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Production-based Multi-criteria Design Optimisation of an Unconventional Composite Fuselage Side Panel by Evolutionary Strategies and a Surrogate Model of Manufacturability Analysis

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1. Abstract
This paper introduces a novel multi-criteria optimisation framework that efficiently combines manufacturing analysis of composite structures with respect to various production criteria such as manufacturability and limitation of process-based material deviations. These criteria include gaps induced by fibre placement systems as well as structural constraints regarding material failure, stability and damage tolerance. Within this optimisation framework, evolutