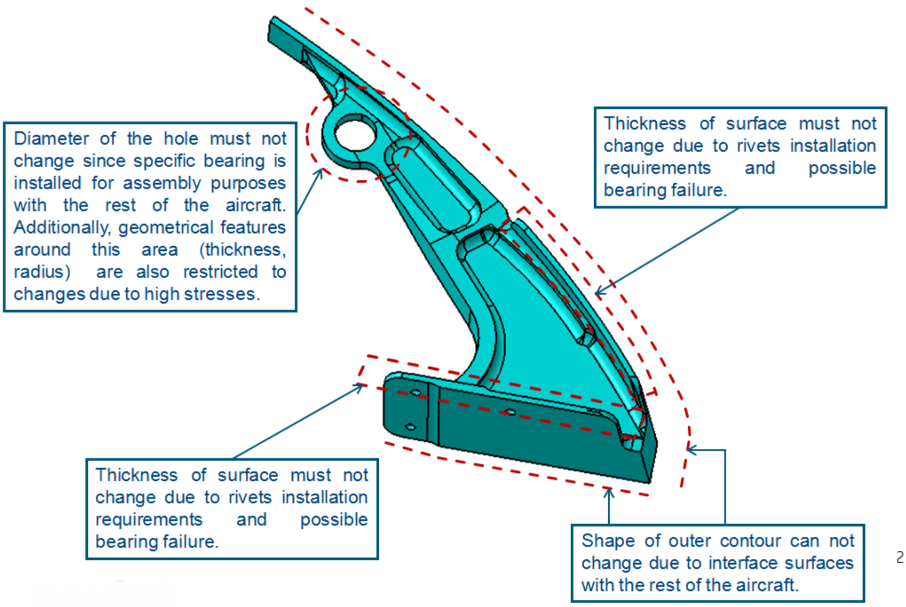


Figure 3.1: Design limitations

3.2 Synchronous Modeling and Expression

The original CAD model is modeled in a software called CATIA v4. The model file was initially made in the file format STEP (STandard for the Exchange)[13]. This format is supported by NX, but the software is not able to recognize any features (leaves an empty history tree). Such features is crucial for changing the geometry. Several CAD systems provides feature recognizion tool. In NX, this kind of tool is called *Synchronous modeling* (SM).

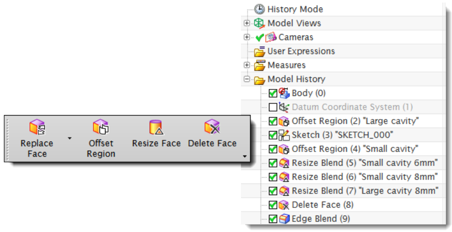


Figure 3.2: Synchronous modeling and history tree

SM is a very powerful tool with various types of commands allowing the user to modify the model regardless of its origins, associativity or feature history [4]. SM creates new features in the history-tree which the user can edit.

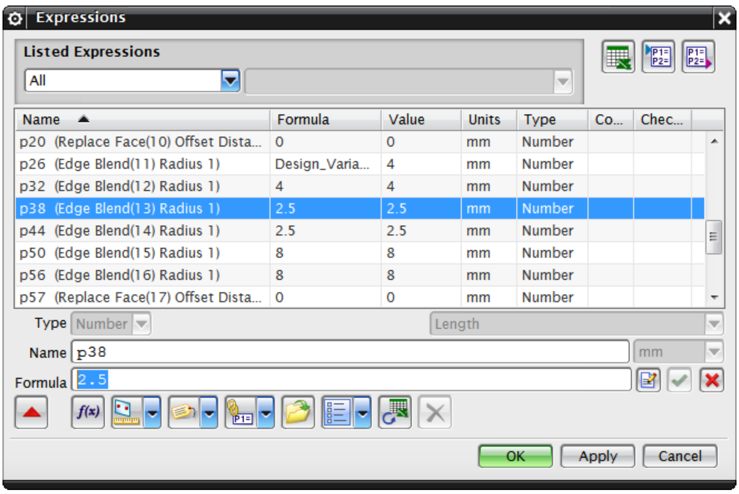


Figure 3.3: Expressions in NX

Each SM features is expressed by a design variable. The design variable is given by a value referring to the size of either an offset, radius or similar. The value will be entered when applying a feature, or it can be edited later in the history tree. NX also has a tool called *Expressions* (Tools → Expressions) where all variables are shown (Figure 3.3) . Be aware of that the terms design parameters and design variables can be used interchangeably.

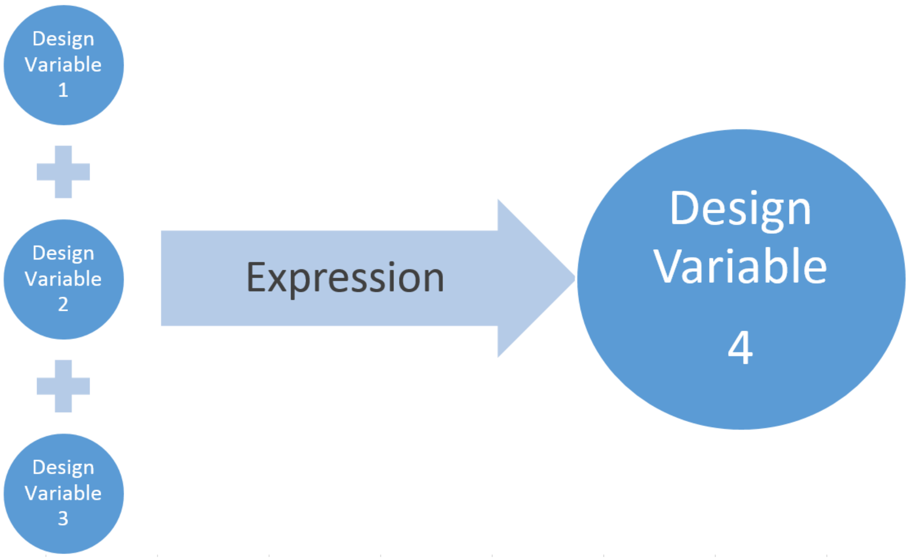


Figure 3.4: Linking design variables using user expressions

To limit the amount of design variables in future analysis, user defined variables can be added. One user defined variable can be used for several design variables (Illustrated in Figure 3.4).

In the following chapter, a practical approch for performing parameterization in NX is discribed by practical implementation.

3.3 Practical Approch for Parameterization in NX

Design parameterization implies creating solid features and relating dimensions that can be changed and still preserve a model update properly. The selection of the design variables is left to the user. Therefore, the quality will most likely differ due to the users experiences and creativity.

The SM commands which were used are:

- **Offset Region:** Moves a face in a direction perpendicular to the face
- **Resize Blend:** Changes the radius of a blend
- **Delete Face:** Removes selected geometry or holes

In addition to these SM commands, **Edeg Blend** was used.

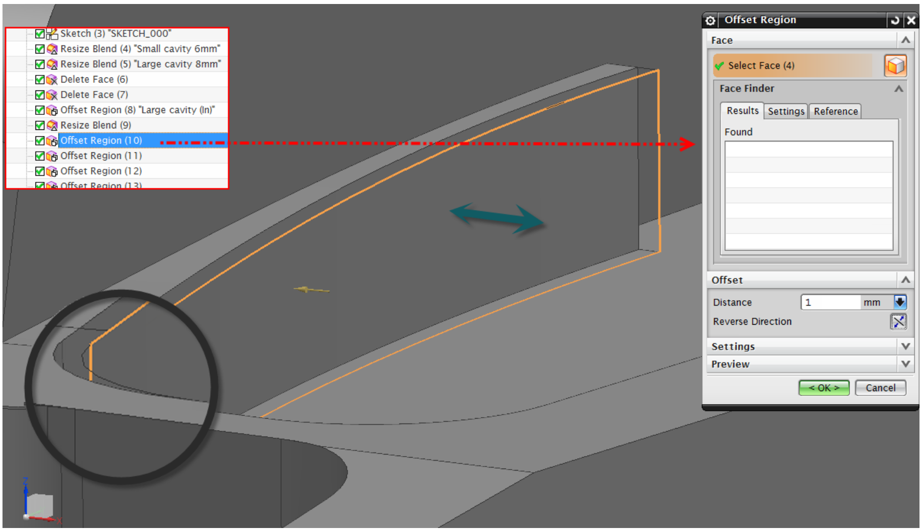


Figure 3.5: Offset Region (10)

In Figure 3.5 it is shown how the command, **offset region** adjusts a face. The function can adjust the face in both directions, but can not be set equal to zero. This command was used on all faces where the thickness should be adjusted. The thicknesses of the webs inside the two cavities needed four such features (two cavities, top and bottom).

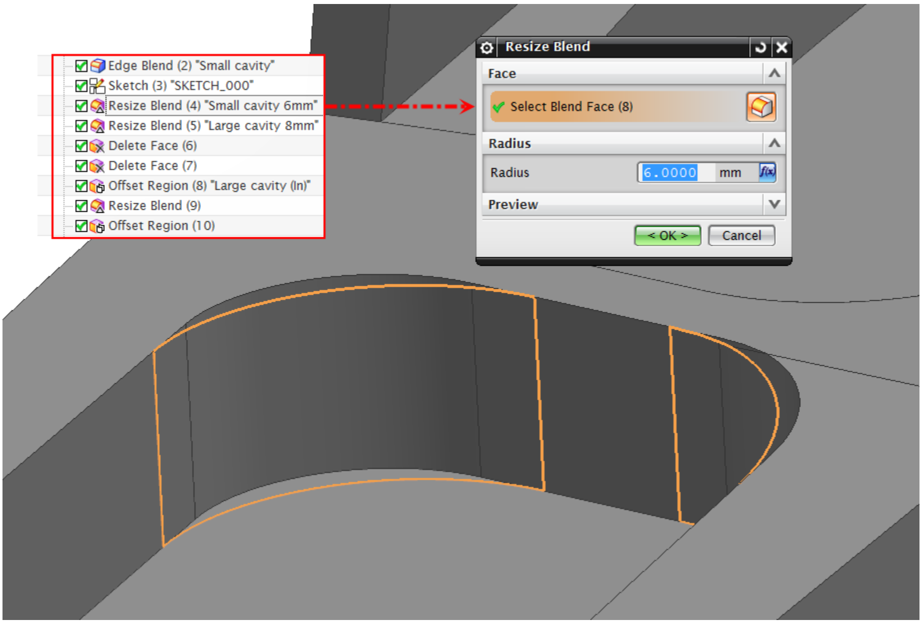


Figure 3.6: Resize blend (4)

Resize blend was used in all four corners of the small cavity and in two corners in the large cavity.

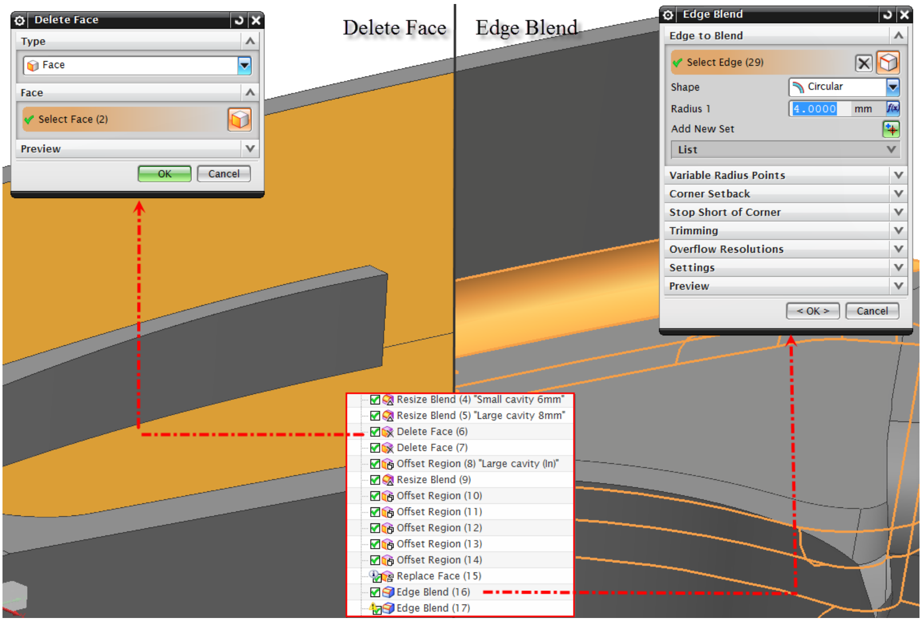


Figure 3.7: Delete face and edge blend

For the blends along the edges, inside the two cavities, the command **resize blend** did not manage to recognize the initial blends. For that reason, **delete face** was first used to remove the inital blend by then apply a new blend with the command **edge blend**.

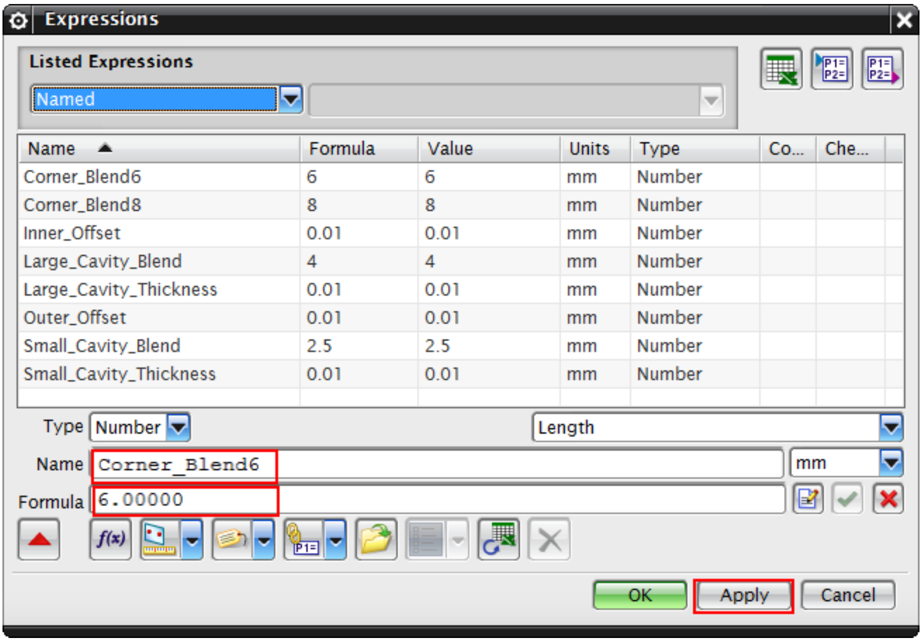


Figure 3.8: Expressions

It is reasonable to let equal design variables be controlled by one user expression. The parameter needs a name, and a value. A total of eight parameters were established to control almost the whole surface of the component, except the areas which are restricted by the design limitations (Figure 3.8).

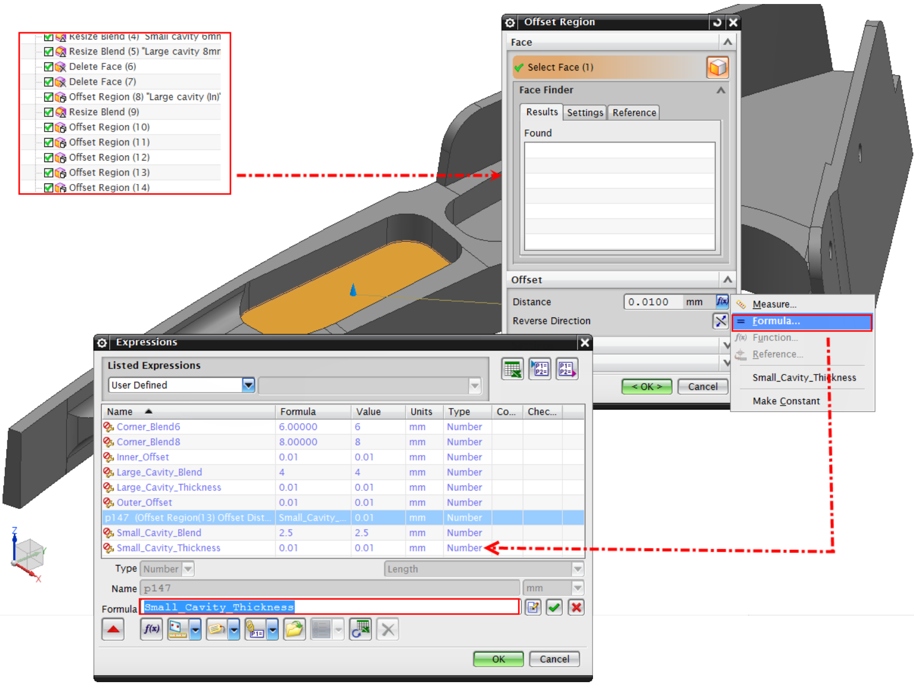
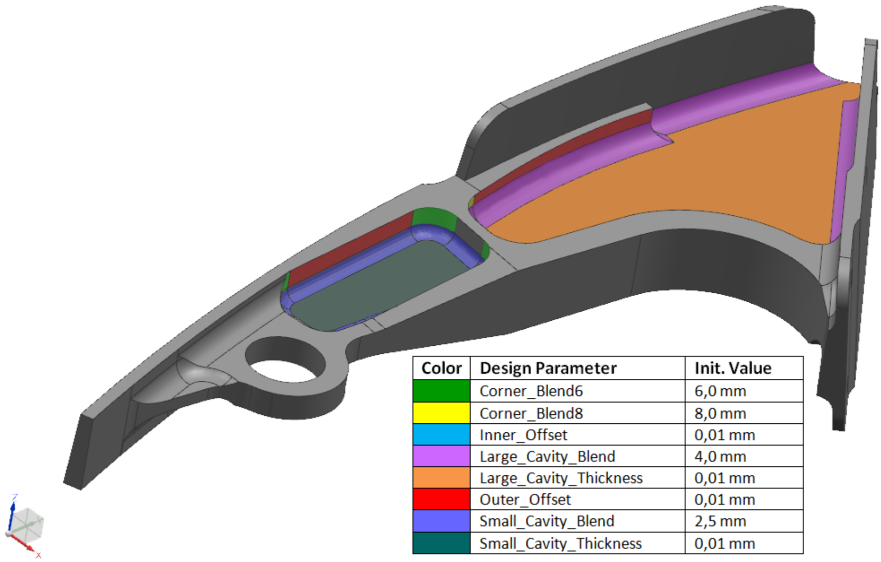


Figure 3.9: Assign parameters to Offset Region (13)

In order to assign user expressions to the various design parameters, the features need to be edited. Instead of the initial constant value, “Formula” is chosen from the menu. This is illustrated in Figure 3.9.

As mentioned earlier, the feature **offset region** is not allowed to be set equal to zero. For that reason it was defined as 0.01 mm.



Color	Design Parameter	Init. Value
Green	Corner_Blend6	6,0 mm
Yellow	Corner_Blend8	8,0 mm
Light blue	Inner_Offset	0,01 mm
Violet	Large_Cavity_Blend	4,0 mm
Orange	Large_Cavity_Thickness	0,01 mm
Red	Outer_Offset	0,01 mm
Blue	Small_Cavity_Blend	2,5 mm
Teal	Small_Cavity_Thickness	0,01 mm

Figure 3.10: Parameterized design variables (Top)

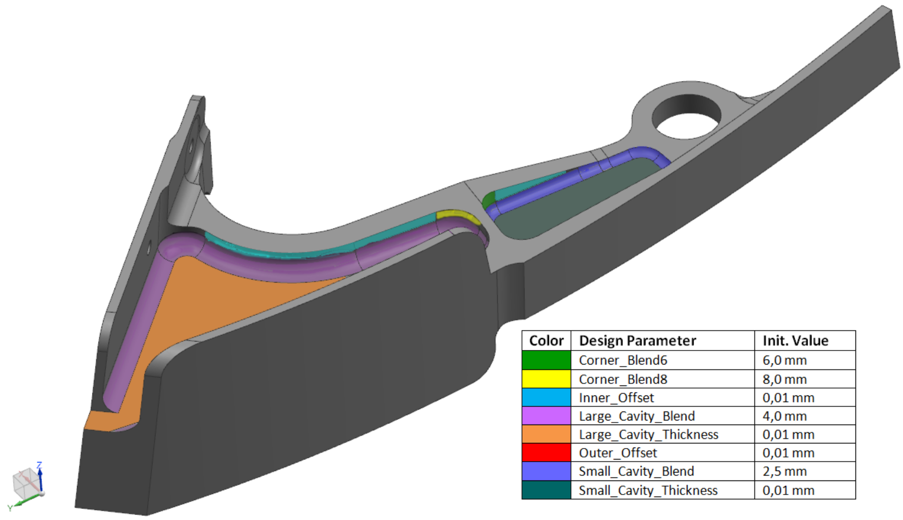


Figure 3.11: Parameterized design variables (Bottom)

Figure 3.10 and Figure 3.11 shows how smart selection of linked design expressions are chosen to reduce the number of parameters. The thickness of the inner flange in both of the cavities, are represented by the same design variable **Inner_Offset**. The same goes for the outer flange **Outer_Offset**.

The thicknesses of the webs in the two cavities are represented by two parameters **Large_Cavity_Thickness** and **Small_Cavity_Thickness**. Defining the positive direction perpendicular outward from the face, prevents the center from misalignment.

All of the four blends is represented by one design parameter each.

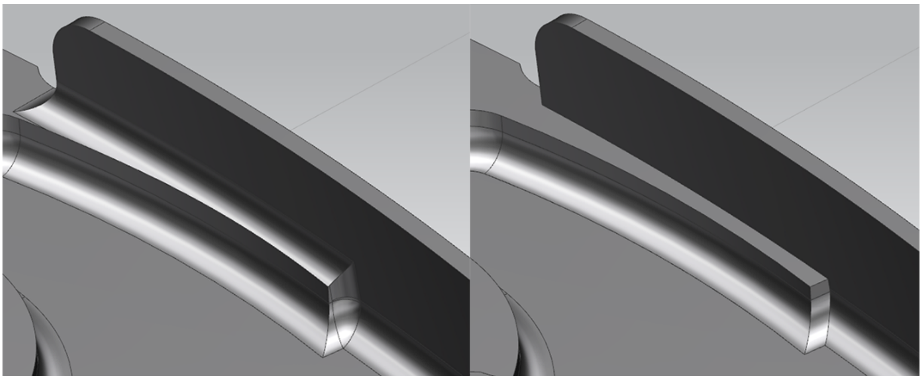


Figure 3.12: Edge Blend (17) removed

Outer_Offset had problems updating the geometry due to a blend which suddenly disappeared when this parameter was changed. This blend was therefore removed in order to achieve a robust design parameterization (Figure 3.12).

3.4 Baseline Design Results after Parameterization

Because of the changes made in the geometry, new simulation results were necessary. Only the displacement plot is shown in Figure 3.13.

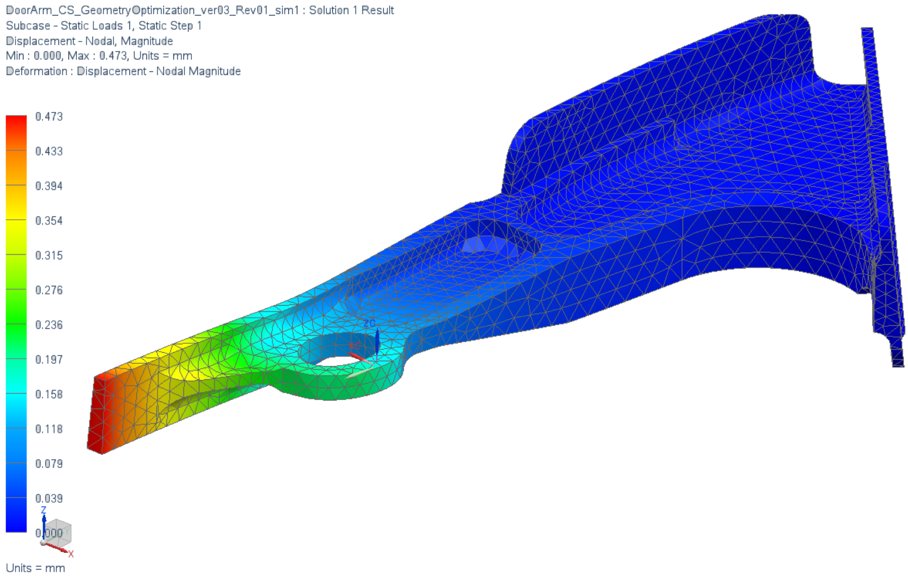


Figure 3.13: Displacement (magnitude)

The values from the optimization are presented in Table 3.1.

Table 3.1: Results after parameterization

	Mass	**Displacement (x-direction)**	**Displacement (y-direction)**	**Displacement Magnitude**	**Von Mises Stress (Elemental-Nodal)**
Max	201.4 g	0.449 mm	0.166 mm	0.473 mm	186.15 MPa
Min		0 mm	0 mm	0 mm	0 MPa

The new simulation showed a slight increase in the displacement, due to the blend that was removed. This gave a slight mass reduction which will form the basis of the optimization criteria.

3.5 Summary

The part has been successfully parameterized in order to capture design intents. A qualitative evaluation of the parameterization can be done in relation to the five principles regarding an ideal parameterization. SM has provided the model with possibility of generating a large variety of realistic shapes.

Many of the design variables have been linked by use of expression, so one design parameter is able to control several design variables. This helps save computational time, but also compromises the flexibility.

3.6 Discussion

Not every parameter value is feasible in order to return a successful model update, so the design range for each parameter needs to be explored further. In order to run an automated computer based optimization run, it is necessary to define a range for each of design variables. This will help make the parameterization robust.

In many cases, there may be many more design variables to choose from. The parameterization will then be more dependent on the user experience. It is then sensible to start with the design variables which apparently have most impact on the load case.

One aspect mentioned in the principles was to make the parameterization generic and integrable. It is not certain that the SM features is supported by other CAD systems. Compatibility issues like these are common for any other CAD system as well.

Futher investigation by performing sensitivity analysis will help to minimize the design space and remove parameters which have minor influence on the optimization.

In this case, nearly all allowed surfaces and fillets were included in the paramterization. **Outer_Offset** and **Inner_Offset** could be divided into four parameters, implementing even more opportunities for the sensitivity.

Chapter 4

Sensitivity Analysis

Flexibility was mentioned as an important aspect of optimization in the previous chapter. But flexibility also has its price. A large number of parameters may appear to give more freedom of choice to the design. However, as the dimensionality of the design space grows, looking for better designs becomes more complex. This results in huge computational cost (time consumption) as the number of parameters increases. Accordingly, efforts should be made to keep the number of input variables as low as possible without sacrificing independence of design intents

Global Sensitivity in NX is a process that enables you to determine how sensitive the design objective is to each design parameter. This helps predict which parameter has the most impact on critical model response [4]. In addition, the design space can contain values which will lead to unsolvable geometry. Performing such an analysis can help to find the values causing this issue. It is important that the design space is continuous so the optimization becomes successful.

In this Chapter, a sensitvity analysis will be performed by use of NX Advanced Simulations.

4.1 Sensitivity Analysis in NX

Prior to the sensitivity analysis, it is necessary to run a standard linear simulation with desired loads and constraints. This is because the geometry optimization will use this simulation as a basis for further optimization. The simulation performed in Section 2.5 will be used futher.

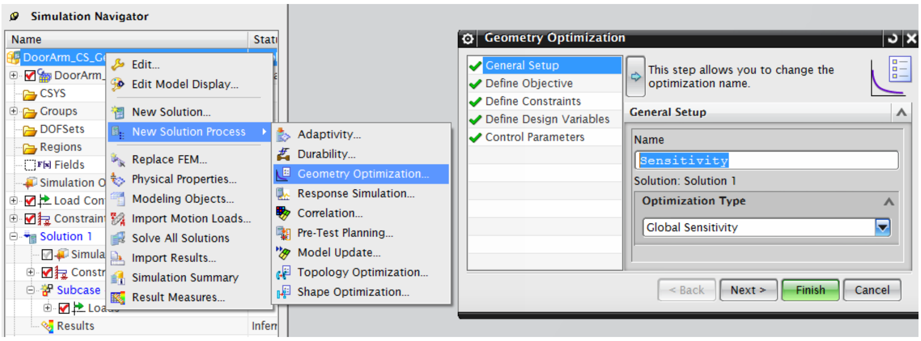


Figure 4.1: Global Sensitivity

The wizard window to perform such an analysis is similar for both of the geometry analysis in NX. Many of the options are not as relevant for a *Global Sensitivity* analysis, as to an *Altair HyperOpt* optimization (will be discussed in Chapter 5).

In NX you can choose objectives like:

- Weight
- Volume
- Result measures (stress, displacement, rotation and reaction force)

During a sensitivity analysis in NX, objective and constraints are basically the same. Both ways, the wanted output variables can be extracted from the analysis.

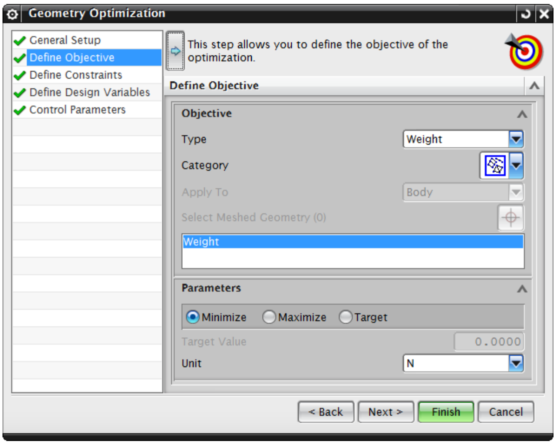


Figure 4.2: Defining objective

Figure 4.2 depict how weight has been chosen as the objective. NX only allows single-objective geometry analysis.

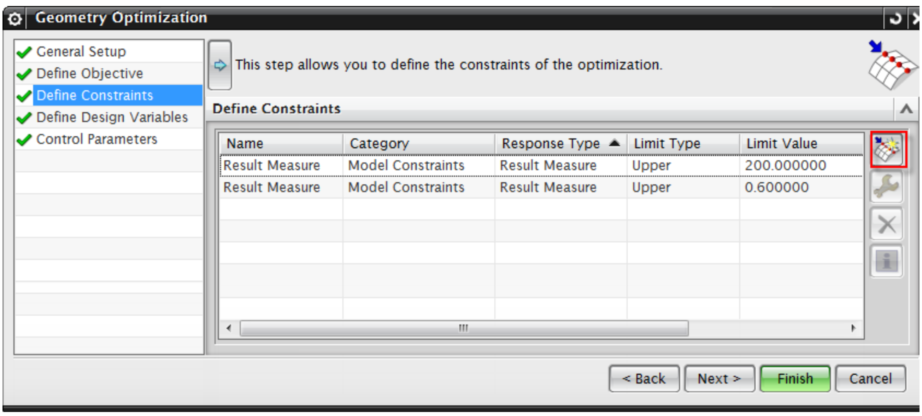


Figure 4.3: Defining constraints

To get more outputs variables, these had to be defined as constraints (Figure 4.3).

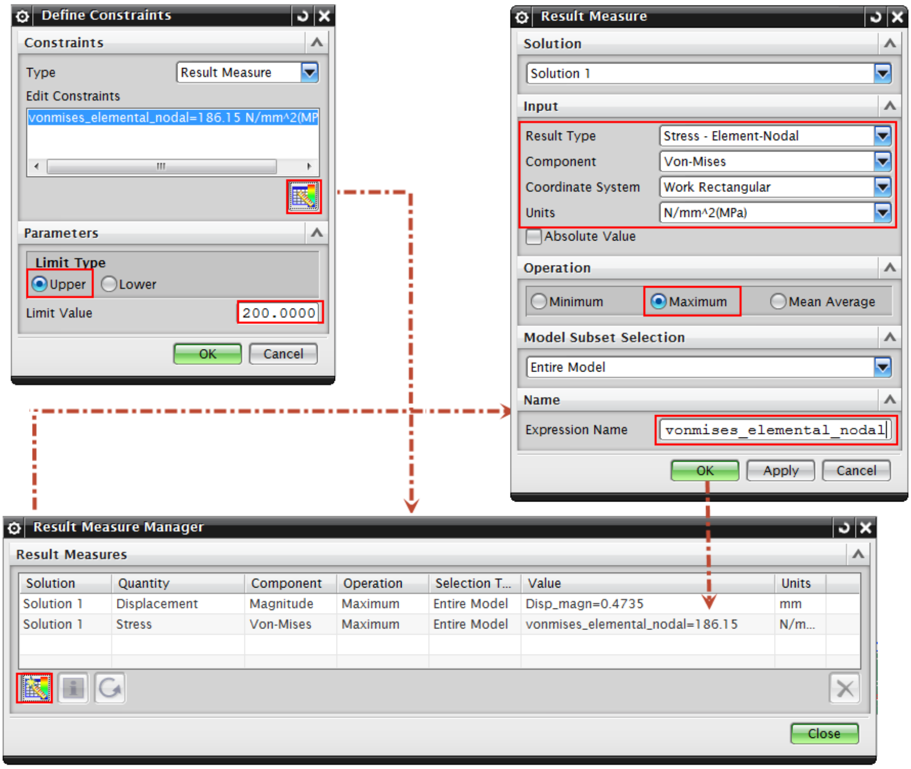


Figure 4.4: How to add constraint

Figure 4.4 describes how to add von Mises stress as a constraint. The von Mises stress (elemental nodal) is used as output variable. In addition, displacement (magnitude) is also defined as a constraint.

The defined limits for constraints and objective, does not have any influence on the result during the sensitivity analysis other than highlighting the exceeded values in red.

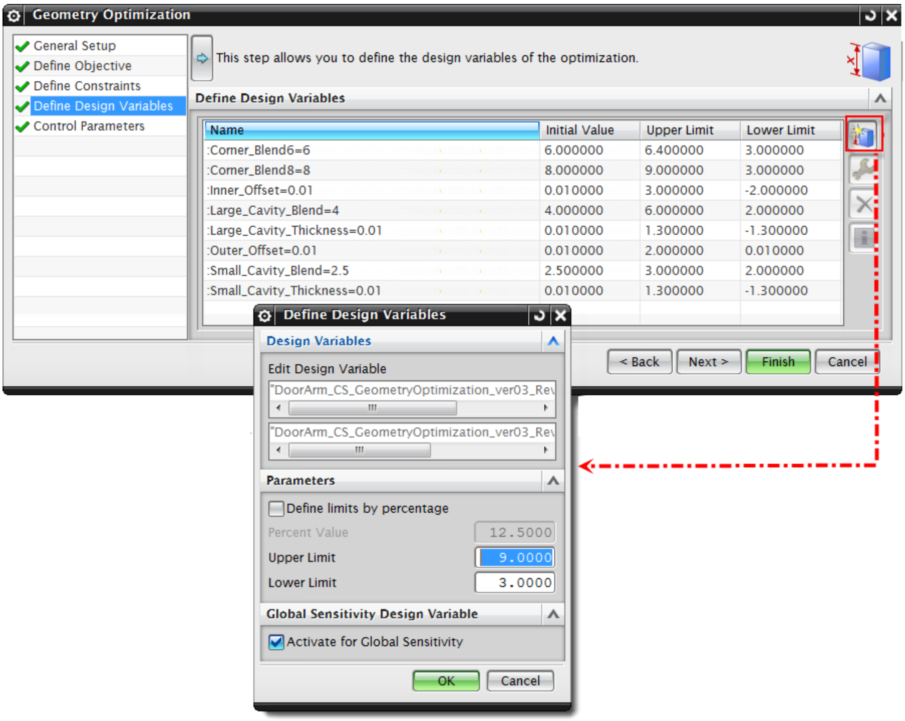


Figure 4.5: Defining design variables for the sensitivity analysis

An attempt to change the design parameters by trial and error, verified to what extent, and how the design range for each parameter could be changed. A rough evaluation of these values were used to define the upper and lower limit. When running such a analysis it is necessary to tick of "Activate for Global Sensitivity" in order to achieve results.

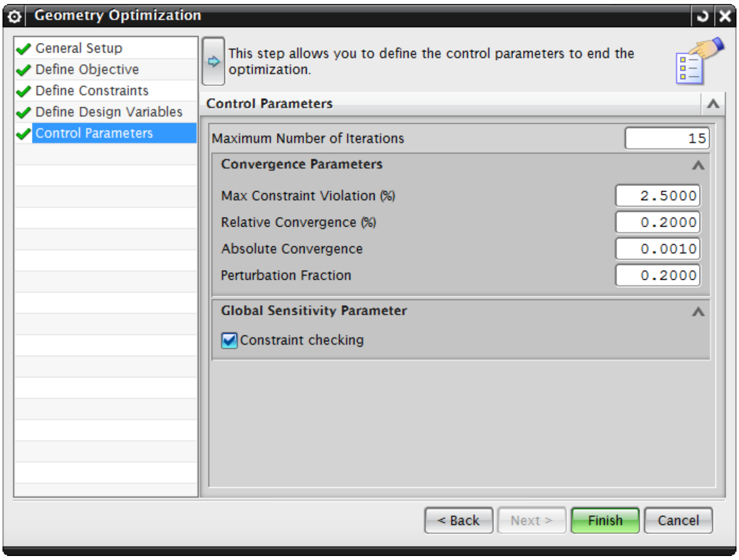


Figure 4.6: Control Parameters

The last step for setting up an analysis, is the control parameters (Figure 4.6). “Maximum Number of Iterations” has been set to 15. This specifies how many uniformly distibuted steps each of the design ranges should be devided into. As an example, if the lower limit is 0 mm, and the upper limit is 3 mm, the increments will be 0.2 mm when the amount of iteration is set to 15. In order to return output values for each and every design, *Constraint checking* needs to be ticked off.

4.2 Results

NX returns an Excel spreadsheet with the results from the analysis (Appendix A). An analysis like this took less than half an hour.

Sensitivity History							
Design Objective Results							
Weight (Minimum) [N]							
Design Variable Results							
	Step #1	Step #2	Step #3	Step #4	Step #13	Step #14	Step #15
Large_Cavity_Thickness	-1,30	-1,11	-0,93	-0,74	0,93	1,11	1,30
Objective Result	1,70	1,74	1,78	1,82	2,17	2,21	2,25
Result Measure							
Upper Limit = 0.600 [mm]	0,56	0,52	0,50	0,49	0,46	0,46	0,46
Result Measure							
Upper Limit = 200.000000 [N/mm^2(MPa)]	186,45	184,98	184,99	184,92	185,17	184,99	185,32
	Step #1	Step #2	Step #3	Step #4	Step #13	Step #14	Step #15
Small_Cavity_Thickness	-1,30	-1,11	-0,93	-0,74	0,93	1,11	1,30
Objective Result	1,91	1,92	1,93	1,94	2,02	2,03	2,03
Result Measure							
Upper Limit = 0.600 [mm]	0,50	0,50	0,49	0,49	0,46	0,46	0,46
Result Measure							
Upper Limit = 200.000000 [N/mm^2(MPa)]	190,37	188,52	187,68	186,93	186,35	183,44	183,23

Figure 4.7: Sensitivity analysis results in Excel

Figure 4.7 depicts a screenshot, showing some of the outcome from the sensitivity analysis. Each of the design ranges was split into 15 uniformly distributed steps. For each step, the weight (as the objective), stress and displacement (as constraints) were extracted.

The first thing to notice from the spreadsheet, is how the stress is affected. While the displacement either increases or decreases smoothly, the stress tends to shift inconsistently.

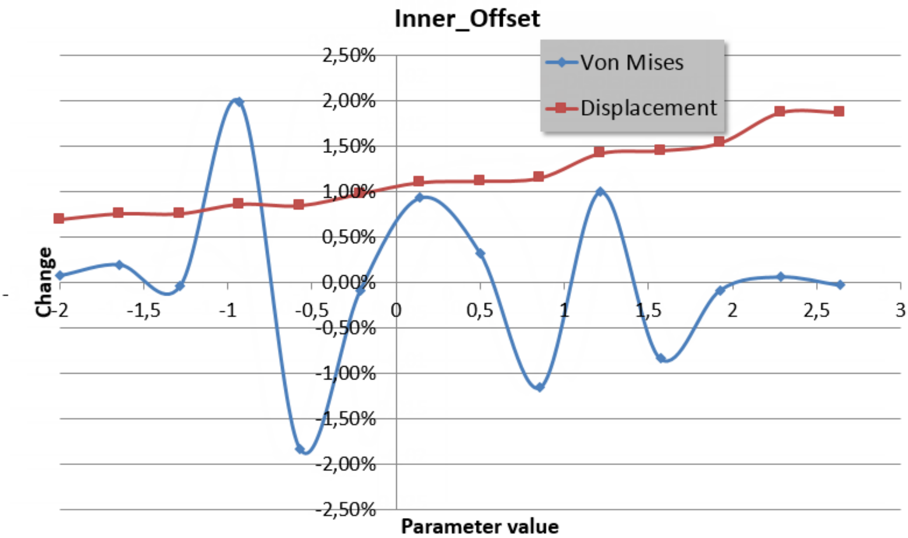


Figure 4.8: Changes of displacement and stress for Inner_Offset

Figure 4.8 shows respectively the percentage change from one parameter value to the next, for the parameter **Inner_Offset** (parameter values in millimeters). Here, the percentage change increases more or less consistently for the dispacement. The von Mises stress on the other hand, tends to alternate unconsistently.

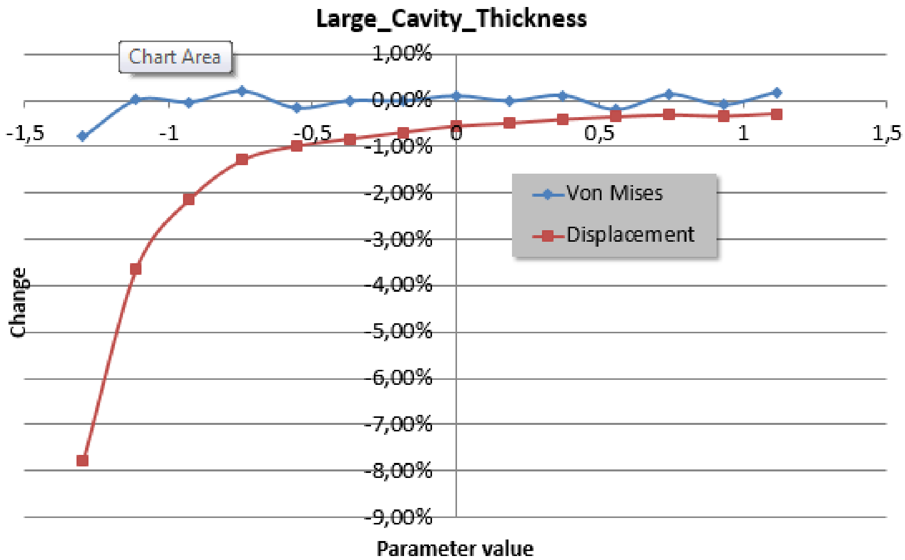


Figure 4.9: Changes of displeacement and stress for Large_Cavity_Thickness

For **Large_Cavity_Thickness**, the von Mises stress is insignificantly affected. The displacement experiences substantial changes in the beginning. This is caused due to the thickness of the web in the large cavity, where the cross section becomes so small that most of the stiffness disappears.

This proves how stresses around the hole, will not be affected to the same extent as the displacement, since the changes in the geometry is made in an area remote from the hole where the stresses are remarkably less.

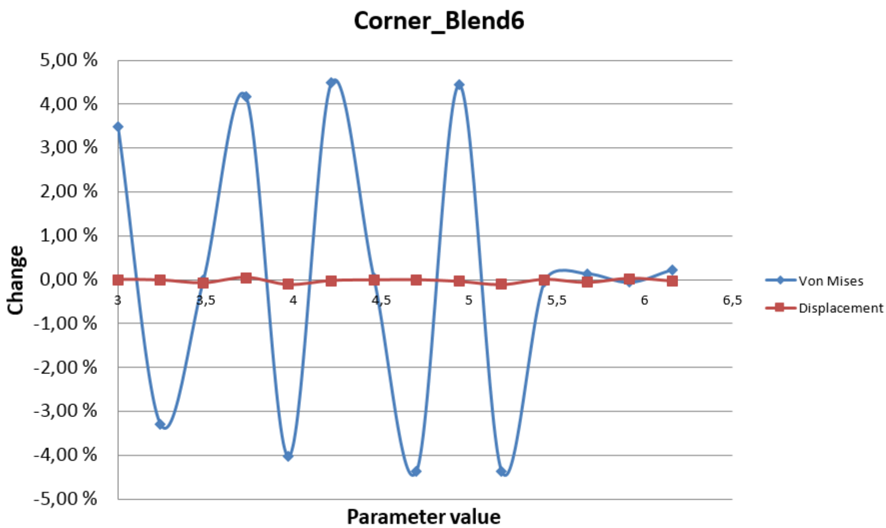


Figure 4.10: Changes of displeacement and stress for Corner_Blend6

Figure 4.10 shows how **Corner_Blend6** has little influence on the displacement, while the von Mises stress has a tendency to alternate rapidly.

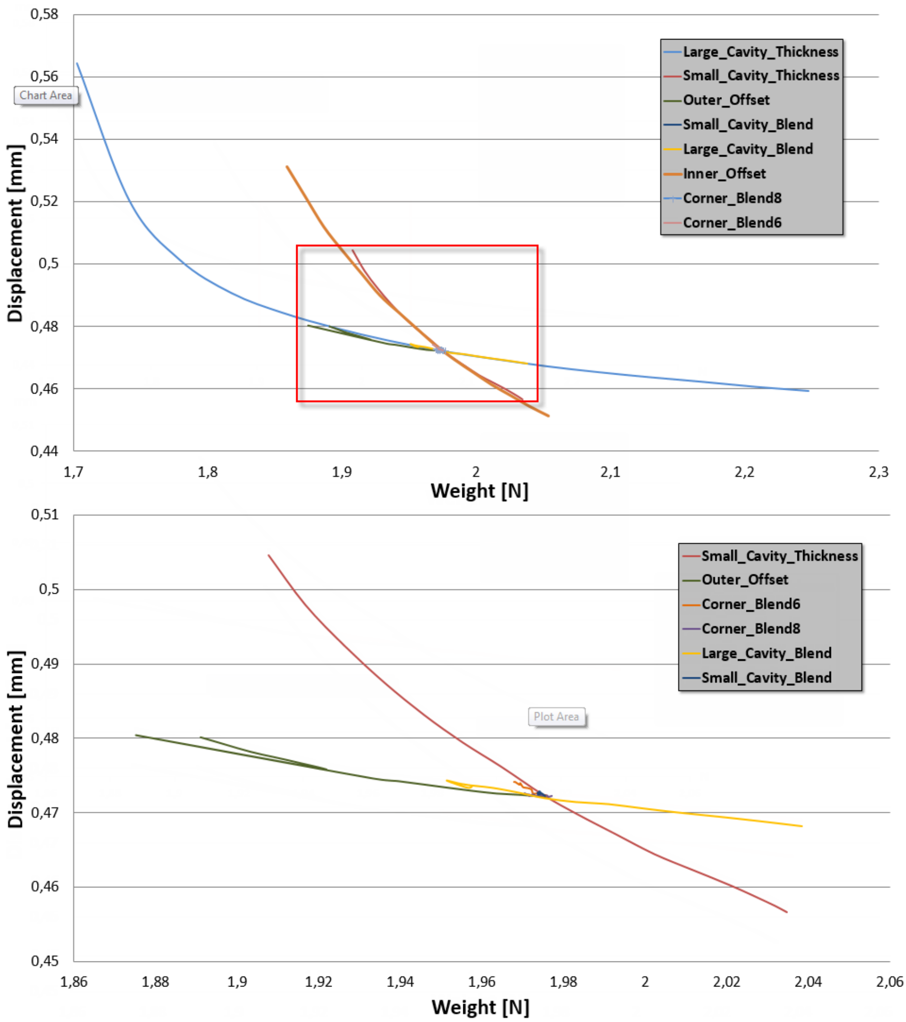


Figure 4.11: Sensitivity of the design parameters parameter.

In Figure 4.11, displacement (y-axis) is plotted against weight (x-axis). This gives a good visualization of how each of the design parameters respond to changes. The gradient along the curves expresses the impact displacement has in relation to weight . The flatter sections of each curve is where we can achieve most weight reduction without compromising deformation excessively . This also goes for the shorter lines, which have less influence on the optimization. **Large_Cavity_Thickness**, **Small_Cavity_Thickness** and **Inner_Offset** are the most important design variables, since they have great influence on the objective.

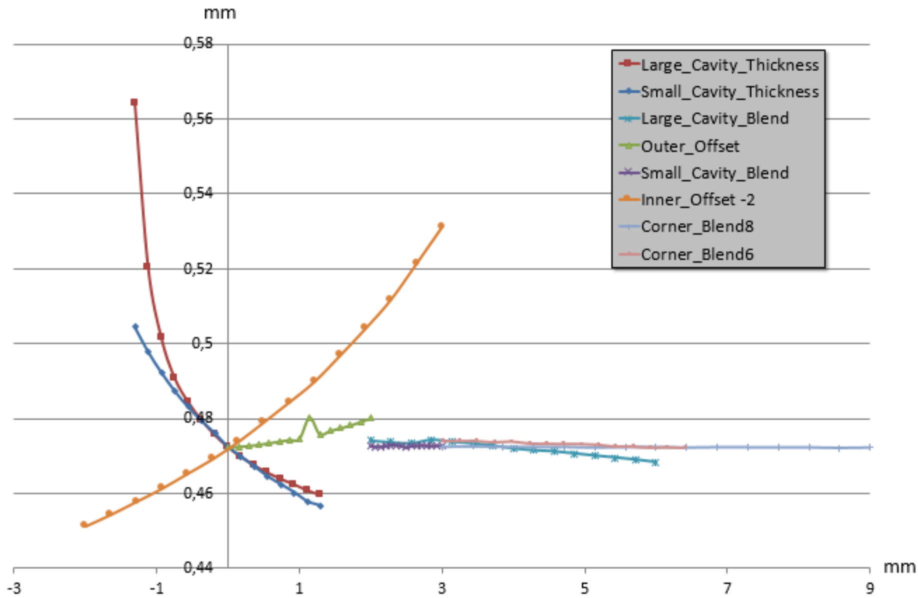


Figure 4.12: Displacement (y-axis) plotted against design variable (x-axis) for each of the design parameters

The lower plot shows a zoomed section of the curves inside the red box. Some of the curves are even so short it is not possible to spot. There is no reason to use those design parameters in further optimization analysis since they will have negligible impact on the objective.

Outer_Offset makes an unsuspected turn. It is clear that the parameter struggles to make a solvable geometry update for certain parameter values. To be able investigate the design range for the design parameters, and determine which value is causing this issue, another plot is needed. The plot underneath shows the displacements (y-axis) plotted against the design variables (x-axis) for all parameters (fig. 4.12).

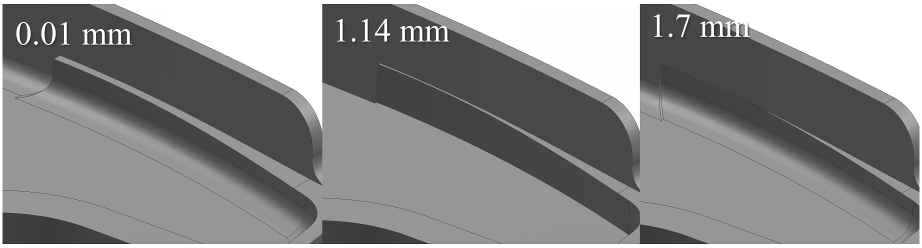


Figure 4.13: Comparrison of different parameter values for Outer_Offset

As can be seen from the green curve, **Outer_Offset** has problems updating the geometry for the value 1.14 mm. The model was updated manually with this value. This proved how the blend (represented by **Large_Cavity_Blend**) appears to fail as the flange penetrates the inner face of the bracket. Letting the face penetrate the bracket was not the intention in the firste place, when the design range was stated. It also conflicts with design limitations (Section 3.1).

4.3 Summary

Use of global sensitivity in NX has proven to be a very simple way of performing a sensitivity analysis and is not very time consuming either.

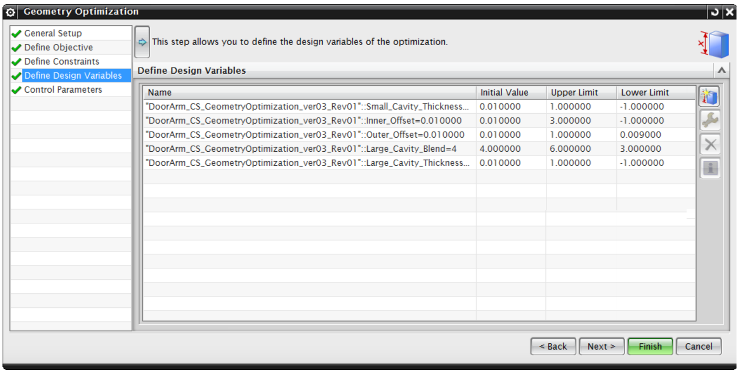


Figure 4.14: Revised design parameters

After a sensitvity analysis, the following questions should be answered:

- Which are the most important design variables?
- Should any of the design variables be excluded from the analysis?
- Can the design space be reduce by changing upper and lower limit for each design variable?
- Which objective and constraints are suitable for my optimization?

Based on the sensitivity analysis we will continue with the following design parameters and limits in the optimization analyses. Three of them were discarded. leaving five to the optimization.

The upper limit of the design range for **Outer_Offset**, has been reduced to 1.00 mm. The lower limit for **Inner_Offset** is reduced since the value increased the flange thickness more then necessary in comparison to the other variables.

4.4 Discussion

How sensitive each design parameter is compared to weight, stresses or displacements are of great interest in relation to the optimization. If changing one parameter results in negligible influence on the objective, it can be excluded from the optimization analysis. This will help saving computational time. A sensitivity analysis is helpful when it comes to understanding how the design parameters affects the objective and constraints.

Performing a sensitivity analysis is strongly recommended in order to gain knowledgment of the design space. This can help to decreasing the computational time of the optimization analysis.

When it comes to validating what parameters to bring into the further optimization analysis, there will be a compromise between flexibility and robustness. In this case, it could also be beneficial to exclude **Large_Cavity_Blend** from the optmization, but since it had a gentle gradient, it was kept in.

The sensitivity analysis has proven why stresses in this case should not be used as an optimization objective. Peak stresses are likely to occour in areas where the force is applied, and these stesses will not be affected by the structural changes in remote regions. Displacement is then a more robust objective to use in further analysis.

Mesh Control is a tool NX tool that can refine the element model in specific areas. If this was applied in the areas around the hole, the stresses would perhaps behave gentler.

Chapter 5

Single-Objective Design Optimization with NX 8.5

Single-objective optimization, as the name implies, is a optimization where you only deal with one objective. It can either be to maximize, minimize or reach a certain target for the objective by changing the assigned parameters. The geometry optimization tool in NX is based on a software called *Altair HyperOpt*. The *Altair hyperOpt* is an adaptive response surface method (ARSM). Hyperopt uses a quadratic polynomial that is found and updated for each of the iterations. These are based on current and previous iterations. Least square algorithm is used to define the polynomial (See Altair documentation for more detailed information about the algorithm) [14].

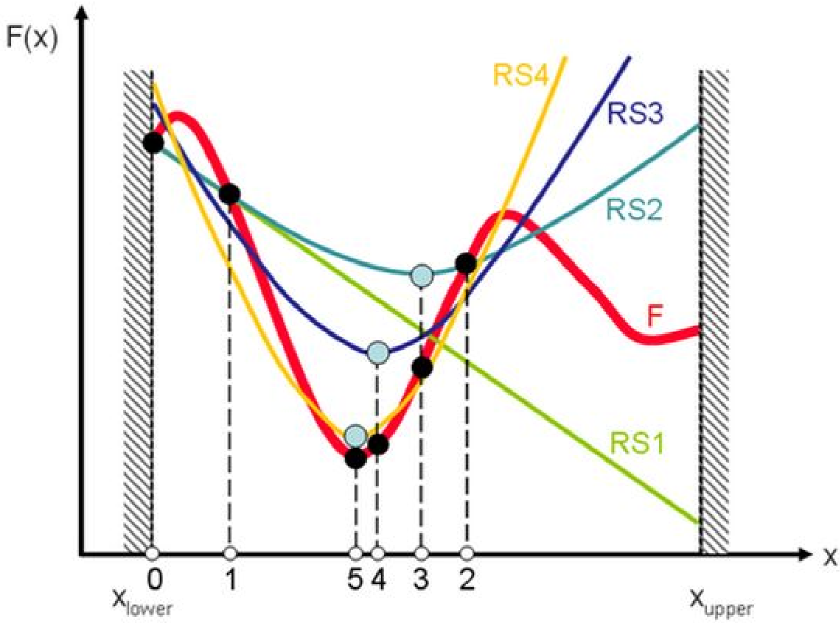


Figure 5.1: Altair HyperOpt curve fitting

In Figure 5.1, the algorithm tries to estimate a quadratic polynomial which will fit the actual function curve (F). As new designs are found along F, the response surface curve is updated (RS1, RS2, ..., RSx) until convergence is reached. In case the last quadratic polynomial curve does not converge sufficiently, the process is restarted from the first linear RS1 and quadratic response surfaces is generated for RS2, RS3 and so on. [4, 15].

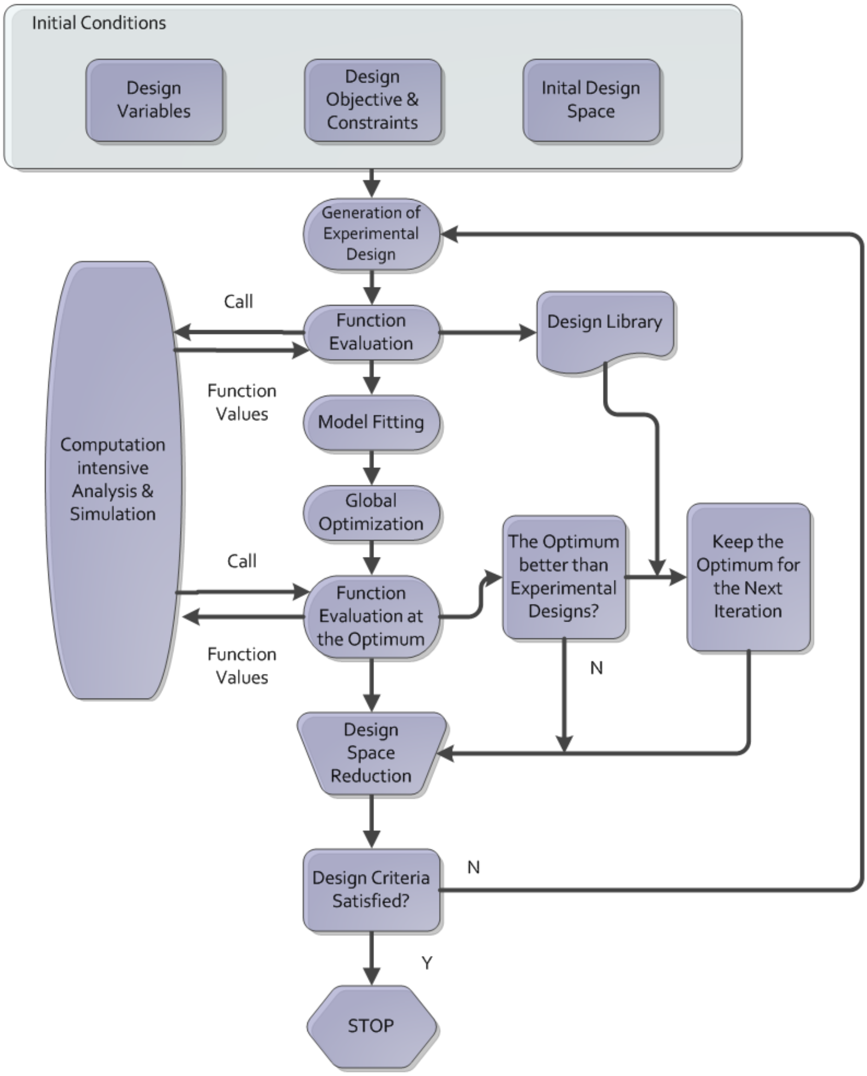


Figure 5.2: Flowchart ARSM

Figure 5.2 shows the overall process of the ARSM procedure. [16]

5.1 Work Sequence

Performing a geometry optimization is performed almost the same way as the global sensitivity. Therefore, most of the dialog box illustrations will be omitted.

The objective was kept with the same properties, trying to minimize the weight. Instead of using both deformation and stress as constraint limits, the stress was excluded from the optimization as a concequence of the results in the *Global Sensitvity* analysis. The design parameters will be defined as shown earlier, in Figure. 4.14.

There are many ways of defining the control parameters and without performing a test run, it can be difficult to predict how these parameters should be defined. Therefore, it could be advisable to run the first analysis with the default settings. We will here try to give a short description of each of the parameters:

Table 5.1: Control parameters [4]

Control Parameter	Description
Maximum Number of Iterations	The maximum number of iterations that the optimization is allowed to run. The analysis will stop prior to this if has reached convergence
Max Constraint Violation (%)	How much the analysis is allowed to violate the constraints. The constraints which are violated with be marked red in the excel sheet.
Relative Convergence (%)	Controls the percent change of the objective from the last two iterations at which the optimization is considered converged.The design is converged when the the percentage change is less than this value or if the allowable constraint is exceeded in the last iteration
Absolute Convergence	Controls the actual change from the last two iterations at which the absolute change of the objective is considered converged. The most conservative control parameter of the relative or the absolute criteria is when the analysis is converged
Pertubation Fraction	How many percent the design variable is allowed to change during the first few iterations. The deisgn parameter is allowed to change as much as this value times the difference between the upper and lower limit for each of the design parameter.

5.2 Results

One run will be performed with the default settings, the other with more stringent control parameters.

It will be possible to determine whether there is much to be gained by setting more stringent convergence requirements.

5.2.1 Run 1

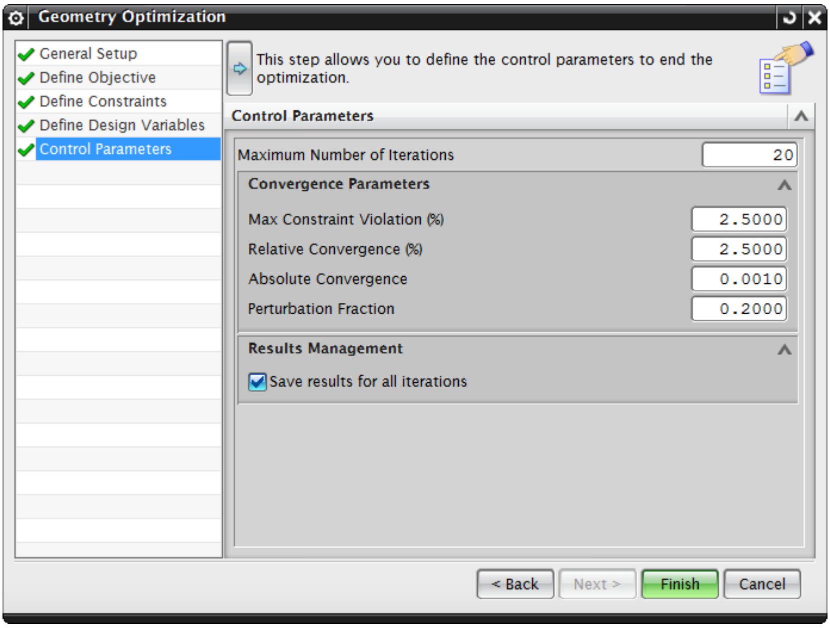


Figure 5.3: Default control parameters for the geometry optmization

After nine iterations the analysis stopped. The analysis with default control parameters returned the following values in an Excel spreadsheet (Appendix C):

Optimization History
Based on Altair HyperOpt

Design Objective Function Results									
Minimum Weight [N]	0	1	2	3	4	5	6	7	8
	1,9756	1,9948	1,9444	1,9546	1,9919	2,0597	1,9306	1,9090	1,9095
Mass	201,3816	203,3425	198,2010	199,2485	203,0440	209,9603	196,7953	194,5984	194,6518
Difference	0,0000	-1,9609	3,1806	2,1331	-1,6625	-8,5788	4,5863	6,7831	6,7298
Improvement %		-0,97 %	1,58 %	1,06 %	-0,83 %	-4,26 %	2,28 %	3,37 %	3,34 %
Design Variable Results									
Name	0	1	2	3	4	5	6	7	8
Small_Cavity_Thickness=0.010000	0,010	0,410	0,010	0,010	0,010	0,010	-0,095	0,000	0,000
Inner_Offset=0.010000	0,010	0,010	0,810	0,010	0,010	0,010	-0,076	-0,166	-0,261
Outer_Offset=0.010000	0,010	0,010	0,010	0,510	0,010	0,010	0,100	0,195	0,295
Large_Cavity_Blend=4	4,000	4,000	4,000	4,000	4,600	4,000	3,240	3,000	3,000
Large_Cavity_Thickness=0.010000	0,010	0,010	0,010	0,010	0,010	0,410	-0,090	-0,195	-0,191
Design Constraint Results									
	0	1	2	3	4	5	6	7	8
Result Measure									
Upper Limit = 0.475000 [mm]	0,47305	0,46638	0,48338	0,47312	0,47112	0,46693	0,47624	0,47549	0,47432
Limit	0,475	0,475	0,475	0,475	0,475	0,475	0,475	0,475	0,475
Violation %	-0,19 %	-0,86 %	0,84 %	-0,19 %	-0,39 %	-0,81 %	0,12 %	0,05 %	-0,07 %

Figure 5.4: Excel screen shot from the optimization with default values

The red numbers are iterations which violateed the upper limit. To be able to determine the improvements, some data (highlighted in blue) was added to the Excel sheet. The analysis was able to reduce the weight by approximately 3.34%.

Design variable **Small_Cavity_Thickness** seems to be zero, which is not possible because like described in the Chapter 3 . In fact, the variable is not zero, but the table rounds off digits after three decimal places.

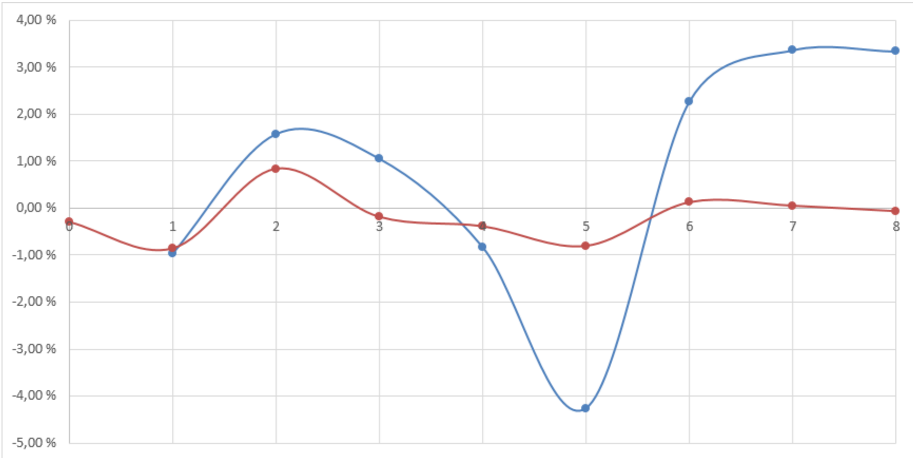


Figure 5.5: Objective plot for optimization run with default control parameters

The analysis is considered converged since the percentage change in the objective from iteration 6 to 7 and 7 to 8 is less than the specified relative convergence (2.5 %). The absolute convergence criteria is also reached from 7 to 8 (0.001 mm).

5.2.2 Run 2

By setting tighter restrictions for the convergence criteria, it will be possible to compare and see if the analysis will return a better optimum. As a consequence of this, the time it takes to run the analysis will increase. By keeping perturbation fraction equal to the last run, it is most likely the objective will converge around the same design variables (Figure 5.6).

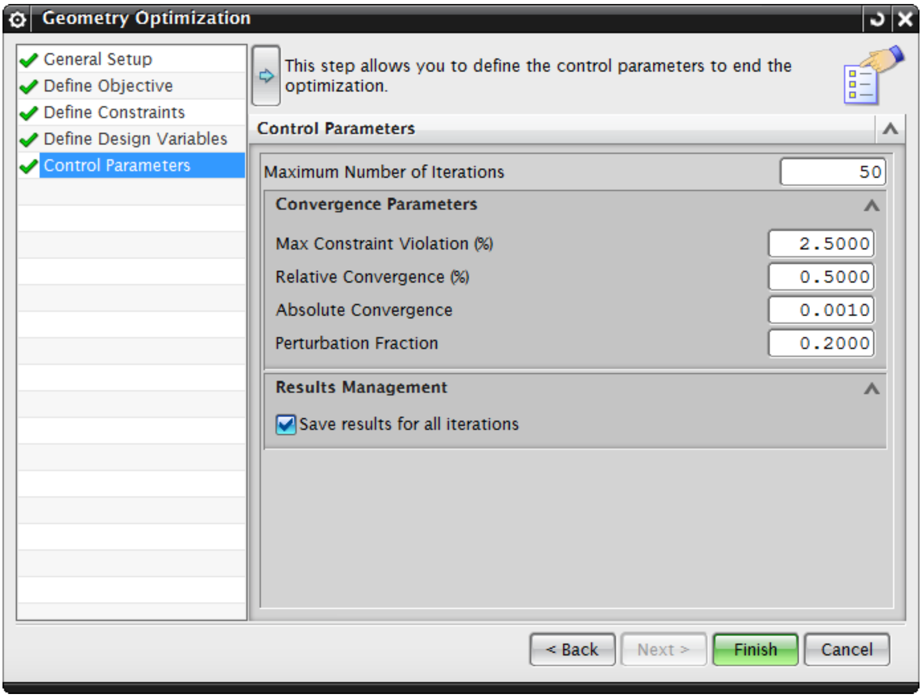


Figure 5.6: Control parameters with harder convergence restrictions

The Excel spreadsheet is shown in Appendix C. After 12 iterations the analysis was completed, returning a slight decrease in constraint violation. The objective improvement was now decreased down to 5.66 %, a remarkable improvement. The displacement constraint was violated by 0.09% for the last pertubation.

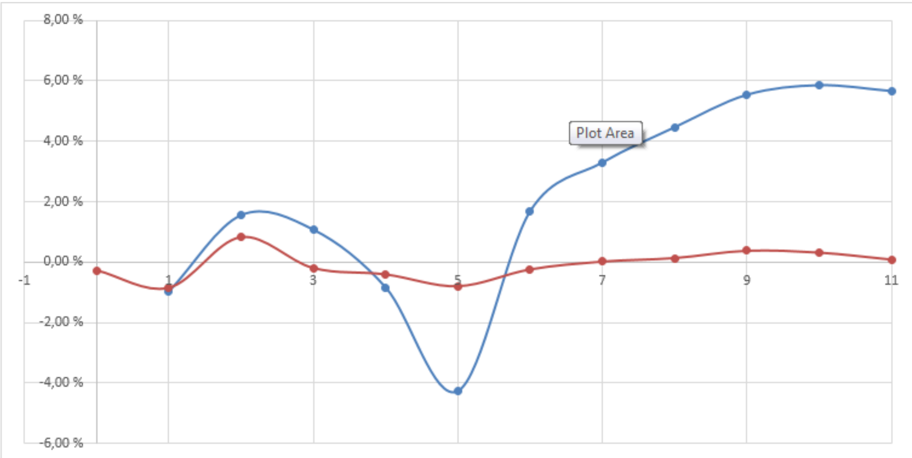


Figure 5.7: Objective plot for optimization run with harder convergence restriction

"Maximum Number of Iterations" is set to 100. Some test runs showed that the analysis stopped long before this value was reached.

5.3 Summary

NX Advanced Simulations contains a simple optimization tool with focus on ease of use. Such analysis is practically easy to perform. Choosing a more stringent convergence criterion, gives a remarkably better outcome in this case.

Table 5.2: Comparison of the design parameters

	Initial		**Run 1**	**Run 2**
Small Cavity Thickness [mm]	0.010		0.00	0.395
Inner Offset [mm]	0.010		-0.261	-0.328
Outer Offset [mm]	0.010		0.295	0.343
Large Cavity Blend [mm]	4.00		3.000	3.000
Large Cavity Thickness [mm]	0.01		-0.191	-0.503
Mass [g]	201.4		194.7	190.0
Mass reduction	-		3.34 %	5.66 %

The improvement from the first to second run is remarkable (Figure 5.2). The constraint violations of the weight limit in the two runs are so small it is justifiable to compare the improvement in the two runs. The solver chooses to increase **Outer Offset** in both runs. In the second run **Small Cavity Thickness** is increased as well. The rest of the design parameters are decreased.

5.4 Discussion

HyperOpt‘s Achilles‘ heel, is the way it searches through the designs. Premature convergence can easily occour when a local optimum is found. This have to do with the quadratic polynomial which is not able to give a comprehensive representation of the entire function curve. One way of controlling this behavior is by experimenting with various values for the Pertubation Fraction, mentioned earlier in this chapter. This will gives a wider search, that may result in finding new unrevealed solutions.

It could also be interesting to see if the convergence had been better if the convergence criteria was tightened further.

The displacement constraint limit was set to 0.475 mm instead of 0.473 mm. This was not the intention, but it would have taken an impractical amount of time to correct the error. This value is so close to the inital displacement, it will have a minor influence on the component.

Chapter 6

Multiobjective Design Optimization with modeFRONTIER

In contrast to the single-objective optimization, we have the multiobjective optimization. Such an optimization deals with two or more conflicting objectives. Most real life problems involve improving one objective sacrificing another. In this case, using a multiobjective approach gives a better understanding of the problem.

This chapter will begin with an introduction to modeFRONTIER and study the various optimization algorithms the software uses. The quality of the algorithms will be benchmarked by practical implementation with the door connection arm.

6.1 Pareto Optimal Solutions

An example of a typical multiobjective solution is depicted in Figure 6.1. Here there are two conflicting objectives, one on each axis. In the case where two objectives is put up against each other, a large variety of solutions can be extracted. The Pareto Optimal solutions (non-dominated solutions) are the solutions which can not be improved in value without impairment in any of the other objective values [5].

A set of such solutions forms a so called *Pareto Front*. By drawing a curve through these points we get a trade-off curve between the two objectives

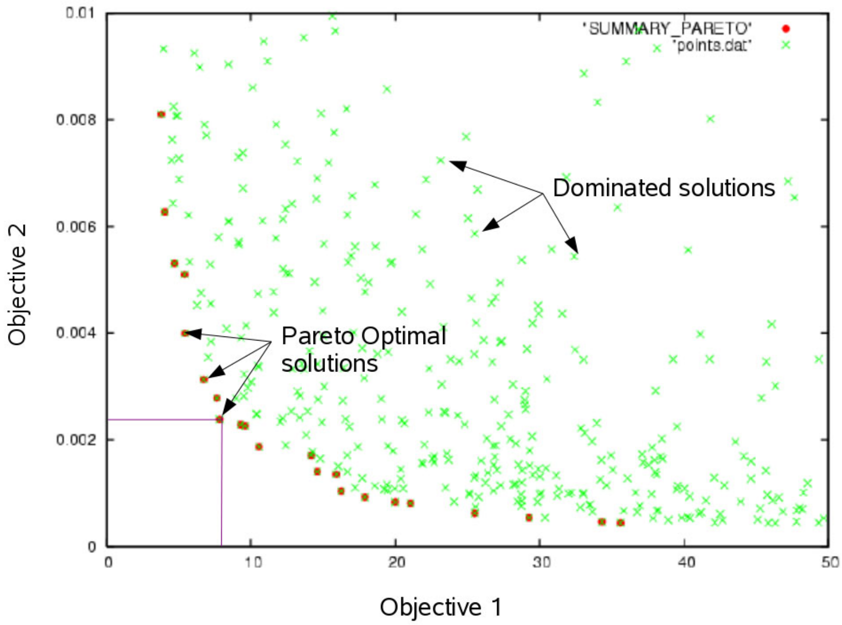


Figure 6.1: Pareto Front[2]

Considering the door connection arm, two objectives may be used; mass and displacement. These two objectives are conflicting in a way that displacement usually will tend to increase (reduction in stiffness), as the mass decreases.

6.2 Introduction to modeFRONTIER

modeFRONTIER is a multiobjective optimization software which allows you to connect several different CAD or FEA software together. Through the graphical user interface (GUI) you are able to build a work flow consisting of nodes (icons) and links (lines betweed the nodes). The blue links represents the data flow, while the black ones represents the process flow. The illustration underneath demonstrates how it is possible to build a workflow which can interact with simulations performed with NX Advanced Simulations. Single-objective optimization is also possible to perform, but is omitted in this case.

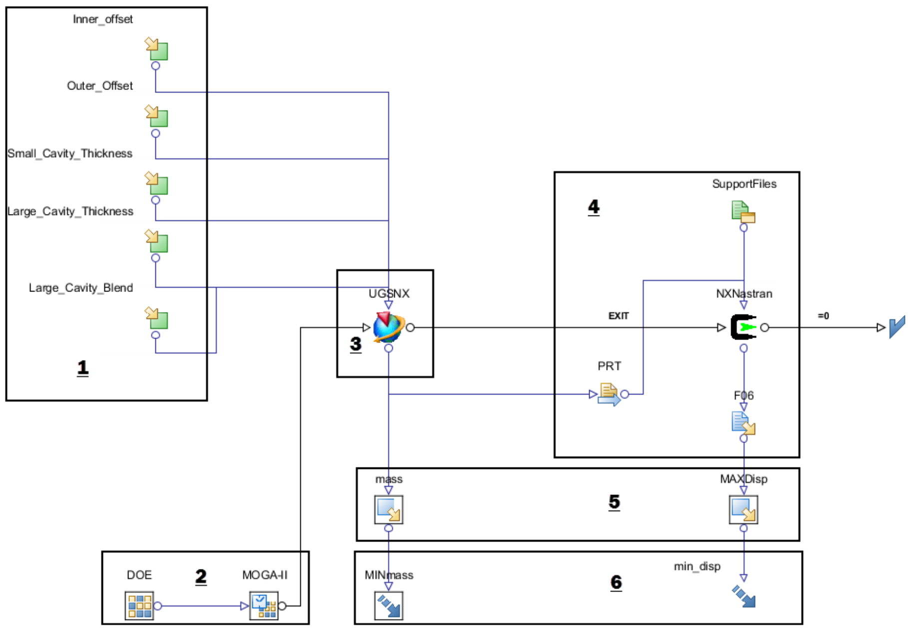


Figure 6.2: Workflow in modeFRONTIER

A description of the content in each of the numbered groups are:

1. Input variables: defines the design space
2. Design of Experiment (DOE) and schedulers: DOE and algorithms provides different values for the input variables
3. NX CAD node: Interacts with NX expressions
4. Support files and Cygwin shell script
5. Output variables: design output variables
6. Objective: minimizing or maximizing output variables

The workflow in Figure 6.2 starts at **2**, where modeFRONTIER desides what kind of designs parameters to try out . These values are based on the design space defined in **1**. In **3**, the NX geometry is updated and geometry outputs are requested. **5** is necessary in order to extract the data. **6** defines the objective.

Since modeFRONTIER has no built-in support for NX Advanced Simulation, **4** is a customized loop section which allows us to execute NX Advance Simulation and update the geometry with the data used in **3**. This is done by a so called Cygwin shell script node[17].

Constraint variable nodes can also be applied in the work flow, either connected to the input or output variables. As we know from chapter 3.3, the offset parameters can not be equal to zero. For that reason a constraint defined to prevent the scheduler from setting these parameters equal to zero could be applied. It is not very likely that this will happen, and even if so did happen, the program would only move on to the next variable.

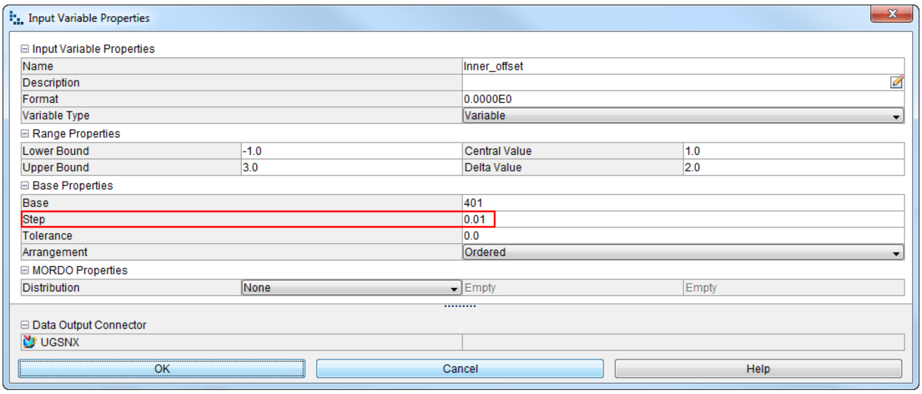


Figure 6.3: Input variable properties

The input variables was defined with the same design range as in the single-objective analysis in NX Advanced Simulations. In modeFRONTIER the size of each step can also be defined. This makes the optimization discrete instead of continuous. All steps are initialy defined to be 0.01 mm, which results in 401 numbers of steps for the design variable **Inner_Offset**. These step sizes can be individually defined for each variable.

All DOE and Scheduler properties settings will be kept default as long nothing else is stated. ESTECO recommended to use the default settings, as long as there is no good reason to do else.

A detailed description of the nodes and how to define them in this work flow is presented in Appendix E.

6.3 Theory

In order to run an optimization process in modeFRONTIER, the optimization algorithm needs to be provided with a number of test runs. Such test runs are called design of experiments (DOEs). The term scheduler is being used for the algorithms solving the problem . The DOEs is a sample of designs generated from the design spaces. The DOEs will form the basis of the analysis, before the scheduler takes over. The scheduler uses the experience achieved from these first runs to generate proper samples.

Schedulers based on different mathematical algorithms. modeFRONTIER contains several such schedulers. In the subsection underneath a selection of the DOE algorithms and schedulers in modeFRONTIER are presented.

6.3.1 Sampling Methods for DOEs

There are several DOE algorithms to choose from. For this type of optimization, the group of so called "Exploration DOEs" is the most relevant one. These are used to explore the design space in an early stage:

- **Random** sequence which spreads points random, without taking into account the previously generated sample points.
- **Sobol** generates an uniform sampling. The designs will try to avoid each other as much as possible.
- **Uniform Latin Hypercube** is a random generator that conforms to different statistical distributions and makes a relatively uniform DOE sampling.

It is up to the user to deside how many DOEs to generate. If time permits it, one should use a large DOE instead of a smaller one. Number of test designs might also depend on the type of scheduler being used. DOE can also be used in sensitivity analysis[18, 17].

6.3.2 Scheduler

The schedulers uses different methods in the search of finding the best solutions. Some of them are discribed her :

- **Genetic Algorithms (GA)** can be compared to the natural evolution of species and uses tools such as natural selection to guide the individuals (designs) towards optimal solutions. This is why a lot of notions like parent and children is used to describe the development of the algorithm.
- **Evolution Strategies (ES)** works in the same way but uses a mutation tool that produces individuals that stands out from the rest of the population. This way the algorithm can break the pattern and produce diversity in the population. These functions can be combined as well.
- **Simulated Annealing (SA)** utilizes an analogy from annealing in metallurgy. This process is based on thermodynamic free energy principles. The algorithm works by slowly removing bad solutions as the solution space is explored. The algorithm utilizes a probability function that determines if the new design is to be accepted or discarded.
- **Response Surfaces Methodology (RSM) based algorithms**: is a collection of mathematical techniques useful for modelling the output functions of interest. If RSM are incoropated within an optimization algorithm in an adaptive way, then the algorithm is speeded up considerably

modeFRONTIER includes a wide range of schedulers based on these methodsalgorithms. Some of them will be presented here.

MOGA – II

MOGA - II is a . This kind of algorithms (GA) utilizes four operators in their search for better designs.

1. Mutation
2. Selection
3. Elitism
4. Crossover

The algorithm will alternate between the use of each of the operators based on a defined operator probability.

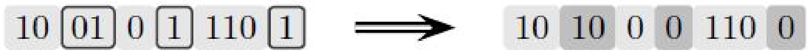


Figure 6.4: Mutation operator illustration with a bit string

Mutation controls how often the program should alter a random parameter (Figure 6.4). This operator may help break the pattern in cases where the algorithm can get stuck.

Selection defines the probability of how often a design parameter should be kept the same through the run.
Elitism will ensure preservation of good individuals. This means that the algorithm will assure that new generated designs is as good as, or better than the previous design.

The overall driving factor used to decide which individuals to choose in a genetic algorithm is the probability of being better than other individuals, called the fitness factor. Another characteristic that have major impact on the outcome is the use of crossover. Crossover can be done in two ways within the same optimization run; classic and directional.

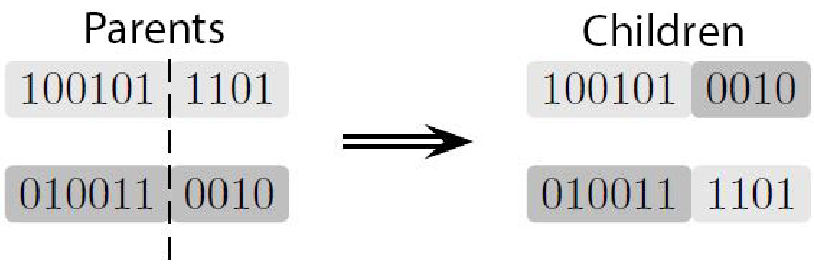


Figure 6.5: One point crossover

The classic way (one point crossover) involves dividing a bit string at a random point. The divided pieces from the parents is then put together to form a new resulting individual. The initial parent is put together by taking a random parent and combining it with the best from a tournament selection. The tournament winner is decided by the individuals fitness factor.

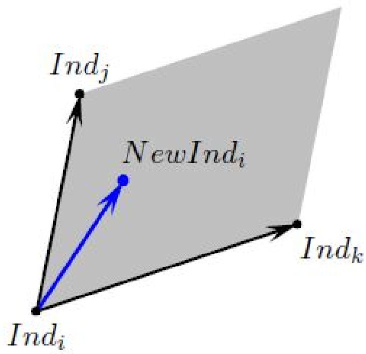


Figure 6.6: Directional crossover

Directional crossover differentiates itself by comparing the fitness value of two reference individuals. It considers the most appropriate direction of improvement by evaluating the parents fitness factor(Indj and Indk) with respect to a weighted direction compared to the new children position(Indi). This generates the New Indi (the actual new individual). Directional crossover represents one of the most helpful properties that make this algorithm a very powerful tool.

Moga – II is a great tool for most uses and is less susceptible for ending up in a local maximum. The method is slower than some of the other algorithms presented, but it is very stable and rarely crashes. When the design space is large, this algorithm can outperform many other schedulers.[19, 20, 17].

Simplex

The Simplex scheduler is a single-objective algorithm. It is based upon the "Nelder and Mead simplex" which is updated to handle constraints and discrete variables. The scheduler utilizes an algorithm to move the initial points along with their values closer to the objective. This will continue until the scheduler exceeds its maximum number of iterations or the points converge. For two input variables, a simplex is a triangle. The method searches and compares values at each vertices in a triangle. The worst vertex (where x and y is largest.) is identified and replaced with a new vertex. This results in new triangles being formed which generates smaller triangles that reveal optimal minimum coordinates.[1] The operators that control the algorithm is presented below in figure 6.7 in sequential order.

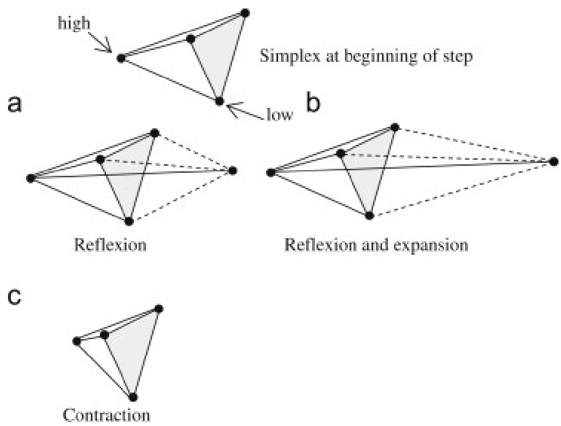


Figure 6.7: Illustrations of simplex steps [3]

This illustration shows a three dimensional simplex and shows how the operators would work towards a converging solution.

- **Reflection** involves an operator that makes the function move in the opposite direction of the worst value.
- **Expansion** will minimize the value(objective) further by expanding the previous goal achievement.
- **Contraction** is used if reflection gives a worse value than the previous. This means that the new point reverts back towards the initial value.

The new design generated is rounded up to the nearest discrete values defined by the initial value of each variable. Simplex iterates each variable in turn. It is not capable of iterating each variable at once[17]

[1] Simplex means a generalized triangle in N dimensions.

Hybrid

Hybrid combines a steady state genetic algorithm and a single objective optimizer (SQP). This makes it a robust multi-objective algorithm, as well as a good single objective algorithm. The amount of robustness versus exploration can be varied by specifying this in percentage. The algorithm works by implementing SQP run as one of the operators in a genetic algorithm. For more information regarding SQP see[17]. . The combination of the two algorithms makes it quick to reach the pareto front. Then the genetic algorithm fine tunes the variables in the end.

Hybrid uses Adaptive filter SQP and may also use RSM within the hybrid algorithm.

The main idea behind the chosen SQP solver is to use gradient information to make an approximation of the lagrangian function related to the objective function and constraints. To avoid local optimum points adaptive filters are introduced in the algorithm. This means that the old designs are stored and evaluated against the new ones. The criterion of the new design is to stand out and prevent local stagnation [17].

The overall process can be logically described as follows:

- Creation of a parent population based on an initial DOE(design of experiments) or performing a tournament selection among the population.
- The genetic algorithm work with its operators like mutation, crossover and SQP that generates offspring.
- Storing old design generated by SQP.
- If a local optimum is created, it gets sorted out as a parent in the population for further optimization.
- The design storage gets analyzed and the best designs are saved according to the elitism function.

MOSA – Multi-Objective Simulated Annealing

The method is a modified SIMPLEX method based on Simulated Annealing. One of the most important control parameters in this algorithm is the "hot" and "cold" phases. As the algorithm iterates it is either in a hot or cold phase. The hot one implies that it explores widely the design space, avoiding local optima. The cold phase allows convergence and local exploration. These two parameters has to be specified in the scheduler properties based on what property is the most preferable.

The fraction of hot iteration tells what the scheduler prioritizes. The total number of designs ($N_{Designs}$) necessary to complete a MOSA run is the number of initial DOEs (n) specified (In DOE properties) times numbers of iterations ($N_{Specified}$) specified in the MOSA scheduler. This yields: $N_{Designs} = N_{Specified} \times n$ [21, 17]

MOGT - Multiobjective Game Theory

Game theory algorithm works by assigning two different objectives to functions called players. These players are influenced by each others choice. They in turn try to minimize each others objective based on the others move. The two players does this until each player has minimized its function, an equilibrium is now found. In this optimization only one initial DOE is required for design space sampling.

MOGT has proved to be useful in economics. It is most commonly used in decision making regarding competitive fields. These strategies has been adopted by other disciplines and modified. Multiobjective game theory algorithms can be combined with different algorithms such as evolutionary algorithms to save computational time. A variety of game theory algorithms exist, one of them is a combination of Nash game theory coupled with the simplex method which is used in modeFRONTIER. This Nash simplex algorithm is a single objective algorithm that works by combining it with a competitive game theory algorithm called Nash equilibrium to make it multi objective [17].

6.3.3 No free lunch theorem

It is hard to predict which of the algorithms that will yield the best results. This is stated by the "no free lunch" theorem (NFL). This theorem uses an analogy about restaurant (problem solving algorithm), a menu that combines a lunch plate (the problem) and a price (performance of the algorithm in problem solving). The menus of each restaurant are alike, except for the prices that are shuffled. A omnivore would pay the same average price for lunch because he could order any plate at any restaurant. A vegan accompanied by the omnivore that seeks economy would however pay a higher average price for lunch. To reduce the average cost, one need to know what the order will cost at each restaurant and what the order will consist of. This means that performance depends on information about the problem.

Another interpretation is that unless it is possible to make prior assumptions about the problem, it is no algorithm that can be expected to outperform any other. This will in turn mean that without assumptions no algorithm will perform better than a blind search.[22, 23, 17]

Despite this NFL theorem, a general assumption based on experiences, a general comparison was mentioned by Esteco. This is presented in Table 6.1:

Table 6.1: General comparison of the

	Pros	**Cons**
MOGA-II	- Stable - Finds global optimum - Suited for non-linear problems	- Slow (many iterations)
Simplex	- Fast	- More sensitive than MOGA-II - Usually finds local optima - Only single objective
Fast	- Lives up to its name	- Not suited for non-linear problems
Hybrid	- Suited to cover global optimum	- Extensive search that takes advantage of two algorithms
MOGT	- Faster than MOGA-II	- Not exploratory, local optima
MOSA	- Finds global optimum - Well suited for large design spaces	- Very slow (many iterations)

6.4 Method

As just mentioned, it is hard to tell which of the algorithms that will give the best results and cost less computational time. Because it is hard to predict the most appropriate approach, a kind of brute force[2] search will be used.

There is almost infinite ways of running a optimization in modeFRONTIER. Based on what we know about the various DOEs and schedulers , we will compare some of these.

6.5 Selection of DOE in modeFRONTIER

In all three cases, the number of DOE samples were set to 30. This is because the minimum number of designs in order to use MOGA-II is 28.[17]

The analyses were performed like a sensitivity analysis without any scheduler by selecting "DOE Sequence" under *Scheduler Properties*.

MINmass and min_disp represents the objectives trying to minimize mass and displacement respectively.[3].

ID	RID	M	CATEGORY	Inner_off...	Large_C...	Large_C...	Outer_Of...	Small_C...	MAXDisp	mass	MINmass	min_disp
0			RNDDOE	1.9300E0	4.2300E0	-5.9000E-1	3.3933E-1	9.4000E-1	5.0300E-1	1.8430E-1	1.8430E-1	5.0300E-1
1			RNDDOE	-9.8000E-1	5.9000E0	8.8000E-1	9.4995E-1	8.8000E-1				
2			RNDDOE	5.9000E-1	4.0400E0	-4.1000E-1	5.0951E-1	-7.7000E-1	5.1206E-1	1.8289E-1	1.8289E-1	5.1206E-1
3			RNDDOE	2.0800E0	4.9800E0	-6.9000E-1	3.7937E-1	-7.2000E-1	5.6231E-1	1.7374E-1	1.7374E-1	5.6231E-1
4			RNDDOE	1.7800E0	5.4200E0	-9.9000E-1	5.2953E-1	4.9000E-1	5.3240E-1	1.7619E-1	1.7619E-1	5.3240E-1
5			RNDDOE	-4.4000E-1	4.4500E0	9.0000E-2	5.7958E-1	-5.9000E-1	4.7846E-1	1.9991E-1	1.9991E-1	4.7846E-1
6			RNDDOE	1.4900E0	3.5500E0	-9.8000E-1	1.6916E-1	-6.5000E-1	5.6348E-1	1.6733E-1	1.6733E-1	5.6348E-1
7			RNDDOE	1.1600E0	5.9300E0	-5.1000E-1	3.9939E-1	-5.7000E-1	5.1626E-1	1.8594E-1	1.8594E-1	5.1626E-1
8			RNDDOE	7.3000E-1	3.7000E0	7.8000E-1	3.9030E-2	1.9000E-1	4.7234E-1	2.1489E-1	2.1489E-1	4.7234E-1
9			RNDDOE	1.6200E0	3.3600E0	3.1000E-1	9.8999E-1	-5.9000E-1	5.2009E-1	1.9187E-1	1.9187E-1	5.2009E-1
10			RNDDOE	5.0000E-1	4.3900E0	-3.3000E-1	4.4944E-1	1.0000E-2	4.8829E-1	1.9057E-1	1.9057E-1	4.8829E-1
11			RNDDOE	3.0000E0	4.8900E0	8.2000E-1	5.0951E-1	-2.0000E-2	5.1967E-1	2.0797E-1	2.0797E-1	5.1967E-1
12			RNDDOE	7.1000E-1	3.9200E0	4.4000E-1	9.6997E-1	-5.8000E-1	4.9529E-1	1.9985E-1	1.9985E-1	4.9529E-1
13			RNDDOE	-3.1000E-1	4.6500E0	1.1000E-1	5.8959E-1	5.8000E-1	4.6220E-1	2.0656E-1	2.0656E-1	4.6220E-1
14			RNDDOE	1.8000E0	3.6100E0	-4.9000E-1	7.7978E-1	-5.5000E-1	5.4139E-1	1.7477E-1	1.7477E-1	5.4139E-1
15			RNDDOE	2.9400E0	5.4100E0	6.8000E-1	1.6916E-1	2.8000E-1	5.0507E-1	2.0991E-1	2.0991E-1	5.0507E-1
16			RNDDOE	-9.7000E-1	4.8900E0	-5.9000E-1	8.8989E-1	4.2000E-1	4.7100E-1	1.9276E-1	1.9276E-1	4.7100E-1
17			RNDDOE	1.9000E0	4.5300E0	9.8000E-1	1.5915E-1	4.2000E-1	4.8004E-1	2.1831E-1	2.1831E-1	4.8004E-1
18			RNDDOE	2.3000E0	3.3700E0	2.4000E-1	4.8948E-1	-8.0000E-1	5.5375E-1	1.8853E-1	1.8853E-1	5.5375E-1
19			RNDDOE	1.4700E0	3.0800E0	1.8000E-1	7.9071E-2	-8.6000E-1	5.2798E-1	1.9144E-1	1.9144E-1	5.2798E-1
20			RNDDOE	1.7200E0	3.8400E0	2.1000E-1	8.4985E-1	-2.9000E-1	5.1146E-1	1.9274E-1	1.9274E-1	5.1146E-1
21			RNDDOE	1.4000E0	3.8700E0	7.6000E-1	7.4975E-1	-1.5000E-1	4.9246E-1	2.0767E-1	2.0767E-1	4.9246E-1
22			RNDDOE	5.0000E-1	3.8100E0	4.6000E-1	8.8989E-1	-9.2000E-1	5.0134E-1	1.9926E-1	1.9926E-1	5.0134E-1
23			RNDDOE	8.3000E-1	5.5900E0	8.1000E-1	6.9061E-2	5.3000E-1				
24			RNDDOE	7.1000E-1	6.0000E0	-8.8000E-1	5.8959E-1	1.4000E-1	5.0512E-1	1.8308E-1	1.8308E-1	5.0512E-1
25			RNDDOE	1.6500E0	5.7300E0	-5.1000E-1	2.4924E-1	4.2000E-1	4.9951E-1	1.8946E-1	1.8946E-1	4.9951E-1
26			RNDDOE	3.5000E-1	4.8200E0	-3.7000E-1	2.9020E-2	-1.0000E-1	4.8770E-1	1.9287E-1	1.9287E-1	4.8770E-1
27			RNDDOE	4.8000E-1	4.3900E0	-6.5000E-1	6.7968E-1	4.3000E-1				
28			RNDDOE	1.9800E0	5.7900E0	1.8000E-1	6.4965E-1	-7.8000E-1	5.3526E-1	1.9510E-1	1.9510E-1	5.3526E-1
29			RNDDOE	2.1000E0	3.9200E0	7.7000E-1	6.3964E-1	8.6000E-1	4.7702E-1	2.1195E-1	2.1195E-1	4.7702E-1

Figure 6.8: Design table for random DOE

The Random DOE returned the following list of results. In the run 1, 3 out of 30 design iteration failed.

[2]Brute force search is a wide systematic search based on all possible combinations

[3]Displacements are in millimeters and mass in kilograms

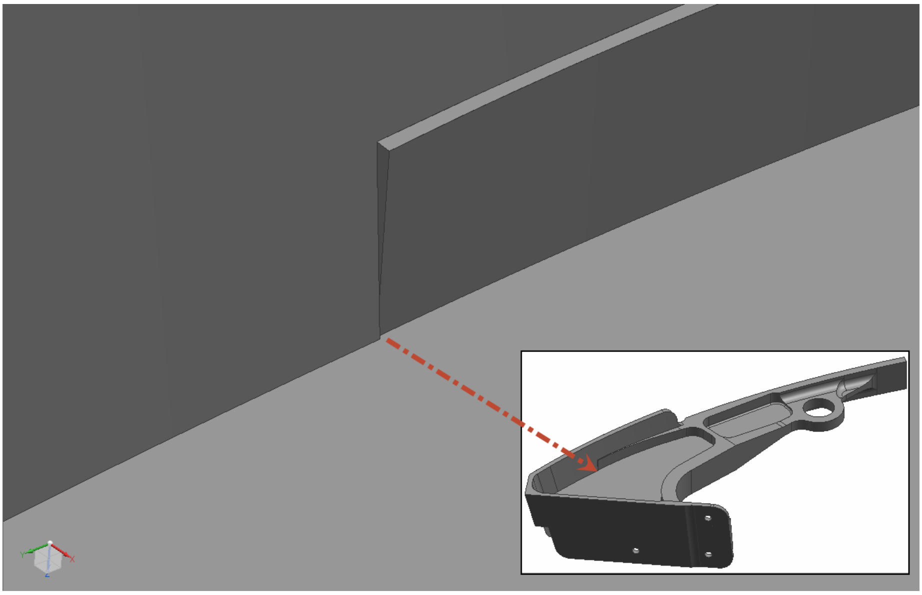


Figure 6.9: Design ID 1

As an example, the reason for the geometry update failure for design ID 1 is illustrated in fig 6.9. The model struggles to update the blend as the blend radius becomes to large, as the **Outer_Offset** is about to penetrate the flange.

When it comes to postprosessing the results, *Scatter Matrix* chart (Assessment → Statistic Charts → Scatter Matrix) is helpful for comparing data. It contains a single sheet showing three different representations [17].

1. Pairwise scatter plots for the variables (top right region)
2. The probability density functions (PDF) charts for each variable (diagonal)
3. Correlation values between the variables (bottom left region)

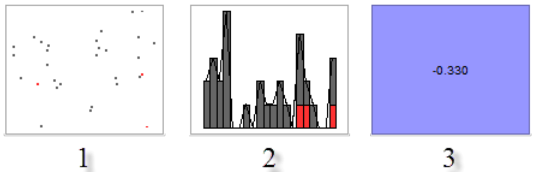


Figure 6.10: Explanation of charts in scatter matrix

The *Scatter Matrix* helps evaluating:

- Correlations[4] between the variable
- Discover outliers in the data
- Reveal clustering groups in the data

[4] Correlation refers to any of a broad class of statistical relationships involving dependence[24]

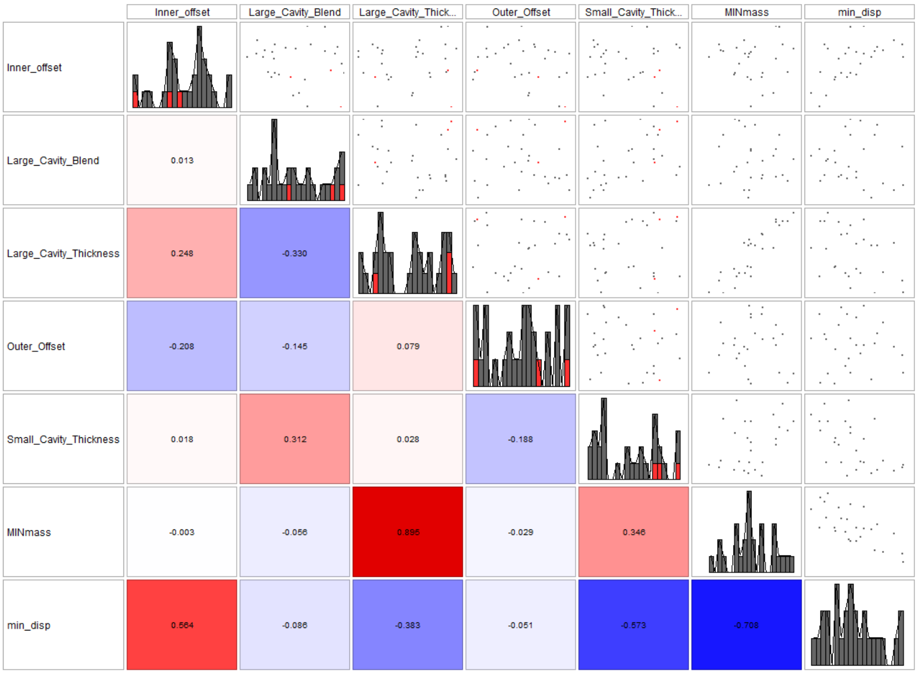


Figure 6.11: Scatter matrix (Random DOE)

30 iteration using “Random DOE” gave the following scatter matrix (Figure 6.11. The PDF shows an uneven distribution of the input variables. It is easier to determine this based on the PDFs, rather than looking at the scatter plots. This uneven distribution is also indicated by the correlation values. The stronger the color is, the more correlation it is between the variables. In this case, a relatively high corrolation factor accours for some of the input variables. This indicate more uneven distribution of the DOEs in this case.

The correlation values for the output variables shows that **Large_Cavity_Blend** and **Outer_Offset** have significant less correlation with the mass and displacement. This is in good agreement with the sensitivity analysis performed in NX. It also seems like **Inner_offset** has low correlation with mass as well.

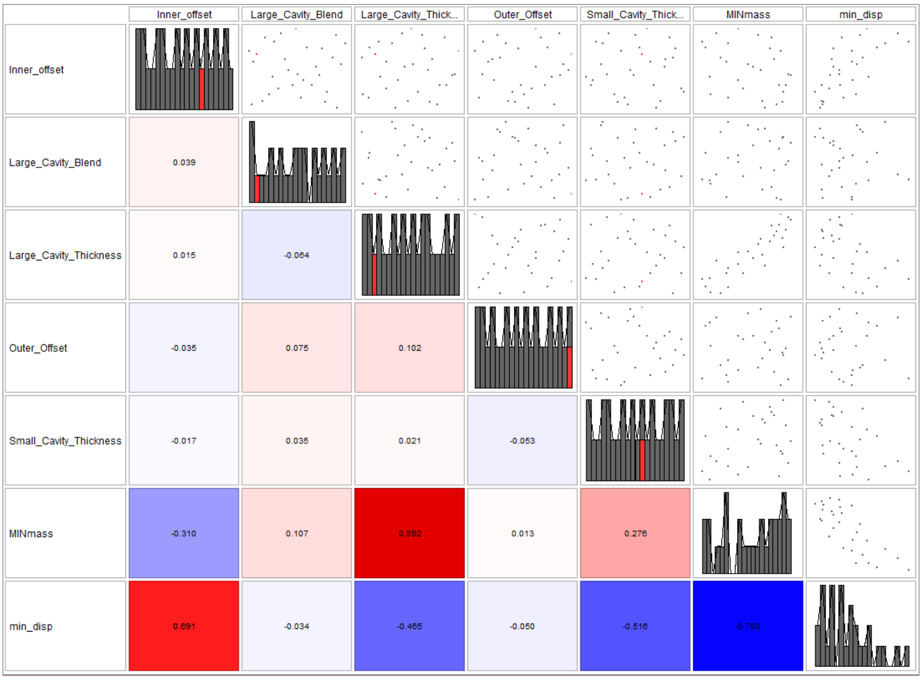


Figure 6.12: Scatter matrix (ULH)

The scatter matrix in Figure 6.12 shows a significant better distribution when ULH is used. Here, only 1 of 30 failed. This can also be clearly seen in the PDF for the input variables. Correlation between **Inner_Offset** and mass is also found.

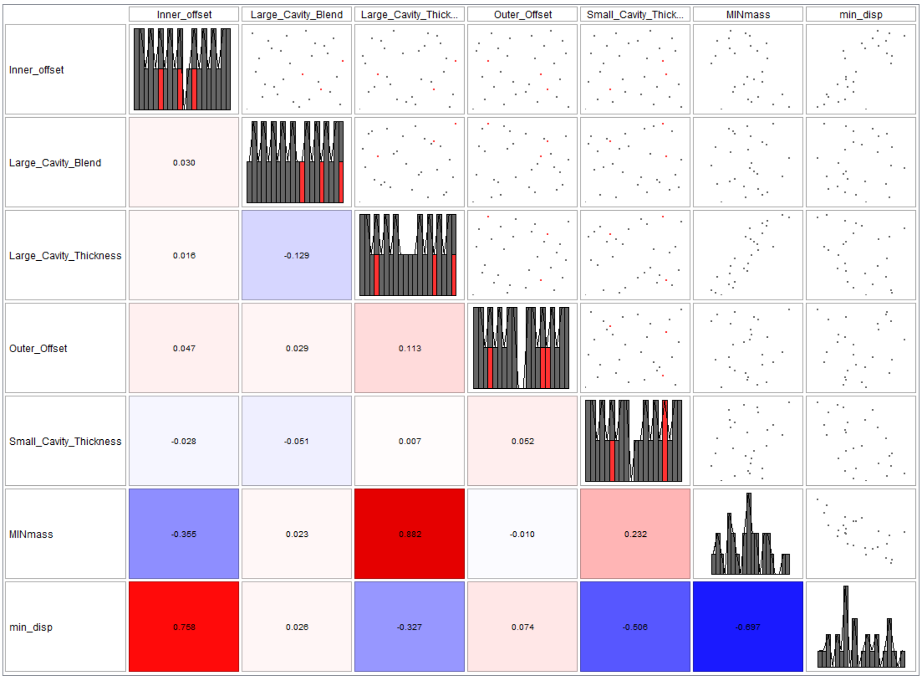


Figure 6.13: Scatter matrix (Sobol)

Sobol returns much of the similar results as ULH. Both of these DOEs are preferable in favor of the Random DOE.

Large_Cavity_Blend and **Outer_Offset** will have minor influence on the objectives. Rather then excluding these from the optimization, the amount of steps will be reduced in order to save computational time (Figure 6.14). The rest of the design variables will be remained as they are.

	Name	Variable Type	Lower Bound	Upper Bound	Base	Step
0	Inner_offset	Variable	-1.0	3.0	401	0.01
1	Outer_Offset	Variable	0.01	1.0	10	0.11
2	Small_Cavity_Thickness	Variable	-1.0	1.0	201	0.01
3	Large_Cavity_Thickness	Variable	-1.0	1.0	201	0.01
4	Large_Cavity_Blend	Variable	3.0	6.0	31	0.1

Figure 6.14: Base and steps

6.6 Comparison of Schedulers

A suitable optimization analysis normally takes some hours and even up to days. For that reason, a selection of the most preferred schedulers will be evaluated. The results will be compared with the single-objective optimization in NX. Only in the first section with MOGA-II, all steps will be shown. In the next sections, only the steps that differ from the MOGA-II, will be commented.

6.6.1 MOGA-II

Like stated in section 6.5, ULH with 30 designs is used.

By double-clicking the scheduler node, the Scheduler Properties appears. On the left hand side, all the different algorithms are listed. Here we are looking at the MOGA-II properties, where the users can adjust the algorithm parameters.

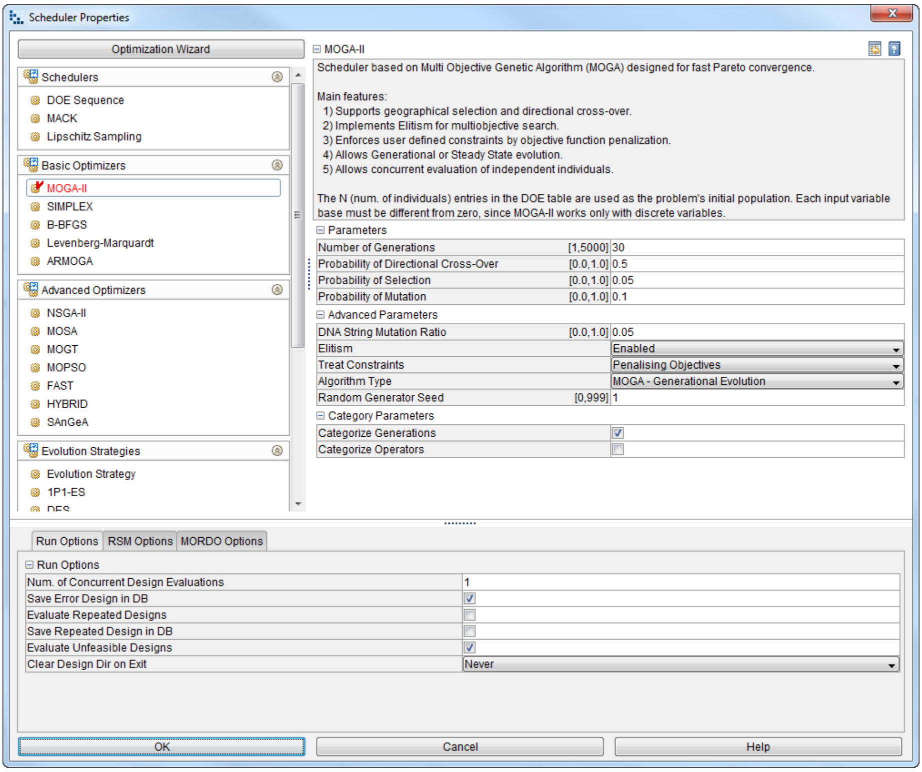


Figure 6.15: MOGA-II scheduler properties

Only *Number of Generations* was necessary to adjusted here. This specifies the maximum size of the run. For this run it will be set to 30 generations which gives a total of 900 iterations. (The other user specifications governs how the algorithms uses the different opterator as explained under 6.3 A briefly explanation of the other parameters is given in the modeFRONTIER help section [17].

The run can be started by clicking Project → Run/Stop. modeFRONTIER then executes the process by starting up NX and run the recorded macro. The first row with input variables in the DOE is used to update the model parameters. The mesh (finite element model) is then updated before proceeding to the simulation file. The first output variables (mass and displacement) appear on the first row in the design table. One iteration is completed, leaving one design.

modeFRONTIER automatically moves one with the next design. Each of the iterations took about 55 second. With 900 successful iterations, a complete run takes about 14 hours.

"Save Repated Design in DB" should be uncheck to avoid that designs, which is already presented will be evaluated twice. Designs like these appear as missing rows in the design table6.16.

83		MOGA2_...	-1.0000E0	5.4000E0	1.8000E-
84		MOGA2_...	-6.8000E-1	4.0000E0	-6.9000E-
85		MOGA2_...	1.9100E0	4.8000E0	-8.0000E-
86		MOGA2_...	-2.8000E-1	5.7000E0	-2.8000E-
87		MOGA2_...	-9.1000E-1	6.0000E0	-2.7000E-
88		MOGA2_...	2.1600E0	3.9000E0	-2.4000E-
89		MOGA2_...	4.0000E-2	5.7000E0	-3.4000E-
91		MOGA2_...	-2.9000E-1	3.4000E0	-8.8000E-
92		MOGA2_...	3.2000E-1	5.4000E0	-3.4000E-
93		MOGA2_...	-8.1000E-1	3.0000E0	-2.6000E-
94		MOGA2_...	7.3000E-1	3.6000E0	5.8000E-
96		MOGA2_...	8.4000E-1	3.9000E0	1.0000E-
97		MOGA2_...	1.5200E0	4.3000E0	4.4000E-
98		MOGA2_...	1.6200E0	3.2000E0	-5.0000E-

Figure 6.16: Removed designs which is already presented

The optimization run finishes after 11 hours and 44 minutes, returning 742 unique sucessful designs.

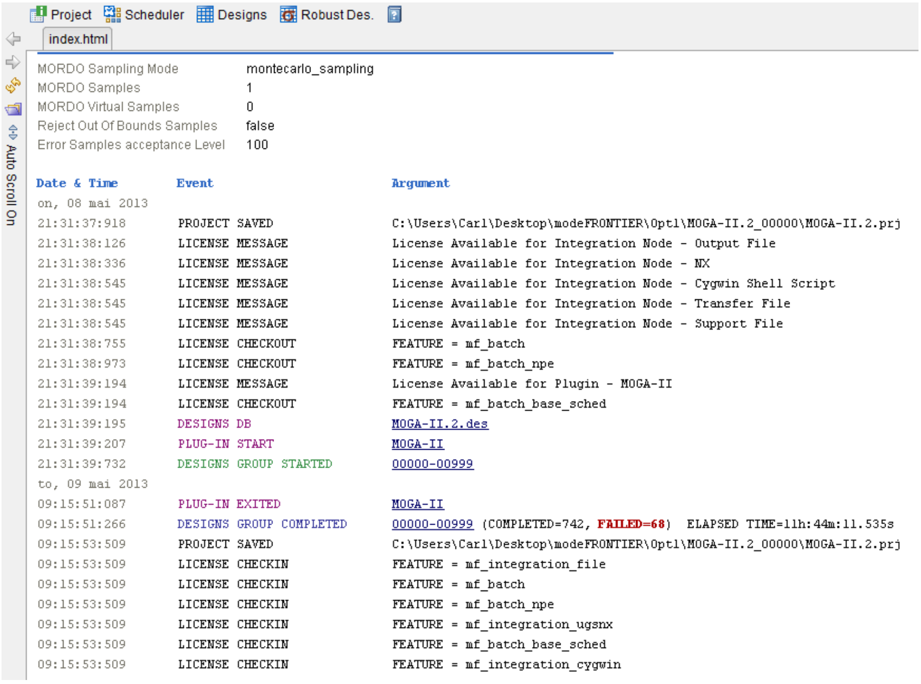


Figure 6.17: Run log

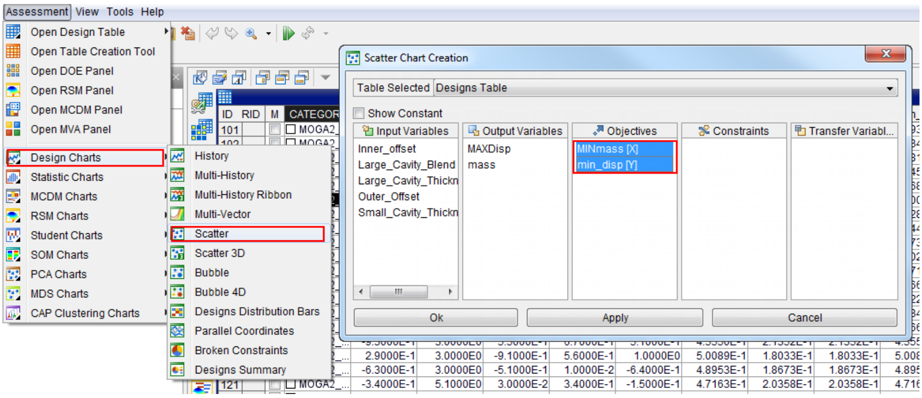


Figure 6.18: Scatter diagram

The scatter plot in 6.19 shows all the solutions, except the ones which failed due to unsolvable geometry. The scatter plot can either be extracted from the *scatter matrix*, or it can be plotted separately (see 6.18).

The green points indicates the Pareto front. By right-clicking in the design table, choose Mark Designs → Mark Pareto Designs → Only Real, the Pareto front becomes visible.

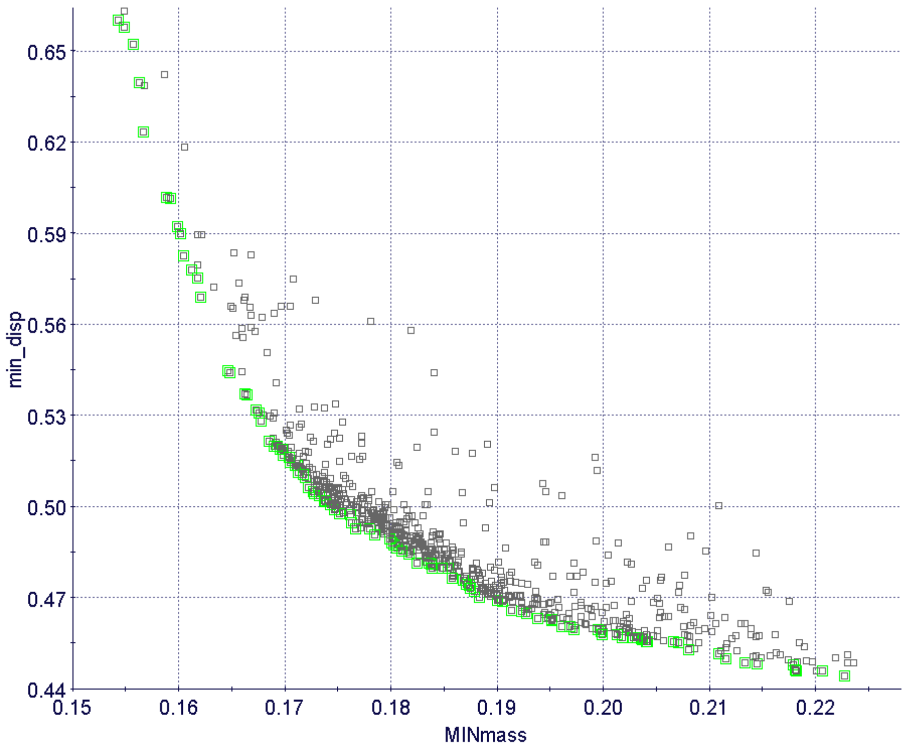


Figure 6.19: Scatter plot for MOGA-II

It is possible to sort out only the Pareto solutions. This can be done by opening "Designs Table", right-clicking in the table, choose Mark Designs → Mark Pareto Designs → Only real. The Pareto solution will then get marked. Right-click in the table once more. Select "Create Table". Name the table (6.20)

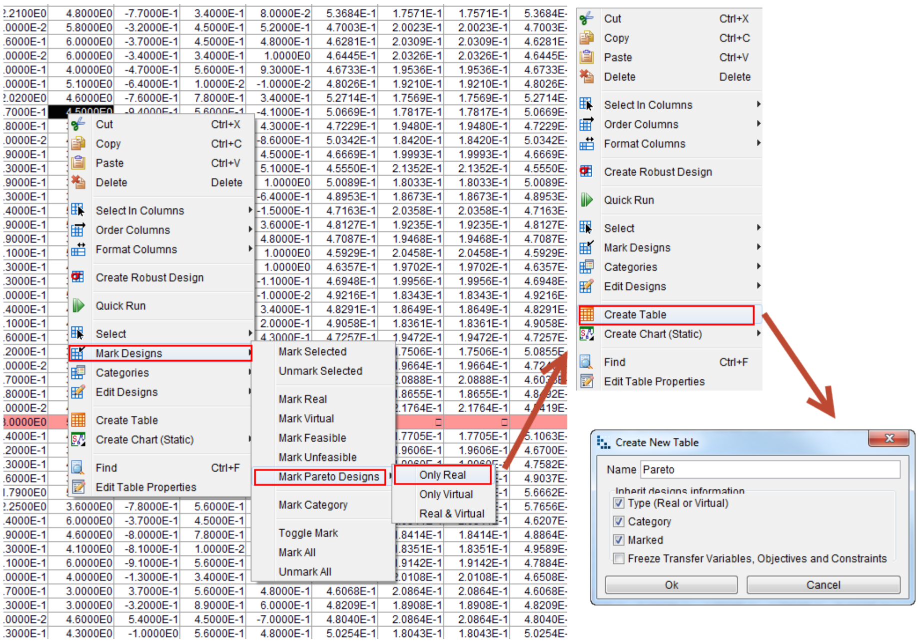


Figure 6.20: Mark Pareto designs

"Pareto(1)" now appears in the explorer window at the left side. These can then again be plotted in a new scatter plot

The designs that have a displacement well above 0.475 mm, were not of interest in this case. These were excluded from the pareto solutions simply by unchecking these from the "Pareto (1)" table.

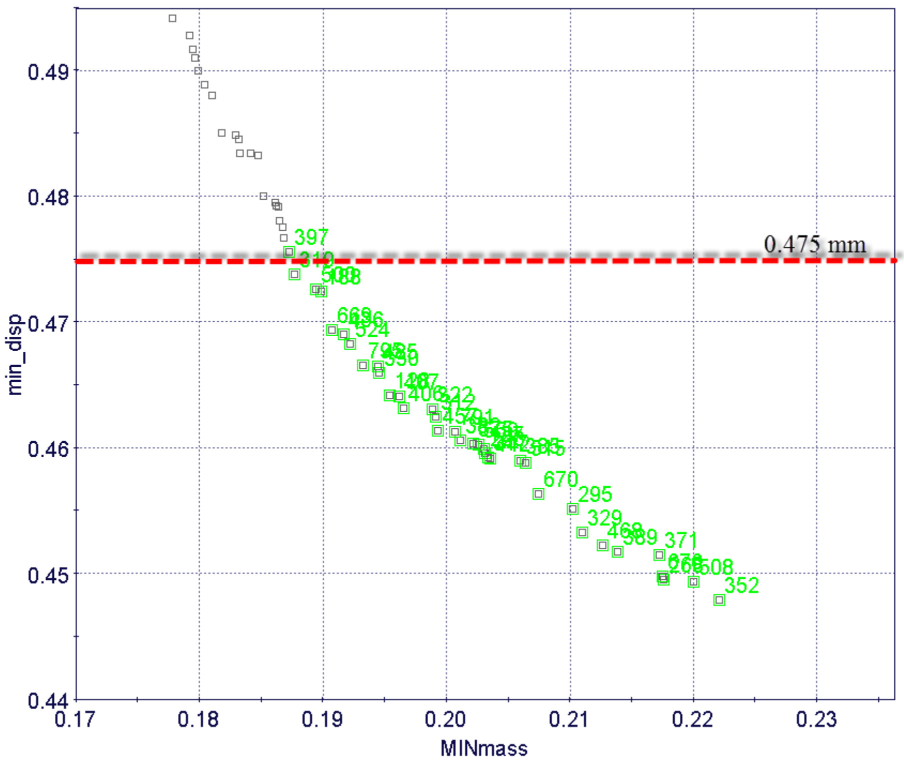


Figure 6.21: Feasible designs

There are several ways of choosing the best design. In a problem like this where you only have two objectives, it is simple to sort out the results manually from the DOE table by sorting the displacements. A detailed description of this is shown in Appendix F

The following designs that lay close the constraint limit were chosen.

Table 6.2: Results MOGA-II

	Design (319)	**Design (397)**	**Design (861)**
Inner_Offset	-0.980	-1.000	-1.000
Large_Cavity_Blend	3.400	4.200	3.000
Large_Cavity_Thickness	-0.710	-0.770	-0.740
Outer_Offset	0.890	-0,890	0.560
Small_Cavity_Thickness	1.000	0.770	0.830
Mass [g]	189.2	188.8	188.4
Displacement [mm]	0.473	0.475	0.476
Mass reduction	6.06 %	6.26 %	6.45 %

When dealing with problems that are more complex, it can often be difficult to rank and select between the solutions. Multi Criteria Decision Making (MCDM) assists you in selecting the best design based on a relative value. MCDM is also applicable for problems like this.

6.6.2 MOGT

Only one DOE is required to perform a run with MOGT. Therefore the DOE was defined manually with a value lying in the middle of the design range (fig. 6.22)

	M	CATEGORY	Inner_offset	Large_Cavity_Blend	Large_Cavity_Thickness	Outer_Offset	Small_Cavity_Thickness
0		RNDDOE	1.0000E0	4.5000E0	9.0000E-3	5.0000E-1	9.0000E-3

Figure 6.22: DOE for MOGT

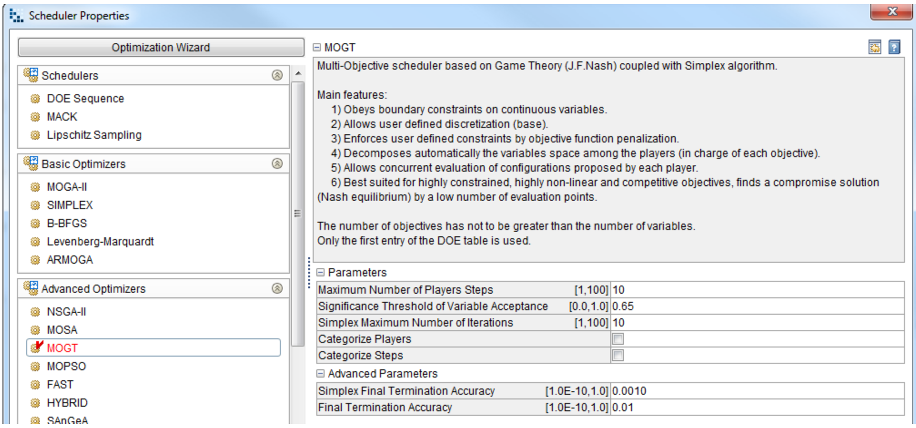


Figure 6.23: MOGT - Scheduler properties

The scheduler settings are depicted in Figure 6.23.

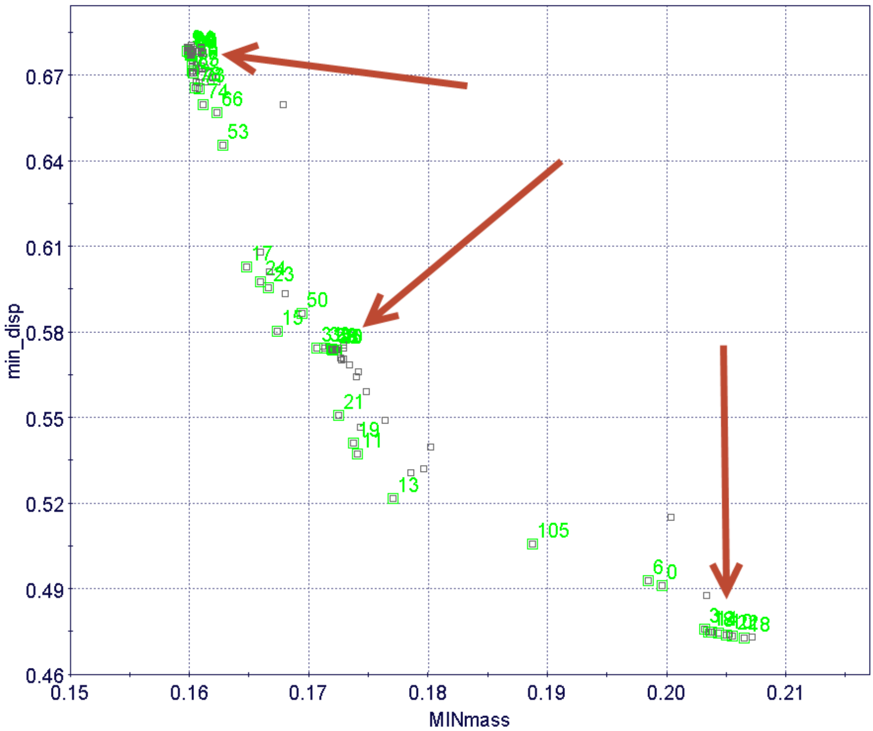


Figure 6.24: Scatter plotfor MOGT

With the default settings, MOGT finished after 102, with only one error design. A typical clustering effect occurred at three separate places (fig. 6.24). It was not enough solutions to decipher a coherent Pareto front here .

Table 6.3: Results MOGT

	Design (12)	**Design (3)**	**Design (7)**
Inner_Offset	1.000	1.000	0.927
Large_Cavity_Blend	4.500	4.500	5.910
Large_Cavity_Thickness	0.009	0.009	-0.059
Outer_Offset	0.916	0.867	0.500
Small_Cavity_Thickness	1.000	0.901	0.009
Mass [g]	200.0	199.7	0.199
Displacement [mm]	0.473	0.474	0.485
Mass reduction	0.70 %	0.84 %	1.19 %

Three of the most promising results are presented in the Table 6.3. The optimization left no proper improvements. However, it needs to be kept in mind that this run only performed a fraction of all the iterations that MOGA-II did.

6.6.3 MOSA

30 DOE deisgns and 100 schedular iterations gave a total of 2932 unique designs. Designs which have displacement below 0.476 mm were sorted out in a seperate table.

ID	MAXDisp	mass	Rank Value
849	4.7508E-1	1.9005E-1	1.000
2949	4.7584E-1	1.9033E-1	0.365
879	4.7589E-1	1.9070E-1	0.309
819	4.7490E-1	1.9079E-1	0.301
1680	4.7399E-1	1.9113E-1	0.274
81	4.7469E-1	1.9114E-1	0.273
2218	4.7385E-1	1.9122E-1	0.267
2116	4.7527E-1	1.9127E-1	0.264
2026	4.7414E-1	1.9138E-1	0.258
2649	4.7596E-1	1.9140E-1	0.257
1696	4.7583E-1	1.9152E-1	0.250
2709	4.7556E-1	1.9155E-1	0.249
2759	4.7536E-1	1.9157E-1	0.248
2985	4.7454E-1	1.9173E-1	0.241
2604	4.7561E-1	1.9184E-1	0.236

Figure 6.25: Ranking of the designs

The Linear MCDM algorithem gave a ranking of the designs as shown in Figure 6.25.

Table 6.4: Results MOSA

	Design (1710)	**Design (849|)**	**Design (1830)**
Inner_Offset	-0.780	-0.990	-0.810
Large_Cavity_Blend	3.500	3.200	3.200
Large_Cavity_Thickness	-0.360	-0.590	-0.530
Outer_Offset	0.890	-0.339	0.229
Small_Cavity_Thickness	0.200	0.260	0.190
Mass [g]	191.9	190.0	189.8
Displacement [mm]	0.473	0.475	0.476
Mass reduction	4.72 %	5.66 %	5.76 %

As we can see, design ID 849 got a remarkable better rank value than the second most promising design. A selection of the best desings which are comparable with the designs from the previous optimizations is given in table 6.4.

MOGA-II used 300-400 designs to find solutions which were much better then those MOSA found after more than 1700 designs.

6.6.4 Hybrid

Two attempts to run Hybrid resulted in failure in both cases. After some hours, the program automatically shuts down. No failure log was reported.

6.7 Additional Reduction of Design Space

In section 6.5 , we confirmed how small impact **Outer_Offset** and **Large_Cavity_Blend** had on the objectives, compared to the other design variables. It could therefore be interesting to see what would happen if these were excluded.

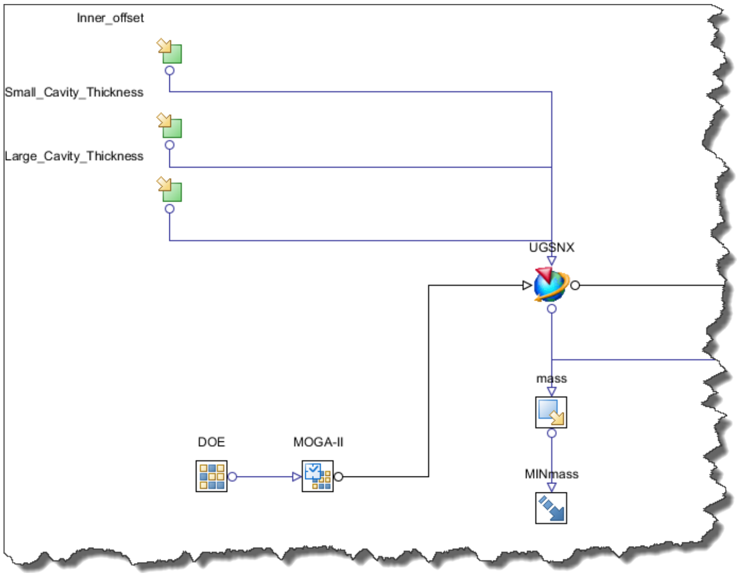


Figure 6.26: MOGA-II workflow (reduced run)

The scheduler properties were kept the same as in the first MOGA-II run.

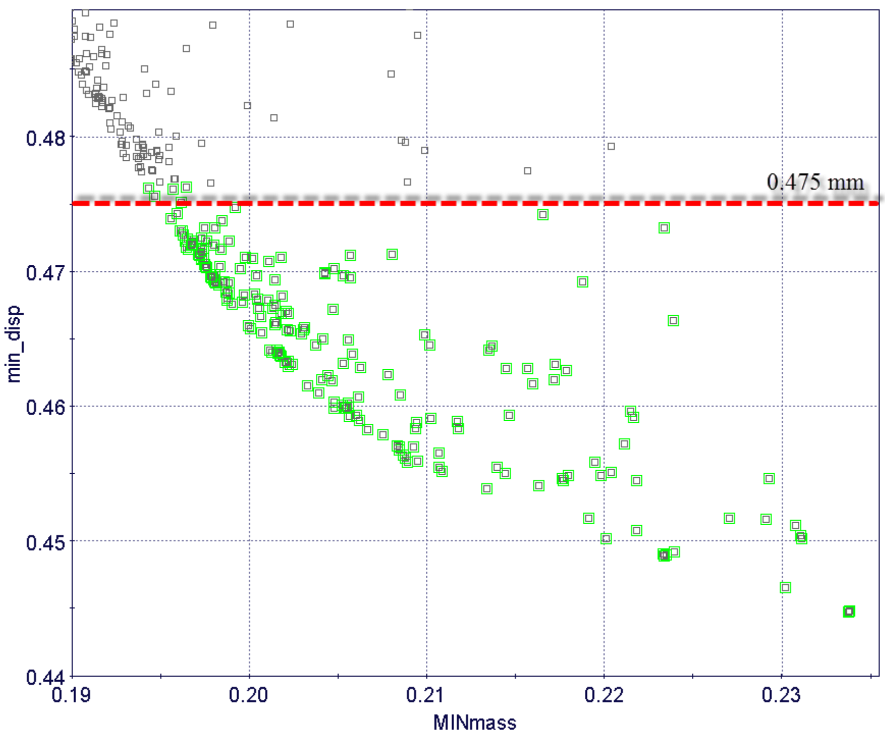


Figure 6.27: MOGA-II (reduced run)

Fig. 6.27 shows a zoomed plot av the results achieved form this analysis. The deisgns with less displacement than 0.476 mm is marked green. A total of 773 designs completed successfully, 35 failed.

Table 6.5: Results MOGA-II (reduced)

	Design (770)	**Design (412|)**	**Design (294)**
Inner_Offset	-0,890	-1.000	-0.980
Large_Cavity_Thickness	-0.680	-0.690	-0.720
Small_Cavity_Thickness	0.520	-0.330	0.300
Mass [g]	192.4	191.7	190.8
Displacement [mm]	0.473	0.475	0.476
Mass reduction	4.47 %	4.82 %	5.26 %

Table 6.5 shows the results from the reduced analysis. They are not as satifying as the inital MOGA-II optimization. Still, several designs tends to fail. Both analysis was set to perform as many design. Therefore, both simulations took approximately the same time.

6.8 Summary

Four different schedulers were tested, showing a remarkable difference in goal achievement for the three of them which succeeded to accomplish. MOGT must said to be the worst one. The analysis had poor distribution of the solutions.

MOSA was the most time consuming analysis. The scheduler struggles to find good solutions, but the distribution seems to be good.

There is a remarkable difference between the sheduler algorithms. The analyses shows that the last designs not neccessarily are the more preferable ones. How many iterations which is needed in order to achieve a good solution is difficult to predict

Relatively many designs tends to fail during optimization. It could be reasonable to either exclude the blends as input variable from the optimization analysis or remove them entirely from the model. By doing the former, flexibility is reduced and the blend could still be an issue for some designs. Removing them completly will have a major impact on the baseline result.

When the program discovers an unfeasable design, it will not try to extract the displacement, which is the aspact of the analysis which is most time consuming.

Table 6.6 shows the results for each scheduler with displacement equal to 0.475 mm.

Table 6.6: Results for each scheduler

Algorithm	total designs	successful designs	Time	Improvement
HyperOpt (NX)	11	11	30m	5.66 %
MOGA-II	810	742	11h 44m	6.26 %
MOSA	2932	2723	57h 49m	5.75 %
MOGT	102	101	1h 17m	0.94 %
MOGA-II (reduced)	773	738	15h 48m	4.82 %

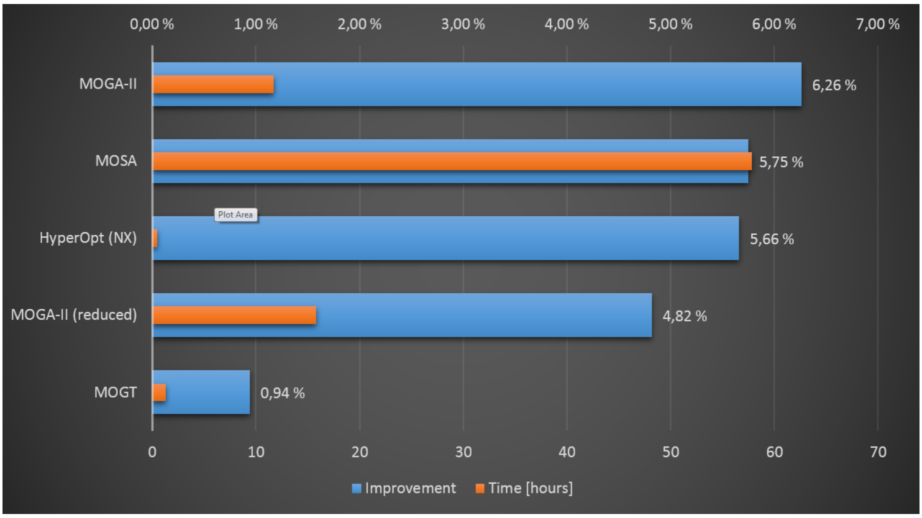


Figure 6.28: Mass reduction and time consumption

6.9 Discussion

The time consumption is an important aspect. Since modeFRONTIER have no built-in support for NX Nastran simulations. The NX GUI was therefor executed successively, running the analyses by use of a macro. This contributes to a large computational cost, spent on running the GUI, instead of performing the actual calculations. One single run used an average of 55 seconds per design. By running the analysis silent (no windows pops up), it is reason to believe that the computational time could be decreased significantly.

The multiobjective optimizations have revealed several unfeasible designs, which the sensitivity analysis was not able to detect. This is caused of certain design values which are not compatible. It is hard to tell how much impact this have on the final results.

modeFRONTIER is a complex software. This is necessary when performing complex optimizations with several objects (more than two). In terms of this load case, using modeFRONTIER is like using a sledgehammer to crack an egg.

Chapter 7

Conclusion

This thesis has gained results in terms of documenting the process and benchmarking how single- and multiobjective design optimization can be applied and implemented to improve products. Guide lines for performing an ideal strategy for model parameterization are presented and evaluated by practical use.

It has not been possible to meet the objective, reducing the mass by 10 % without exceeding the displacement requirement. Though, the mass reduction must be considered substantial, since it was reduced by more than 6 %. Geometry optimization must therefore be said to be suitable for problems where the topology should be kept as it is.

Single-objective geometry optimization in NX (HyperOpt) proves to be satisfactory, both in terms of computational time and mass improvement. On the other hand, if the optimization problem has to be expressed by more than one objective, this will be unsuitable.

Multiobjective optimization with modeFRONTIER has proven to be a complicated process, involving more work. The program does not provide one solution which is best, but a whole set of best solutions (*Pareto optimal solutions*). Here it is up to the user to deside what design to choose. Among the schedulers which have been tried out, MOGA-II has proven to be the best one. MOGA-II gives a good distribution (in contrast to MOGT) of the output values and succeeds in finding better solutions than MOSA scheduler. This is not necessarily the case for any general geometry optimization problem. This has been proven in accordance with the No Free Lunch theorem.

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Appendix A

Sensitivity Analysis Results

Sensitivity History

Design Objective Results
Weight (Minimum) [N]

Design Variable Results

	Step #1	Step #2	Step #3	Step #4	Step #5	Step #6	Step #7	Step #8	Step #9	Step #10	Step #11	Step #12	Step #13	Step #14	Step #15
Large_Cavity_Thickness	-1,3	-1,114286	-0,928571	-0,742857	-0,557143	-0,371429	-0,185714	0	0,1857143	0,3714286	0,5571429	0,7428571	0,9285714	1,1142857	1,3
Objective Result	1,7026756	1,7417162	1,779107	1,817908	1,8561401	1,8950722	1,9341622	1,9731527	2,0129123	2,0519756	2,0910725	2,130433	2,1693475	2,2087564	2,2478438
Result Measure															
Upper Limit = 0.600 [mm]	0,56422	0,52031	0,50142	0,49072	0,4844	0,4796	0,47561	0,47233	0,4697	0,46737	0,46545	0,46379	0,46233	0,46075	0,45943
Result Measure															
Upper Limit = 200.000000 [N/mm^2(MPa)]	186,45	184,98	184,99	184,92	185,28	184,97	184,96	184,94	185,12	185,1	185,3	184,93	185,17	184,99	185,32

	Step #1	Step #2	Step #3	Step #4	Step #5	Step #6	Step #7	Step #8	Step #9	Step #10	Step #11	Step #12	Step #13	Step #14	Step #15
Small_Cavity_Thickness	-1,3	-1,114286	-0,928571	-0,742857	-0,557143	-0,371429	-0,185714	0	0,1857143	0,3714286	0,5571429	0,7428571	0,9285714	1,1142857	1,3
Objective Result	1,907812	1,9167748	1,9264892	1,9363494	1,9459347	1,9553614	1,9649921	1,9750389	1,9834792	1,9929112	2,0023942	2,0117527	2,0212596	2,0310727	2,0347918
Result Measure															
Upper Limit = 0.600 [mm]	0,50453	0,4979	0,49234	0,48736	0,48309	0,47941	0,47609	0,47239	0,46977	0,46709	0,46441	0,46229	0,46016	0,4577	0,45664
Result Measure															
Upper Limit = 200.000000 [N/mm^2(MPa)]	190,37	188,52	187,68	186,93	186,41	185,89	185,41	185	184,68	184,4	184,1	183,91	186,35	183,44	183,23

	Step #1	Step #2	Step #3	Step #4	Step #5	Step #6	Step #7	Step #8	Step #9	Step #10	Step #11	Step #12	Step #13	Step #14	Step #15
Outer_Offset	0,01	0,1521429	0,2942857	0,4364286	0,5785714	0,7207143	0,8628571	1,005	1,1471429	1,2892857	1,4314286	1,5735714	1,7157143	1,8578571	2
Objective Result	1,975572	1,9696584	1,9636059	1,9576959	1,9516237	1,9455099	1,9394106	1,9334311	1,8752066	1,9213093	1,9151571	1,9091166	1,9032892	1,8970574	1,8910253
Result Measure															
Upper Limit = 0.600 [mm]	0,47218	0,47246	0,47264	0,47299	0,47341	0,47385	0,47428	0,47462	0,48036	0,47585	0,47671	0,47745	0,47816	0,47913	0,48009
Result Measure															
Upper Limit = 200.000000 [N/mm^2(MPa)]	185,27	184,95	184,99	185,01	185,03	185,51	185,01	185	185,06	185,09	185,54	186,71	185,13	185,22	185,17

	Step #1	Step #2	Step #3	Step #4	Step #5	Step #6	Step #7	Step #8	Step #9	Step #10	Step #11	Step #12	Step #13	Step #14	Step #15
Small_Cavity_Blend	2	2,0714286	2,1428571	2,2142857	2,2857143	2,3571429	2,4285714	2,5	2,5714286	2,6428571	2,7142857	2,7857143	2,8571429	2,9285714	3
Objective Result	1,9735849	1,9736948	1,9742662	1,9742648	1,9741837	1,9739953	1,9744451	1,9754856	1,9746896	1,9739008	1,9738511	1,9738838	1,9741048	1,9743931	1,9744086
Result Measure															
Upper Limit = 0.60000 [mm]	0,47269	0,47248	0,47252	0,47263	0,47285	0,47286	0,47267	0,47229	0,4726	0,4727	0,4728	0,47269	0,47265	0,47273	0,47262
Result Measure															
Upper Limit = 200.000000 [N/mm^2(MPa)]	184,99	185,01	185,02	184,98	185,04	185,02	185,01	185,02	185,02	185,02	184,99	185,06	185,07	185,09	185,16

	Step #1	Step #2	Step #3	Step #4	Step #5	Step #6	Step #7	Step #8	Step #9	Step #10	Step #11	Step #12	Step #13	Step #14	Step #15
Large_Cavity_Blend	2	2,2857143	2,5714286	2,8571429	3,1428571	3,4285714	3,7142857	4	4,2857143	4,5714286	4,8571429	5,1428571	5,4285714	5,7142857	6
Objective Result	1,9523856	1,9575065	1,9565868	1,9513264	1,9557929	1,9623644	1,9684886	1,9754791	1,9830251	1,991008	1,9993252	2,0083539	2,0179345	2,0277864	2,0383066
Result Measure Upper Limit = 0.600000 [mm]	0,47413	0,47368	0,4734	0,47439	0,47384	0,47342	0,47281	0,472	0,47149	0,47121	0,47064	0,47006	0,46952	0,46893	0,46824
Result Measure Upper Limit = 200.000000 [N/mm^2(MPa)]	184,98	184,98	184,98	185,07	186,32	184,98	184,93	184,97	184,93	185,04	185,24	184,96	185,07	185,36	185,02

	Step #1	Step #2	Step #3	Step #4	Step #5	Step #6	Step #7	Step #8	Step #9	Step #10	Step #11	Step #12	Step #13	Step #14	Step #15
Inner_Offset	-2	-1,642857	-1,285714	-0,928571	-0,571429	-0,214286	0,1428571	0,5	0,8571429	1,2142857	1,5714286	1,9285714	2,2857143	2,6428571	3
Objective Result	2,0539215	2,0396091	2,0257048	2,0115561	1,9977526	1,9841858	1,9701187	1,9565364	1,9425986	1,9283253	1,914775	1,900786	1,8867293	1,8730763	1,8592476
Result Measure Upper Limit = 0.600000 [mm]	0,45128	0,45442	0,45787	0,46134	0,46532	0,46926	0,47384	0,47905	0,48439	0,48996	0,49691	0,50411	0,51184	0,52139	0,53115
Result Measure Upper Limit = 200.000000 [N/mm^2(MPa)]	184,33	184,47	184,83	184,75	188,42	184,96	184,79	186,51	187,11	184,94	186,78	185,21	185,05	185,16	185,1

	Step #1	Step #2	Step #3	Step #4	Step #5	Step #6	Step #7	Step #8	Step #9	Step #10	Step #11	Step #12	Step #13	Step #14	Step #15
Corner_Blend8	3	3,4285714	3,8571429	4,2857143	4,7142857	5,1428571	5,5714286	6	6,4285714	6,8571429	7,2857143	7,7142857	8,1428571	8,5714286	9
Objective Result	1,9705232	1,9703597	1,9708631	1,9714196	1,9715196	1,9715516	1,9720758	1,9727123	1,973198	1,9737971	1,9742345	1,9749044	1,975889	1,9761477	1,977006
Result Measure Upper Limit = 0.600000 [mm]	0,47253	0,47266	0,4725	0,47246	0,47247	0,47224	0,47245	0,47243	0,47224	0,47242	0,47237	0,4723	0,47232	0,47212	0,47226
Result Measure Upper Limit = 200.000000 [N/mm^2(MPa)]	185,04	184,99	184,94	185,02	185,02	184,98	184,95	185	185,03	184,99	184,95	185,05	185,45	185,03	185,37

	Step #1	Step #2	Step #3	Step #4	Step #5	Step #6	Step #7	Step #8	Step #9	Step #10	Step #11	Step #12	Step #13	Step #14	Step #15
Corner_Blend6	3	3,2428571	3,4857143	3,7285714	3,9714286	4,2142857	4,4571429	4,7	4,9428571	5,1857143	5,4285714	5,6714286	5,9142857	6,1571429	6,4
Objective Result	1,9677827	1,9680511	1,9681772	1,9691382	1,9692921	1,9699334	1,9705721	1,9710976	1,971261	1,972063	1,9724587	1,9736308	1,9750777	1,9753102	1,9758467
Result Measure Upper Limit = 0.600000 [mm]	0,47409	0,4741	0,47406	0,47373	0,47394	0,47344	0,47334	0,4733	0,47328	0,47309	0,47258	0,47259	0,47229	0,47241	0,47226
Result Measure Upper Limit = 200.000000 [N/mm^2(MPa)]	185,12	191,57	185,24	185,21	192,95	185,17	193,47	193,55	185,1	193,33	184,87	184,79	185,04	184,93	185,36

Appendix B

Optimization in NX (run 1)

Optimization History

Based on Altair HyperOpt

Design Objective Function Results

Minimum Weight [N]	0	1	2	3	4	5	6	7	8
	1,9756	1,9948	1,9444	1,9546	1,9919	2,0597	1,9306	1,9090	1,9095
Mass	201,3816	203,3425	198,2010	199,2485	203,0440	209,9603	196,7953	194,5984	194,6518
Difference	0,0000	-1,9609	3,1806	2,1331	-1,6625	-8,5788	4,5863	6,7831	6,7298
Improvement %		-0,97 %	1,58 %	1,06 %	-0,83 %	-4,26 %	2,28 %	3,37 %	3,34 %

Design Variable Results

Name	0	1	2	3	4	5	6	7	8
Small_Cavity_Thickness=0.010000	0,010	0,410	0,010	0,010	0,010	0,010	-0,095	0,000	0,000
Inner_Offset=0.010000	0,010	0,010	0,810	0,010	0,010	0,010	-0,076	-0,166	-0,261
Outer_Offset=0.010000	0,010	0,010	0,010	0,510	0,010	0,010	0,100	0,195	0,295
Large_Cavity_Blend=4	4,000	4,000	4,000	4,000	4,600	4,000	3,240	3,000	3,000
Large_Cavity_Thickness=0.010000	0,010	0,010	0,010	0,010	0,010	0,410	-0,090	-0,195	-0,191

Design Constraint Results

	0	1	2	3	4	5	6	7	8
Result Measure									
Upper Limit = 0.475000 [mm]	0,47305	0,46638	0,48338	0,47312	0,47112	0,46693	0,47624	0,47549	0,47432
Limit	0,475	0,475	0,475	0,475	0,475	0,475	0,475	0,475	0,475
Violation %	-0,19 %	-0,86 %	0,84 %	-0,19 %	-0,39 %	-0,81 %	0,12 %	0,05 %	-0,07 %

Appendix C

Optimization in NX (run 2)

Optimization History

Based on Altair HyperOpt

Design Objective Function Results

Minimum Weight [N]	0	1	2	3	4	5	6	7	8	9
	1.975534	1.994719	1.944793	1.954334	1.992075	2.059812	1.942221	1.910363	1.887356	1.866109
Mass	201.3796	203.3352	198.246	199.2186	203.0658	209.9707	197.9838	194.7362	192.391	190.2252
Difference	0	-1.95563	3.13359	2.161017	-1.6862	-8.59109	3.395821	6.643351	8.988596	11.15443
Improvement %		-0.97%	1.56%	1.07%	-0.84%	-4.27%	1.69%	3.30%	4.46%	5.54%
		-0.97%	2.50%	-0.49%	-1.93%	-3.40%	5.71%	1.64%	1.20%	1.13%

Design Variable Results

Name	0	1	2	3	4	5	6	7	8	9
Small_Cavity_Thickness=0.010000	0.010	0.410	0.010	0.010	0.010	0.010	0.115	0.005	0.095	0.190
Inner_Offset=0.010000	0.010	0.010	0.810	0.010	0.010	0.010	-0.100	-0.190	-0.213	-0.113
Outer_Offset=0.010000	0.010	0.010	0.010	0.510	0.010	0.010	0.100	0.195	0.295	0.363
Large_Cavity_Blend=4	4.000	4.000	4.000	4.000	4.600	4.000	3.240	3.000	3.000	3.000
Large_Cavity_Thickness=0.010000	0.010	0.010	0.010	0.010	0.010	0.410	-0.090	-0.195	-0.305	-0.395

Design Constraint Results

	0	1	2	3	4	5	6	7	8	9
Result Measure										
Upper Limit = 0.475000 [mm]	0.47332	0.46645	0.48333	0.47305	0.47093	0.46698	0.47257	0.47518	0.47635	0.47879
Limit	0.475	0.475	0.475	0.475	0.475	0.475	0.475	0.475	0.475	0.475
Violation %	-0.17%	-0.86%	0.83%	-0.19%	-0.41%	-0.80%	-0.24%	0.02%	0.14%	0.38%

10	11
1.859824	1.863677
189.5845	189.9773
11.79514	11.40234
5.86%	5.66%
0.34%	-0.21%

10	11
0.290	0.395
-0.218	-0.328
0.253	0.343
3.000	3.000
-0.490	-0.503

10	11
0.47817	0.47585
0.475	0.475
0.32%	0.09%

Appendix D

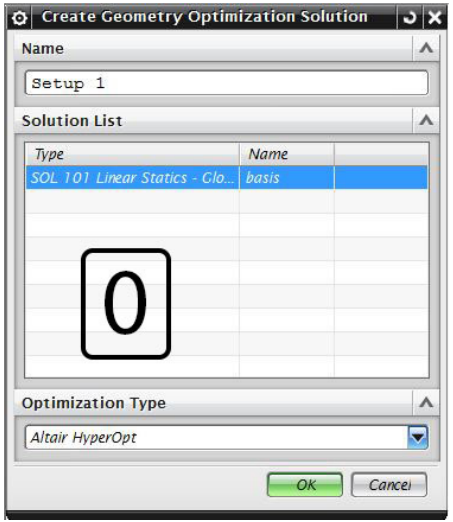
A3 Sheet: Geometry Optimization in NX

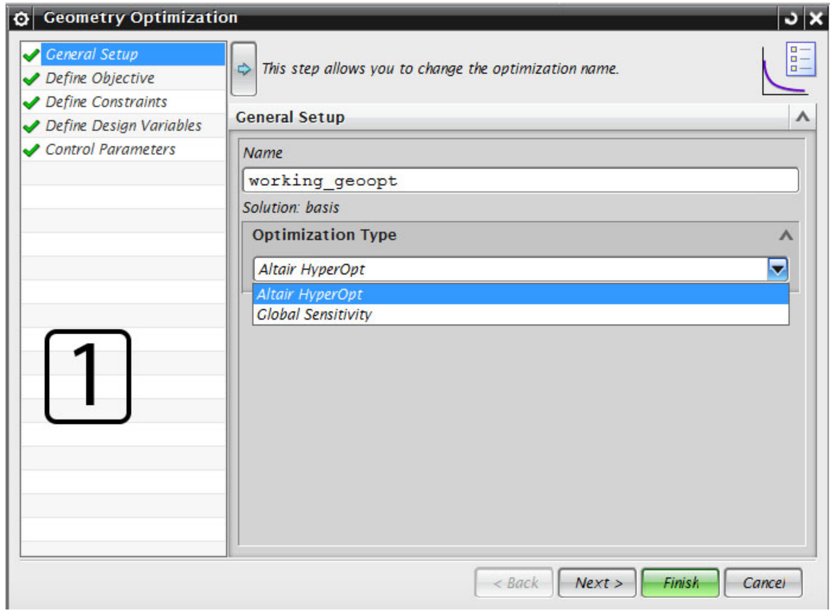
Geometry Optimization

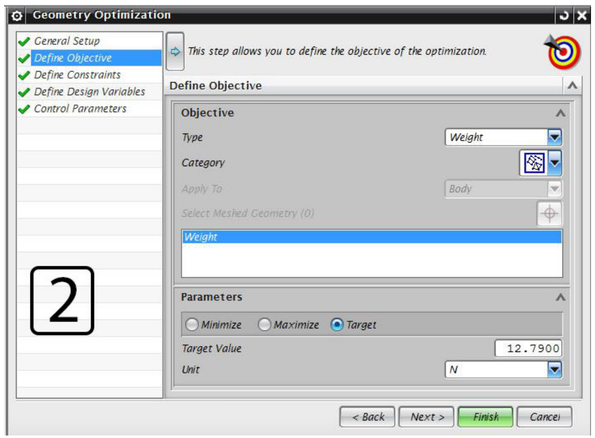
Topic: NX8.5 Optimization Brief | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: March 2013

To perform a geometry optimization in NX it is nescessary to do a initial standard linear simulation with the correct load cases. This is because the geometry analysis uses this as a base line. This is shown in step 0.

1. First off you get to choose what type of optimization you want - choose Altair Hyperopt
2. In this next step it is possible to define your objective. Based on experience it is best to define a target rather than just minimize.







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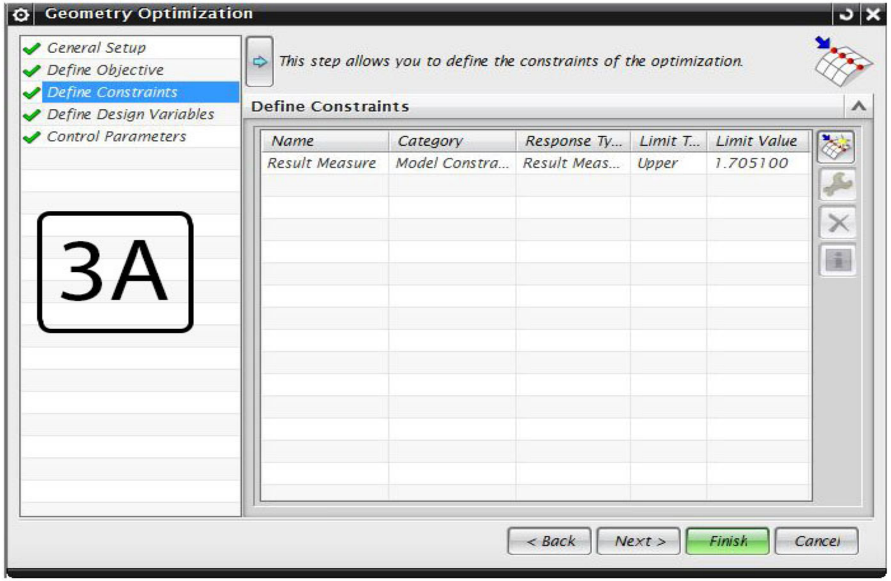
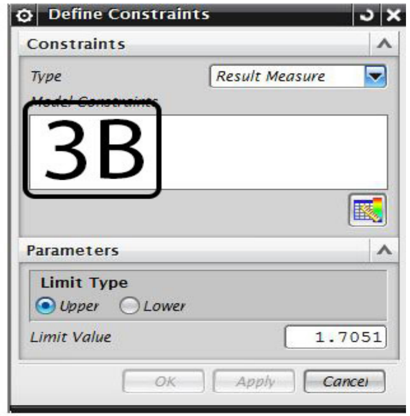
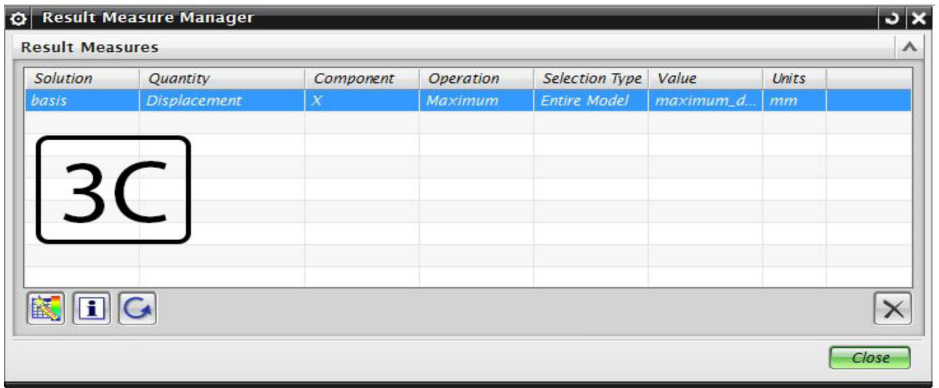
Geometry Optimization

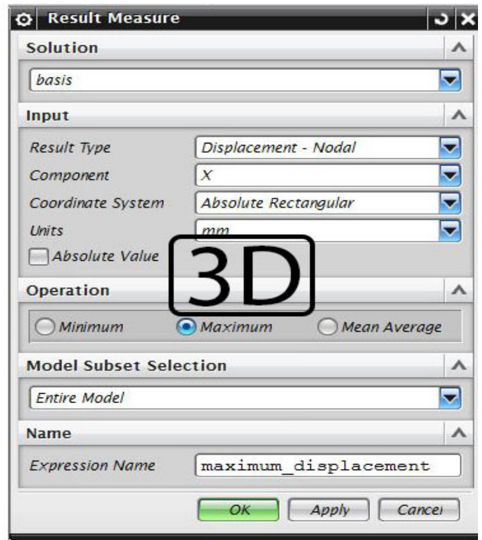
Topic: NX8.5 Optimization Brief | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: March 2013

3. This step is where you link your requirement to the base line that were run before the optimization creation. It is also possible to define which coordinate system the solution should use. In the menu shown in picture 3B it is possible to define some leeway in the constraint for the solution.





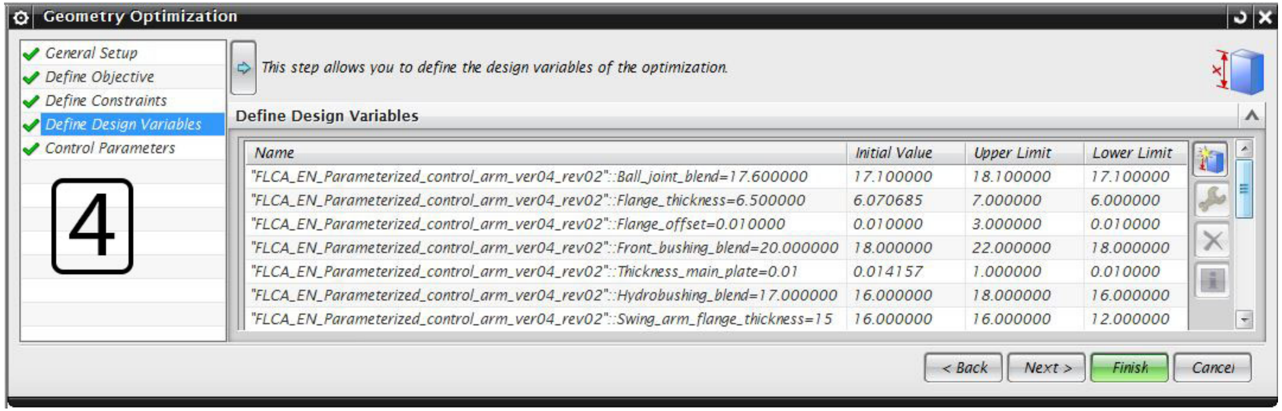


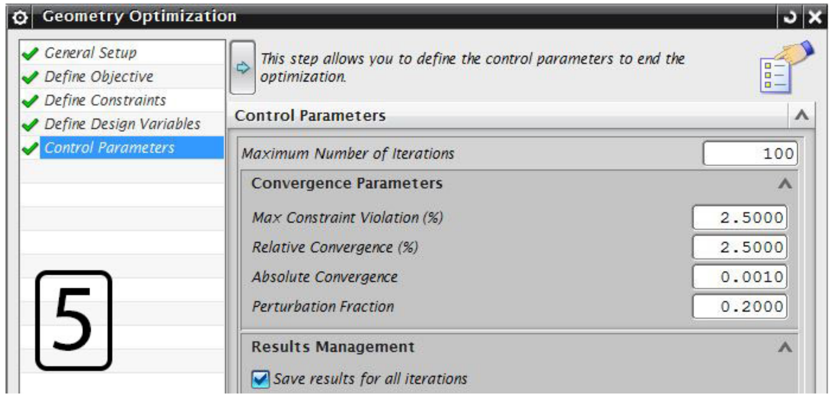


4. Here is the tab that lets you define which variables to define as your design space. The easiest thing is to use expressions that is associated with the model.

5. This is the last step containing some more options. None of these seem to have an enormous impact on the solution, but might help you to some extent. Number of iterations can be kept high since it seldom seem to exceed 30 iterations. Max constraint violations tells NX how much more deviation from target it can tolerate. Relative and absolute convergence decides when NX is satisfied with the results and terminates the iterations. Perturbation fraction is how big percentage of the predefined design space(proportion between upper and lower limit of the design variables) it is allowed to alter between each iteration.

Right click on the geometry solution icon to solve.





Appendix E

A3 Sheet: Optimization Using modeFRONTIER together with NX

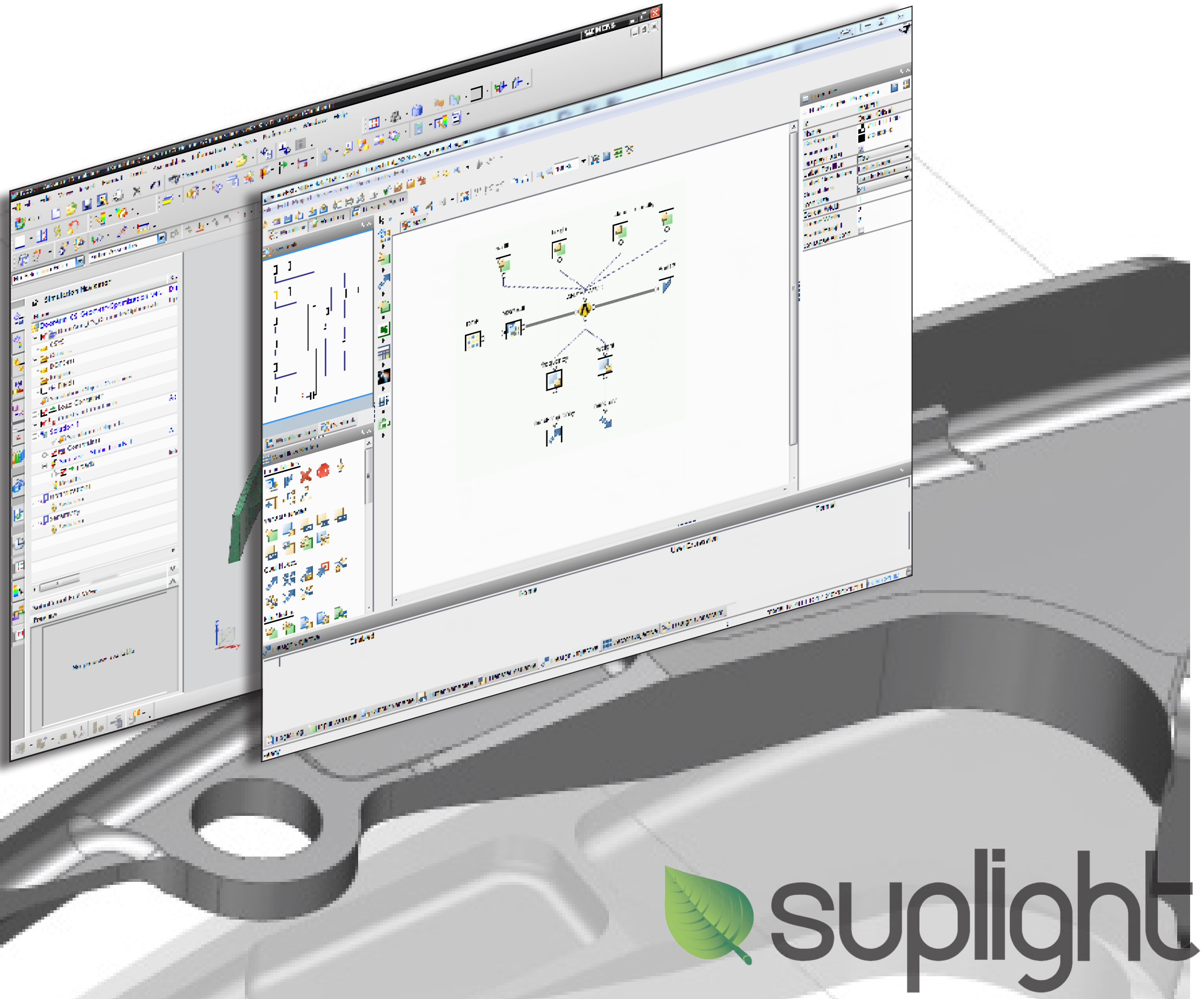
Optimization using NX Advanced Simulations with modeFRONTIER

Topic: Optimization modeFRONTIER	Approved By: Terje Rølvåg	Name: Espen Nilsen, Carl Skaar	Date: 10.04.2013

modeFRONTIER is a multi-objective optimization software which allows you to connect several different CAD or FEA softwares together. Through the graphical interface you are able to set up a workflow consisting of nodes (the icons) and links (lines between the nodes)

We will here demonstrate how it is possible to build a workflow which can interact with simulations performed with NX Advanced Simulations.

The objectives of this simulation will be mass and displacement.



NX 8.5

NX NASTRAN

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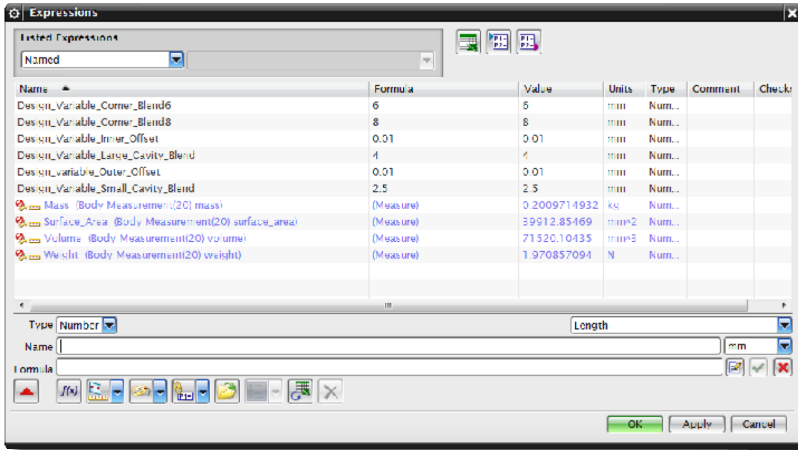
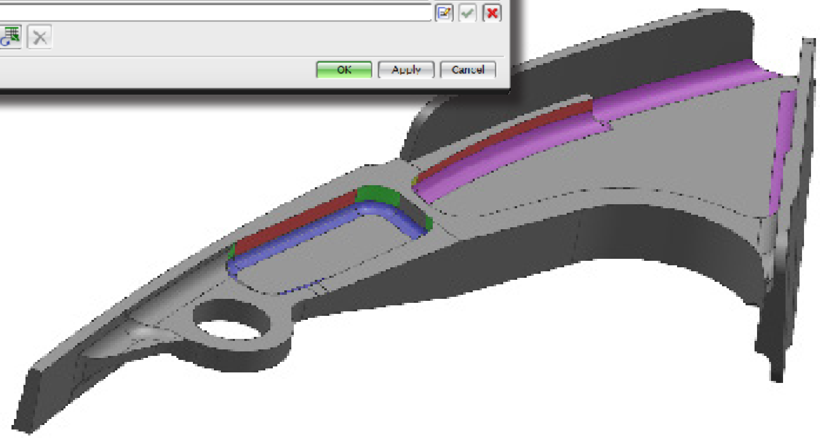
Optimization using NX Advanced Simulations with modeFRONTIER

Topic: Necessary Preperations | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 10.04.2013

The following preparations are necessary in order to run the optimization.

1. Parameterize the model (Expressions) in NX
2. Use Measure Bodies (Analysis --> Measure Bodies) to apply measurements like volume, mass, etc to the expressionslist
3. Run a simulation i NX Advanced Simulation. Make sure you have a .fem- and .sim-file which you store in the same folder as the .prt-file
4. Install modeFRONTIER. It is recommanded to install it in a directory path without spaces.
5. Download Cygwin (cygwin.com). Install it in c:\cygwin\ if possible
6. In addition you need the file killer.vbs stored in the same folder as the rest of the modelling and simulation files
7. You will also need to record a macro with meshing and simulation. Store the macro in the same folder as the rest of the files. Watch the instruction video (NX_macro.mp4)





Optimization using NX Advanced Simulations with modeFRONTIER

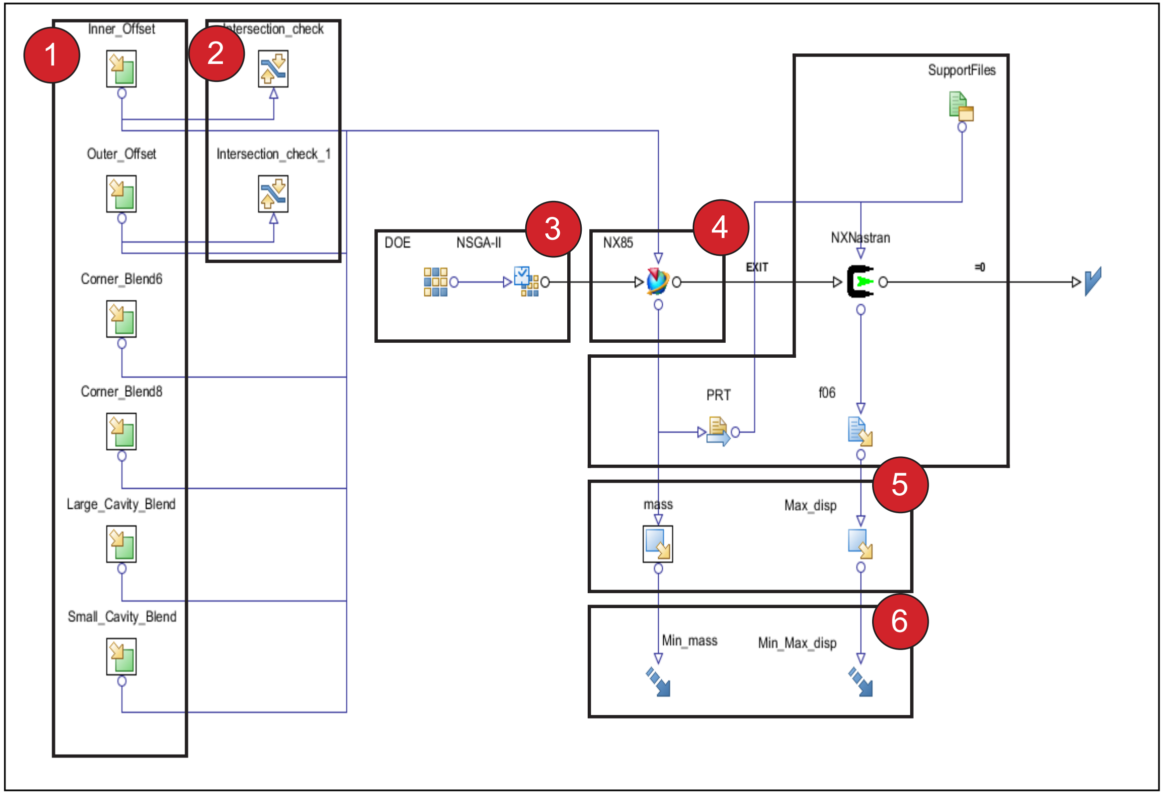
Topic: Workflow in modeFRONTIER | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 10.04.2013

The workflow shows how modeFRONTIER can control NX and NX Advanced Simulation to optimize a prt-file

The following nodes are necessary to run a optimization run:

1. Input Variables: Defines design space
2. Constraints: Contraints on variables.
3. DOE and Scheduler: DOE and algorithms provides different values for the input variables
4. NX CAD Node: Interacts with NX expressions
5. Output Variables: Design output variables
6. Objective: Minimizing or maximizing output variables

The last bulk consists of four nodes that are necessary to derive data outputs from NX Advanced Simulations.

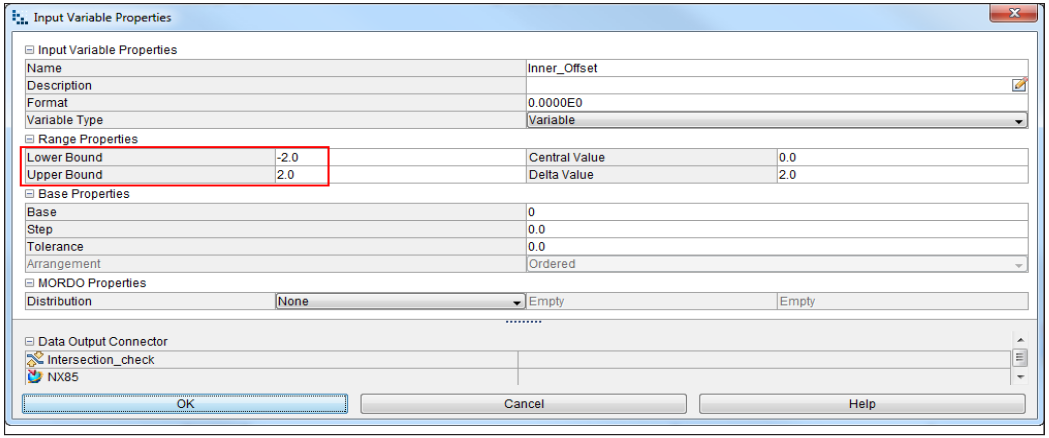


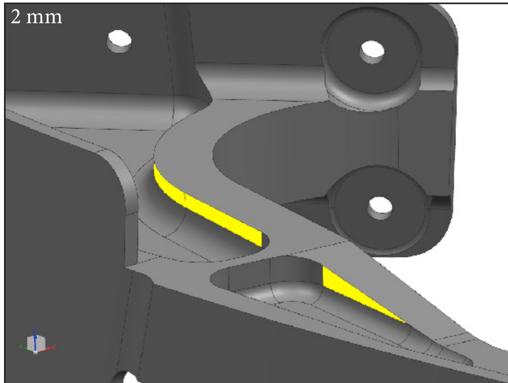
Input variables: Defines the design space by the upper and lower bound

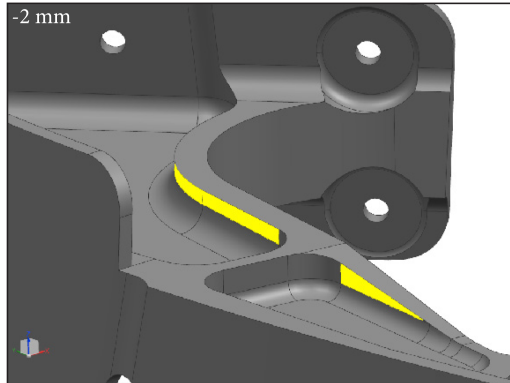
The value range (design space) needs to be defined in order to run a successful optimization run.

1. Open the Input Variable Properties by double clicking the input node icon.
2. Under Range Properties you are able to specify the lower and upper bound for the design parameter. This tells the scheduler what range it should keep within while changing the design parameter.

The screen shots underneath shows how the CAD model responds when the parameter inner_offset is changed.







Optimization using NX Advanced Simulations with modeFRONTIER

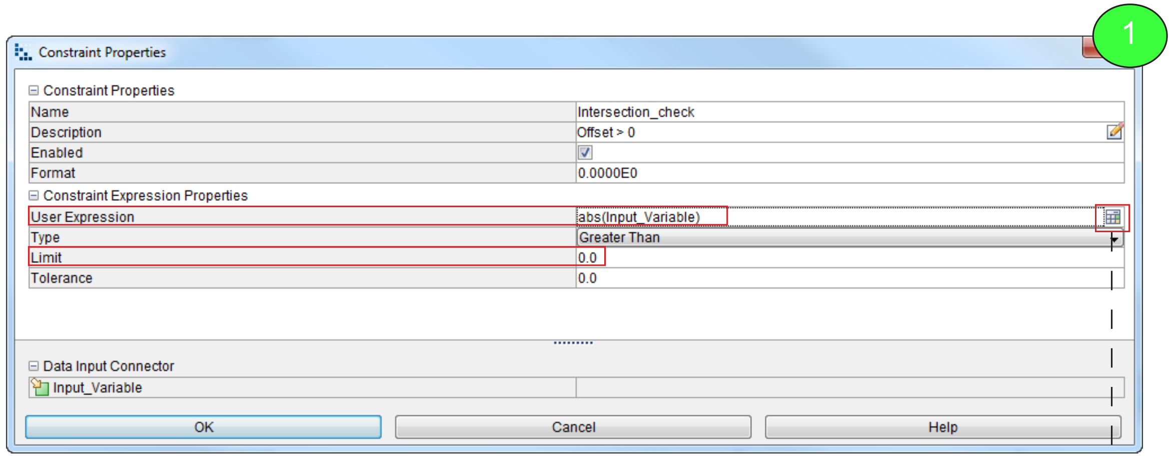
Topic: Define Input Constraint | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 10.04.2013

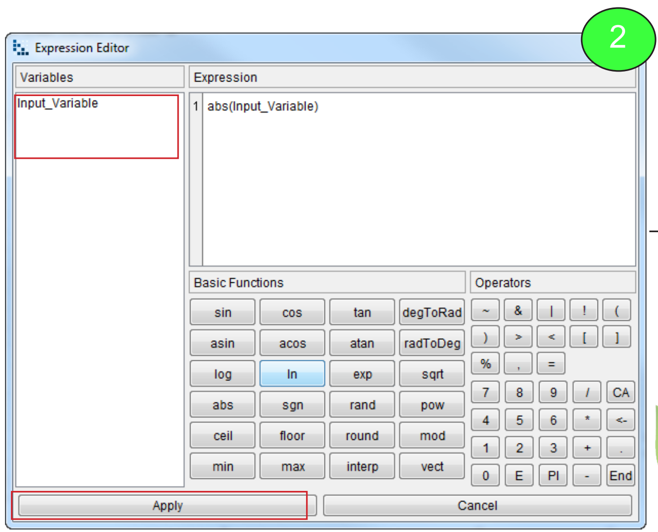
Deisgn Constraint: Additional contraints added to the output or input variable

It is also possible to define additional constraints to the Input or output variable. If one of the design parameters for instace can´t be equal to zero, a contraint node can be linked to the input variable node.

1: What is needed to be defined here is the “User Expression” and “Limit”. To edit the user expression, click the calculator icon behind the “User Expression”.

2: In this case the expression is written as the absolute value of the input variable. The variables connected to the constraint node will occur in a list to the left. Click “Apply” to save the changes. You will then return to the Contraint Properties. Set the limit equal to zero. Save the changes and close the window by clicking “Ok”.





Optimization using NX Advanced Simulations with modeFRONTIER

Topic: DOE and Schedulers | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 10.04.2013

Design of experiments (DOE): Necessary sample of the design space which the scheduler algorithm can base its optimization algorithms on.

From the DOE Properies you can choose what kind of DOE setting you will like to use. In this tutorial we will use the Uniform Latin Hypercube.

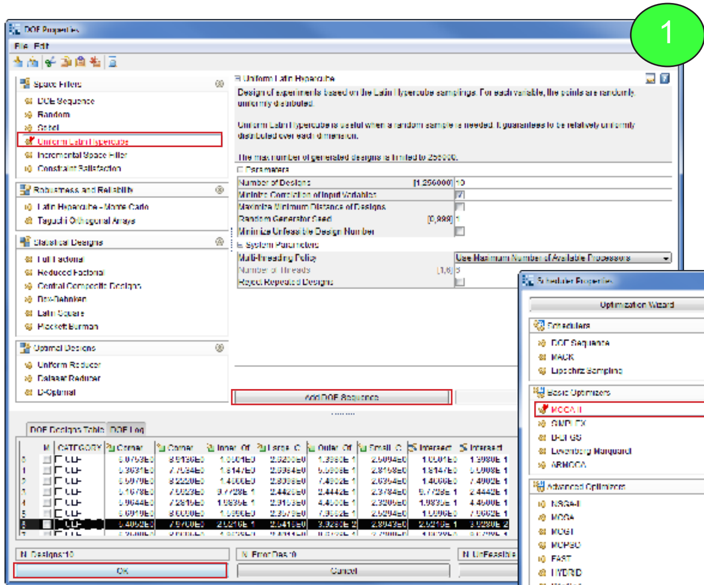
1: Remove the DOE design table by holding shift and mark all the lines. Press "Delete
2: Use the same properties as specified and click "Add DOE Sequence"
3: Click "Ok" to save and close the window.

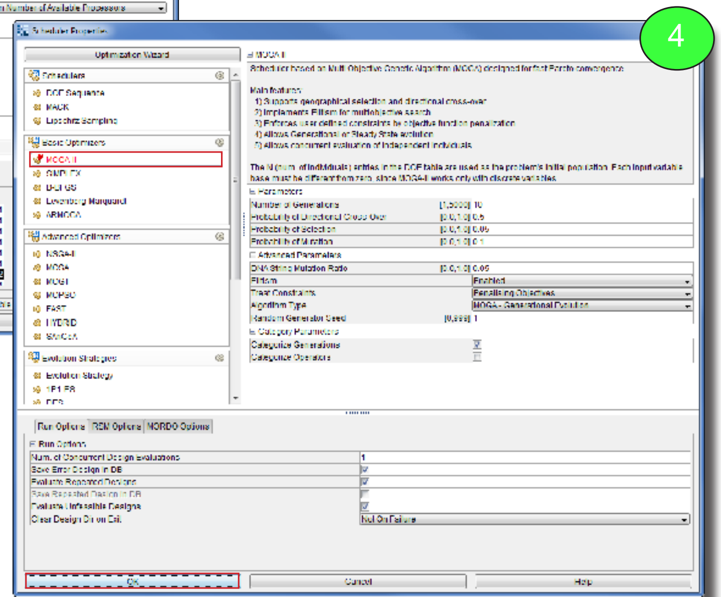
Scheduler: Contains diffrent types of algorithms that work in various ways to reach optimization goals based on the problem at hand.

The scheduler uses the initial DOE to build a population of new designs. The way it controls the evolution varies from algorithm type selected.
As an example we will use the scheduler called MOGA-II.

4: Select "MOGA-II" from the list to the left
5: Click "Ok" to save and close the window.

Look in the help section for more details regarding DOE and Schedulers





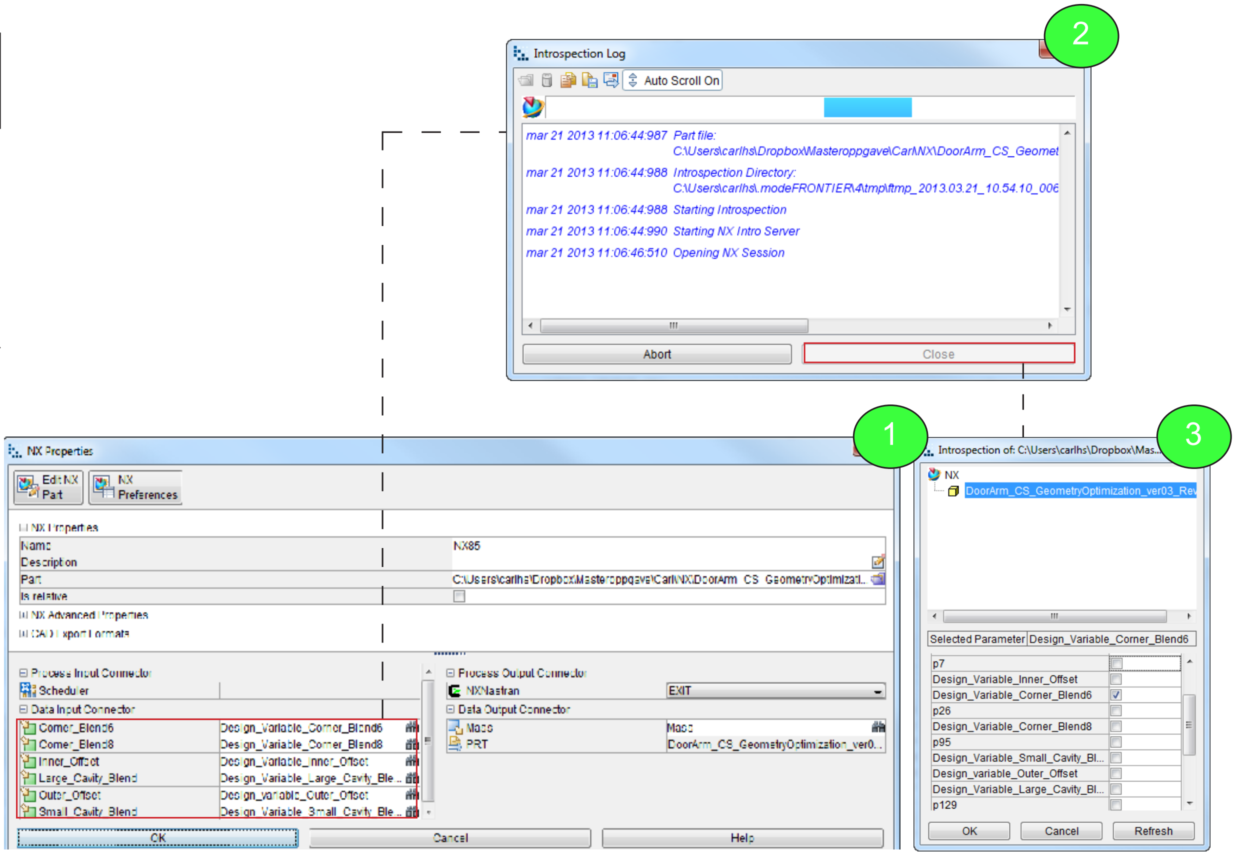
Optimization using NX Advanced Simulations with modeFRONTIER

Topic: Assign Input/Output Variables from part-file. | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 10.04.2013

NX CAD Node: interact with the user expressions in a NX .prt-file.

The NX CAD node can only interact with inputs and outputs involving the geometry.

1: Define all the input and output variables you will like to use by clicking on each of the binoculars behind the input variables listed under "Data Input Connector" .
2: Wait for the introspection log to finish loading, then click close.
3: A new window will open. Click on the part name. A list will be shown underneath with all the deisgn parameters from the expression list in NX.
4: A list will be shown underneath with all the design parameters from the expression list in NX. Tick the design parameter which corresponds to the input node you want to assign. You have to click on each binocular to assign one design parameter to each of the input nodes.
5: The same way you assign the output variables. You will need to apply all the input and output nodes you need in the workflow to be able to assign each and every one of them.



The data output connector called PRT is for the simulations results and has no binoculars.

Optimization using NX Advanced Simulations with modeFRONTIER

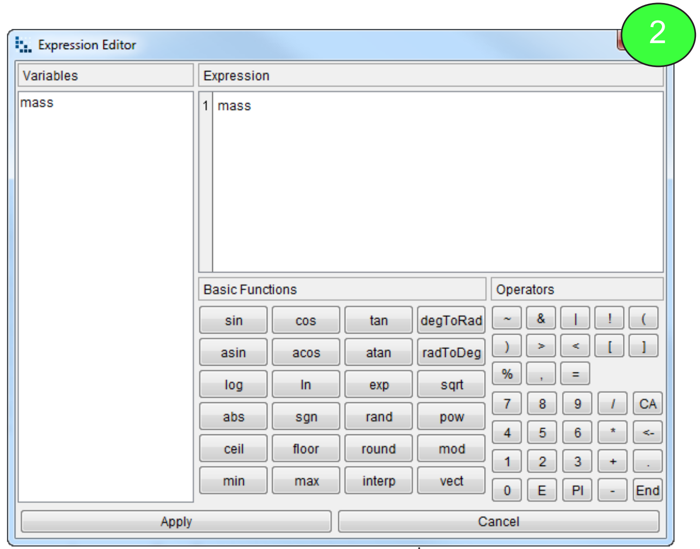
Topic: Define Objective | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 10.04.2013

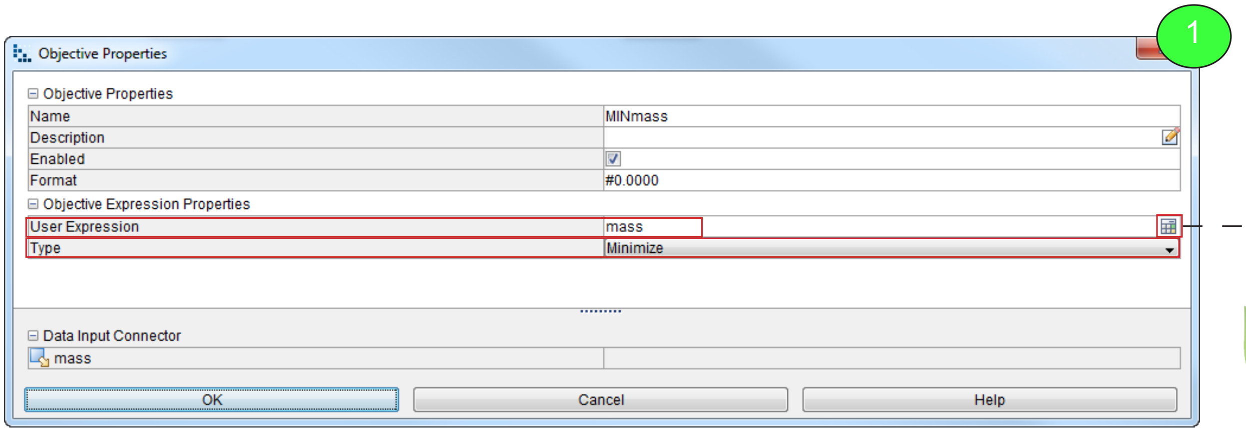
Design Objective: Identifies the output node and represents the optimization objective

The objective node is connected to output node and allows you to either minimize or maximize the output.

1: Double-click the objective node. The objective node is linked to a output node called "mass". Click on the calculator.
2: In the Expression Editor define the expression output value through the calculator icon.

Under "Type" you could either choose minimize or maximize depending on the objective variable chosen.

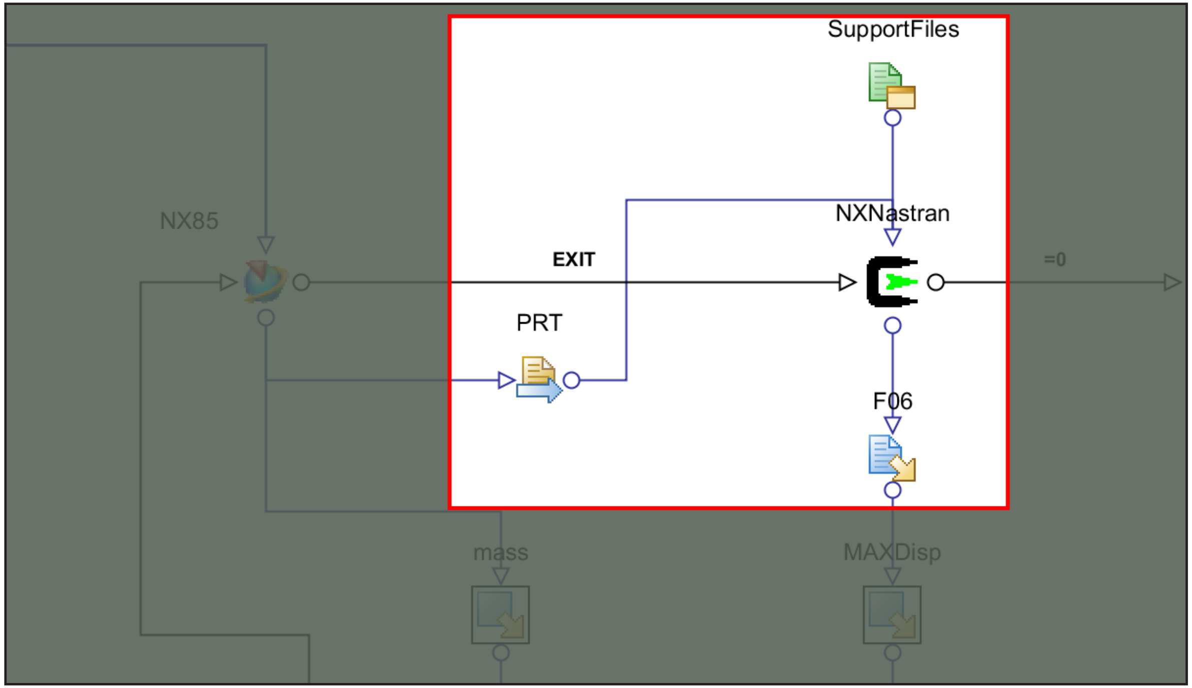




Optimization using NX Advanced Simulations with modeFRONTIER

Topic: Retrieving Simulations Outputs (displacement) | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 10.04.2013

The NX geometry node is only able to deal with the expressions defined in the .prt-file . Unfortunatly, there is no standard simulation node which can interact with NX Advanced Simulations. The way of retrieving simulation results into modeFRONTINER is to use the Cygwin node. The Cygwin node allows you to run a Script which will run the macro recorded in NX.



	Transfer File: Transfers file(s) from one application node to another.
	SupportFiles: Shows the absolute path for all the files included in the script
	Cygwin Shell Script: Executes a script which will load NX and run a macro
	Output File: Uses a mining rule which is able to read results out of the .f06 file.

In the next slides we will show you how each of the nodes needs to be defined, changes needed to be done in the script, and how to record a macro in NX 8.5.

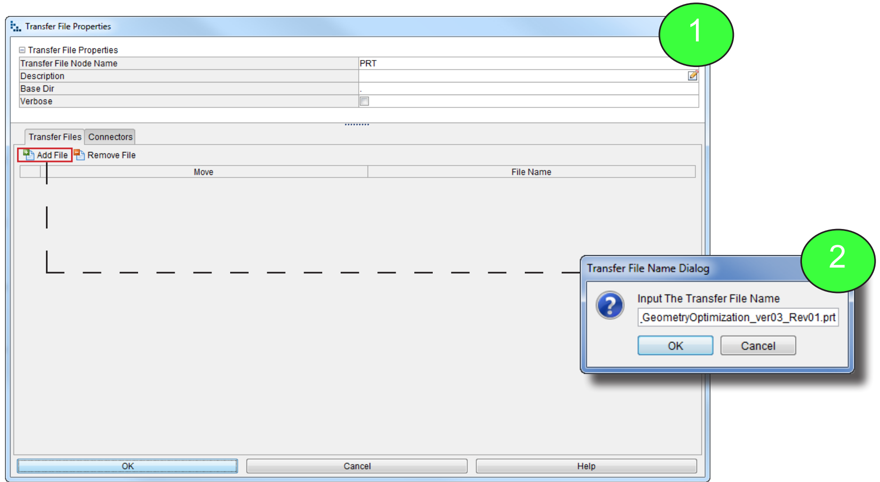
Optimization using NX Advanced Simulations with modeFRONTIER

Topic: Transfer File and Support Files | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 10.04.2013

Transfer File: Transfers file(s) from one application node to another.

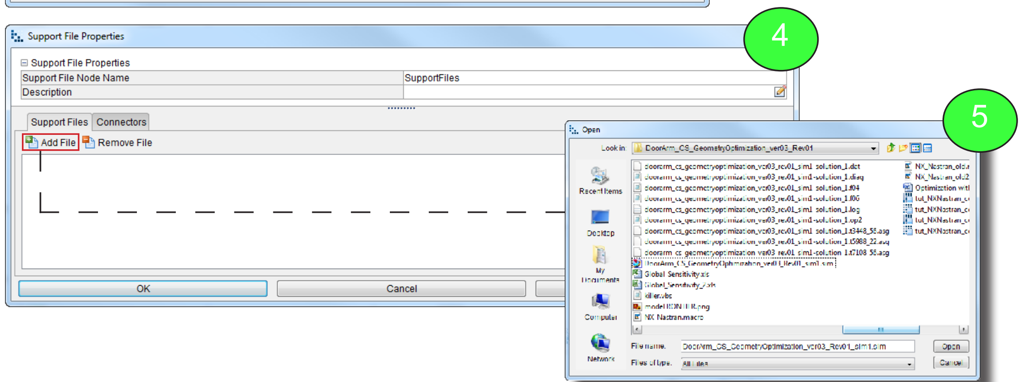
In order to get displacement as output on each of the design iterations the transfer node is needed. The node makes a temporary copy of each of the generated designs and couples it with the cygwin node.

1: Click on Add File
2: Write the .prt-file name. Since you want the temporary copy of the file, insert: filename_copy.prt.
3: If there is other files in the list, remove them by clicking Remove File.



SupportFiles: Shows the absolute path for all the files included in the script

4: Click on Add File
5: Choose the five files: .prt, .fem, .sim, killer.vbs and NX_Nastran.macro.
6: If there is other files in the list, remove them by clicking Remove File.



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Optimization using NX Advanced Simulations with modeFRONTIER

Topic: Cygwin Shell Script | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 10.04.2013

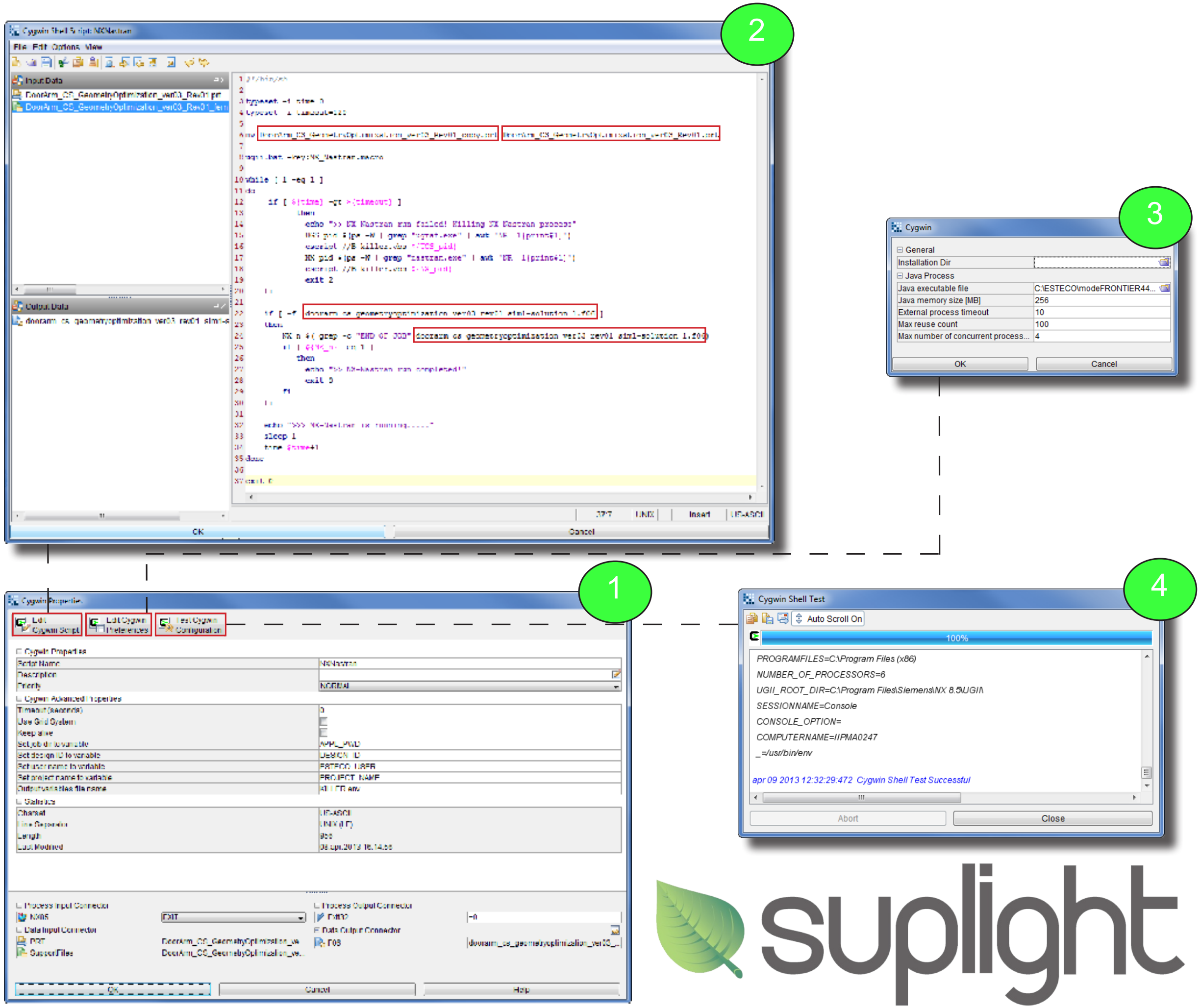
Cygwin Shell Script: Executes a script which will load NX and run a macro

1: There are no changes needed to be done in the main window. Go ahead and click on "Edit Cygwin Script"

2: All the text marked within a red box on the picture underneath needs to be updated with the correct filenames. This involves the .prt-file, the copy of the .prt file and the .F06 resultfile. These can be picked from the list to the left.

3: If the NX does not open during the run, define the java executable file. Do this by specifing the path for java.exe. Normally this is stored in modeFRONTIER installation folder:
(c:\ESTECTO\modeFRONTIER442\jre\bin\java.exe)

4: Check if the script is able to load.



Optimization using NX Advanced Simulations with modeFRONTIER

Topic: Retrieving Simulations Outputs (displacement)	Approved By: Terje Rølvåg	Name: Espen Nilsen, Carl Skaar	Date: 10.04.2013

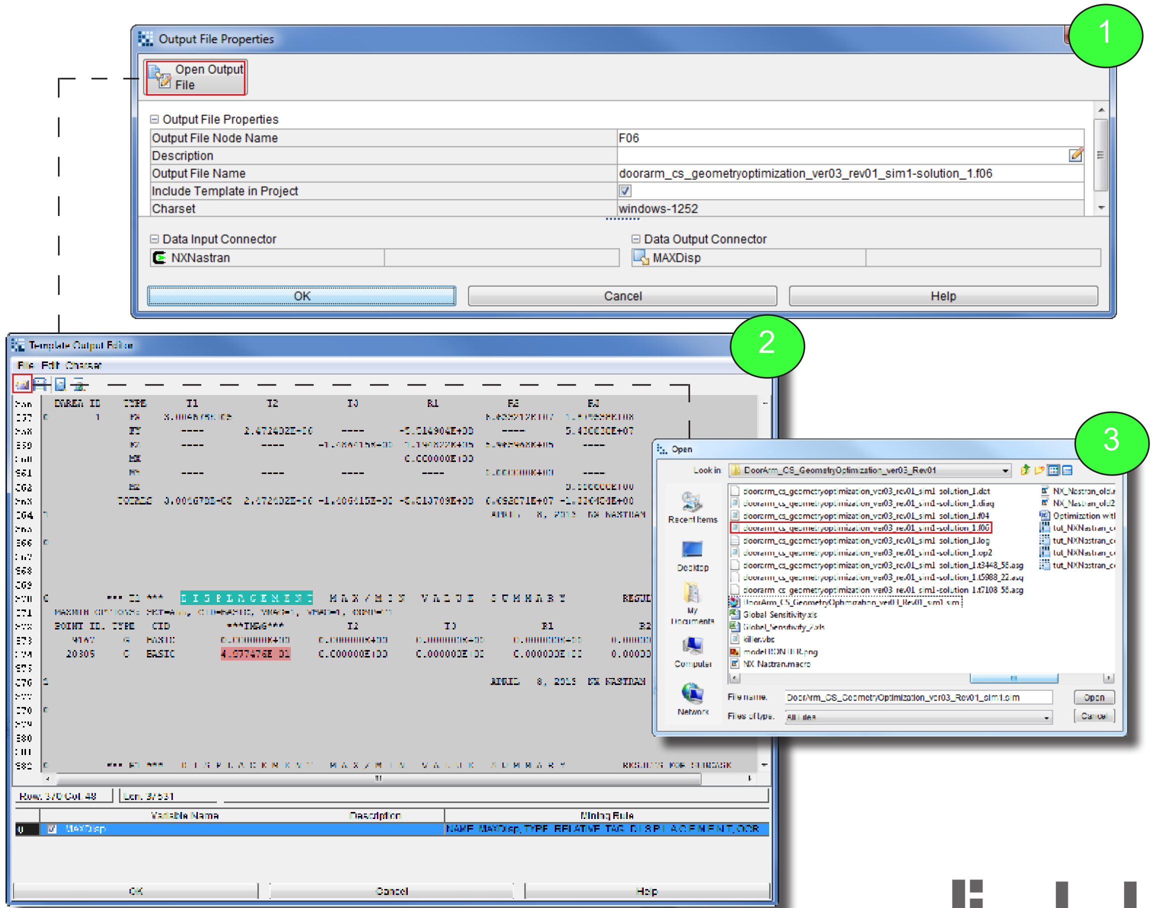
Output File: Uses a mining rule which is able to read out results from the .F06 file and assign it to the output variable

1: Click on "Open Output File"
2: Click open to update the .F06 file
3: Browse to the .F06 file and double-click it.

There is already a mining rule defined. If you need to add a new mining rule for displacement:

5: Mark the text "Displacement"
6: Right-click and choose "Relative Position"
7: Mark the value you will like obtain from the .F06-file, left
8: Right-click and choose "Select Relative". Displacement should become green, and the value red.

Finaly, run the analysis by clicking project --> run



Appendix F

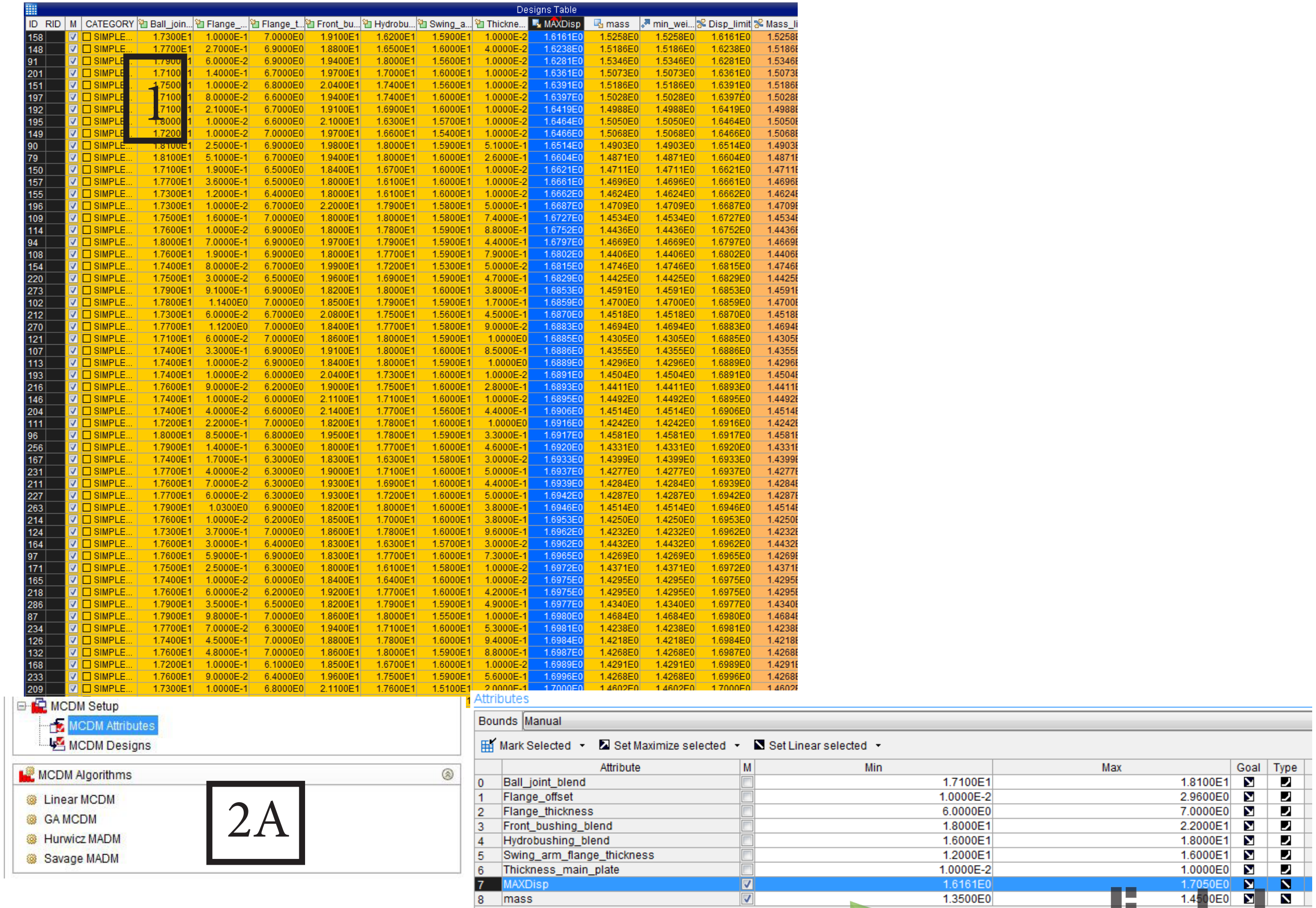
A3 Sheet: modeFRONTIER postprocessing

modeFRONTIER Postprocessing

Topic: Postprocessing	Approved By: Terje Rølvåg	Name: Espen Nilsen, Carl Skaar	Date: 08.05.2013

This A3 intends to provide a guide to decision making once an optimization has been done. This briefing shows an approach with the use of modeFRONTIERs built in MCDM(-Multi Criteria Decision Making).

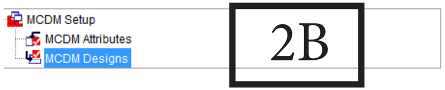
1. When an optimization has been run in modeFRONTIER, it presents all the iterations with its design parameters in a design table.
From this table one can range the smallest to largest and mark the designs that falls within an acceptable range regarding one of the two goals. This is done by highlighting the designs that might be good enough. Right click in the highlighted field and click: mark designs->mark selected. The chosen designs should now be ticked off. In this particular case displacement was chosen as the limiting factor for estimating the best design.
2. A. The next step is: Assessment->Open MCDM panel. Here the variables and goals are displayed in a list in MCDM attributes. Check the boxes regarding goal parameters and proceed. Desired range of the parameters can also be specified manually in the attributes.

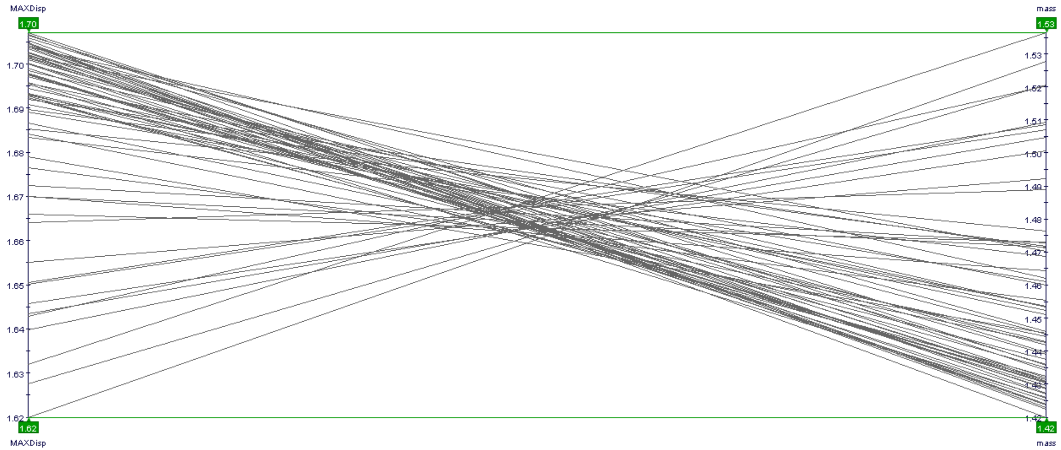


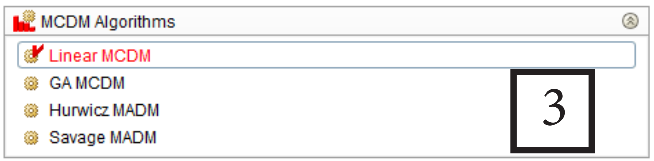
modeFRONTIER Postprocessing

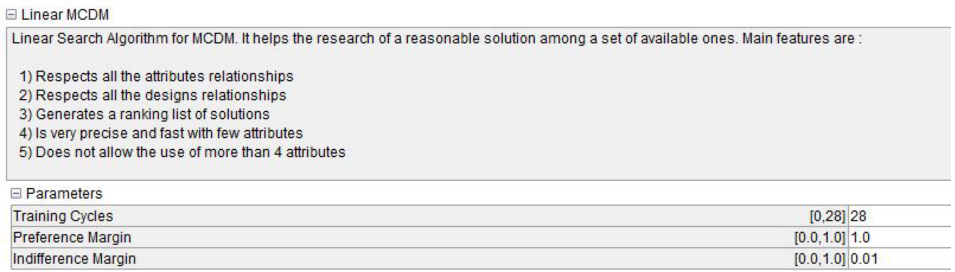
2. B. Choose the tab called MCDM designs in the left top corner. Here the designs is presented in both a table and a parallel chart. It is possible to slide the green numbers on the chart to isolate the designs within a given range. This chart is mainly to see which designs that are related to each other.

3. From here one is given the choice between different algorithms and preferences regarding these. The linear MCDM seems to give the best results in this particular example. Click create MCDM.









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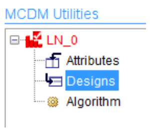
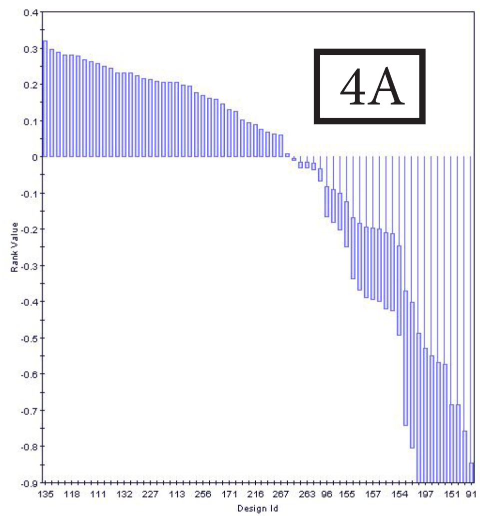
modeFRONTIER Postprocessing

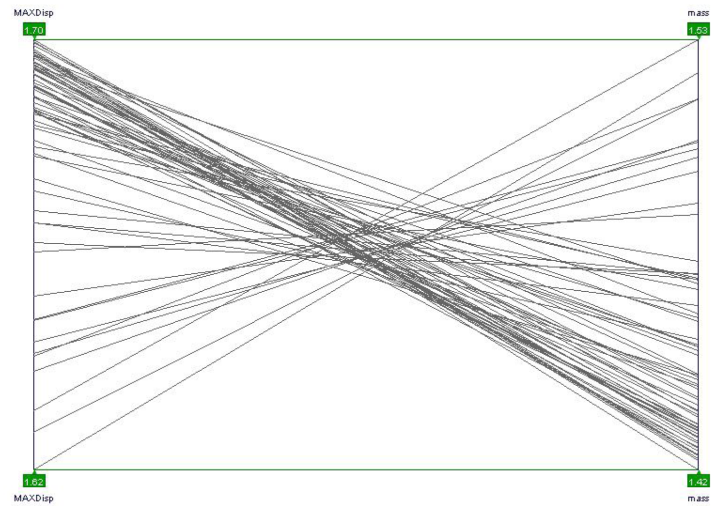
Topic: Postprocessing	Approved By: Terje Rølvåg	Name: Espen Nilsen, Carl Skaar	Date: 08.05.2013

4. A. ModeFRONTIER now creates results under MCDM utilities. The attributes tab shows information regarding the setup. The most interesting is the designs tab that contains designs in ranked order.
4. B. This can be exported to the modeFRONTIER desktop by right clicking MCDM utility(LN_0 in this case) and choose mcdm ranking.
4. C. These tables is now located in design space tab->desktop tab.



4A

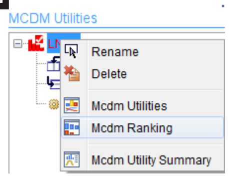




Designs

ID	MAXDisp	mass	Rank Value
135	1.7009E0	1.4180E0	0.320
130	1.7010E0	1.4204E0	0.296
241	1.7015E0	1.4211E0	0.289
126	1.6984E0	1.4218E0	0.282
118	1.7001E0	1.4219E0	0.281
239	1.7003E0	1.4221E0	0.279
124	1.6962E0	1.4232E0	0.268
234	1.6981E0	1.4238E0	0.262
111	1.6916E0	1.4242E0	0.258
214	1.6953E0	1.4250E0	0.250
292	1.7029E0	1.4255E0	0.245
233	1.6996E0	1.4268E0	0.232
132	1.6987E0	1.4268E0	0.232
97	1.6965E0	1.4269E0	0.231
231	1.6937E0	1.4277E0	0.223
211	1.6939E0	1.4284E0	0.216
227	1.6942E0	1.4287E0	0.213
168	1.6989E0	1.4291E0	0.209
218	1.6975E0	1.4295E0	0.205
165	1.6975E0	1.4295E0	0.205
113	1.6889E0	1.4296E0	0.204
290	1.7004E0	1.4301E0	0.199
121	1.6885E0	1.4305E0	0.195
208	1.7033E0	1.4323E0	0.177
256	1.6920E0	1.4331E0	0.169
298	1.7027E0	1.4339E0	0.161
286	1.6977E0	1.4340E0	0.160
107	1.6886E0	1.4355E0	0.145
171	1.6972E0	1.4371E0	0.129

4B

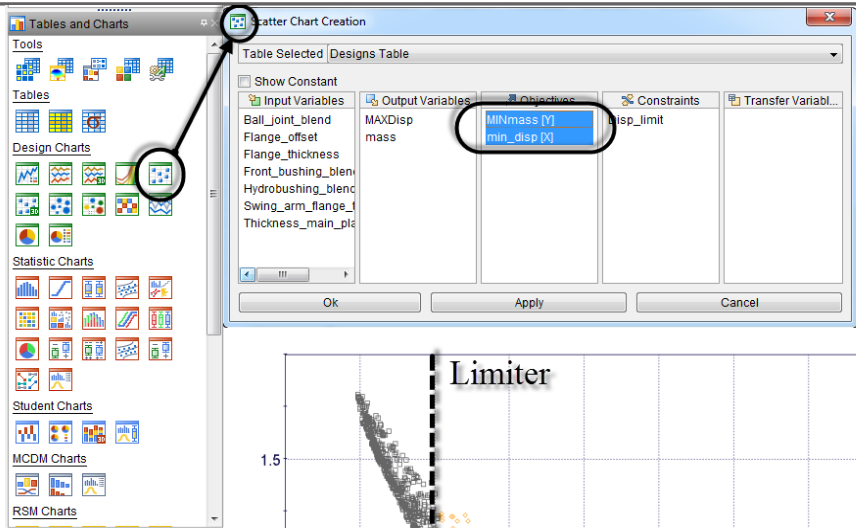


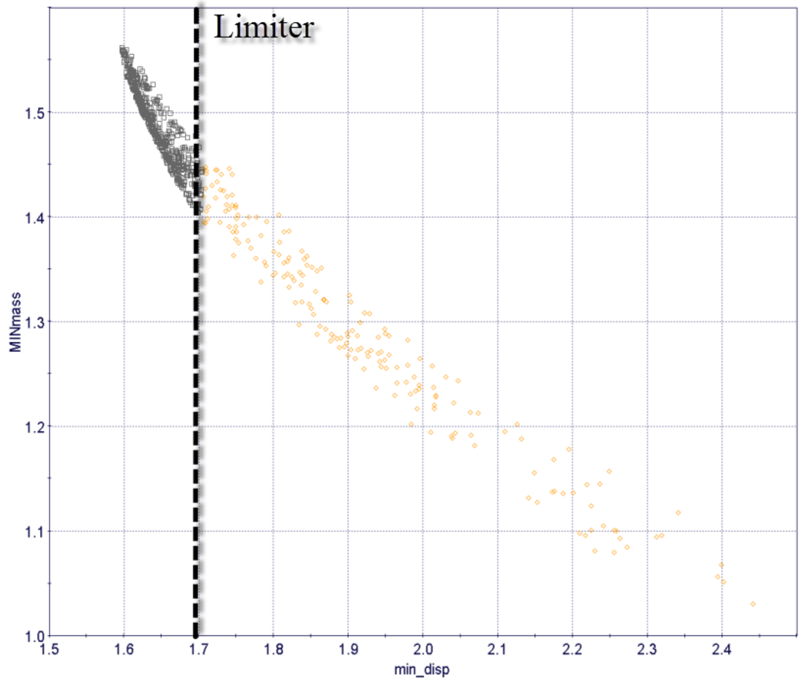
4C

modeFRONTIER Postprocessing

Topic: Postprocessing | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 08.05.2013

5. In the design desktop it is possible to generate a pareto curve by creating a scatter plot of goals. This is done by clicking scatter plot under tables and chart and then select what to display on X and Y axes, as shown to the right. Right clicking the scatter plot gives an option to mark pareto designs(if they exist). Right click: mark designs->mark pareto designs->only real. Here the best designs can be identified visually and marked manually to identify the best results.





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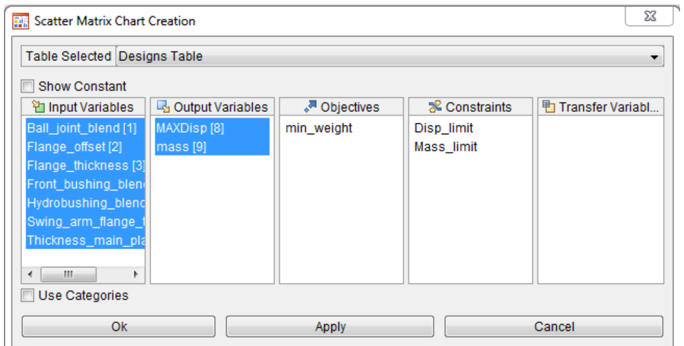
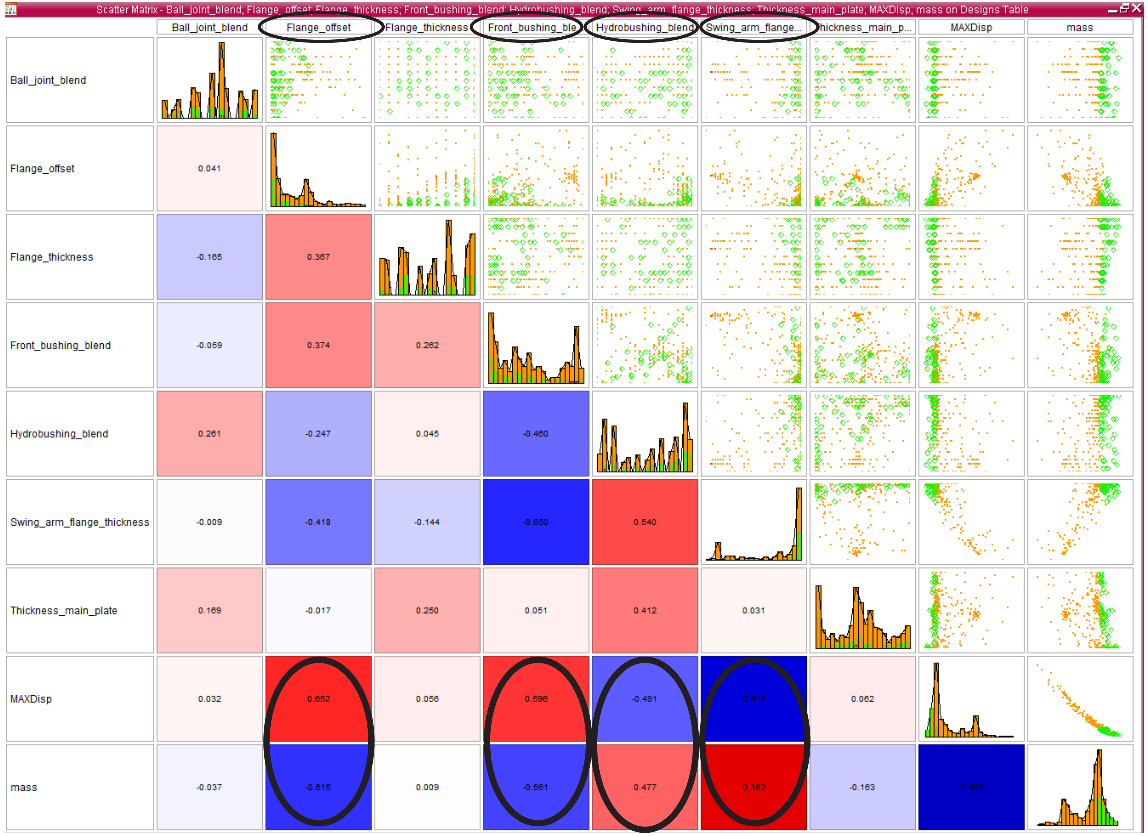
modeFRONTIER Postprocessing

Topic: Sensitivity analysis | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 08.05.2013

6. In case parameter sensitivity is of interest, this can be created by the scatter matrix chart under statistics chart. These tools is located in the left bottom corner of the modeFRONTIER desktop.(remember to be located in:design space tab->desktop tab) Choose all the input and output variables. Click ok and the matrix scatter to the right appears. This shows the correlation between parameters and goals. The four most important parameters is highlighted and shows by a strong color and correlation value, the impact each parameter has on the goal. As one can see the parameters has almost an opposite effect on the conflicting goals as one would expect. This can be used to identify parameters that can be excluded from optimizations to save time. As an example in this case one can see that Flange_offset has a great impact on MAXDisp and the same parameter has almost exactly the opposite effect on mass.

6





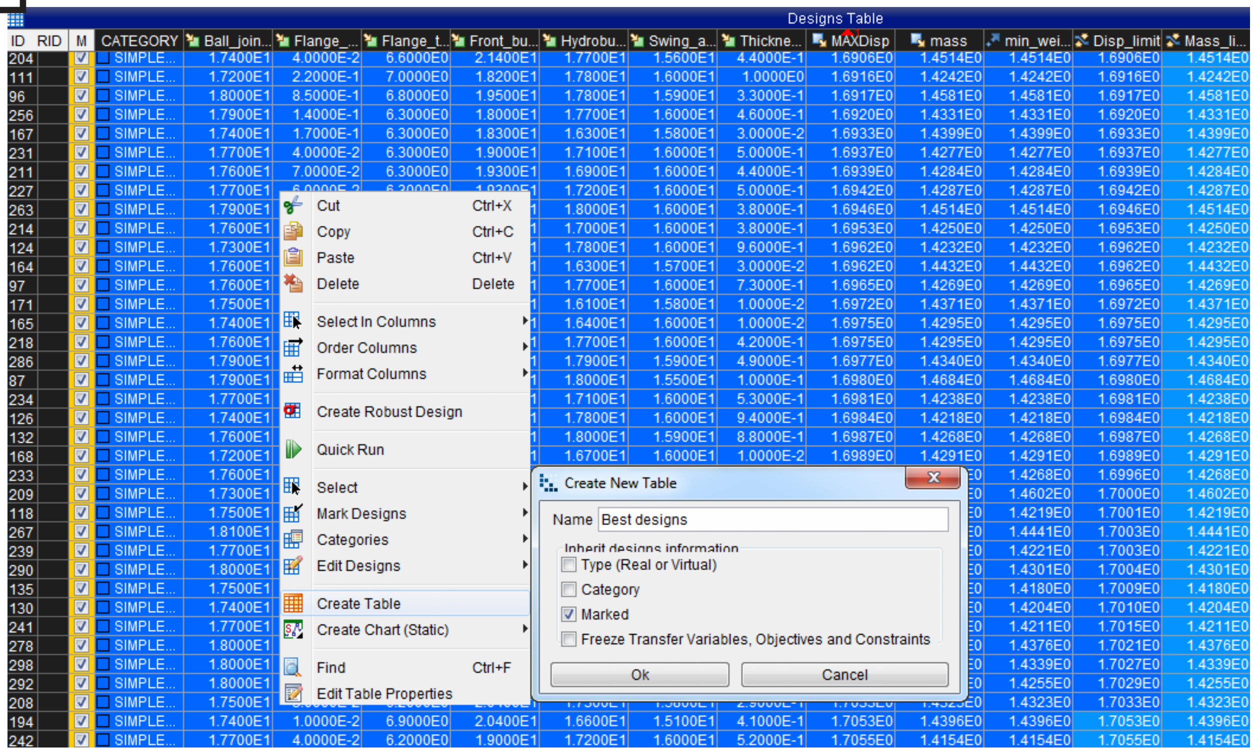
modeFRONTIER Postprocessing

Topic: Manual extraction of designs | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 08.05.2013

In case the MCDM utility does not work satisfactory or modeFRONTIER is unable to mark pareto designs automatically, it is of course possible to do the process manual. One of the ways of doing that is described in detail in the following.

7. First one would have to rank the displacement in descending order from lowest to highest. Then one would have to mark the feasible design that meets the requirements. Right click and choose create table and only keep marked ticked in the next dialog box.

7



modeFRONTIER Postprocessing

Topic: Manual extraction of designs | Approved By: Terje Rølvåg | Name: Espen Nilsen, Carl Skaar | Date: 08.05.2013

8. The next step is to identify the best design manually in the generated table by considering displacement and mass. This can be visualized better by creating a X - Y scatter of the selected designs. This is done by creating a scatter plot containing the designs from the new table. This scatter resembles the method already shown on a previous slide, but this one is narrowed down to contain only designs that is within a certain range. Clicking on the desired design shows the value and id. This makes it possible to locate the design in the table.

8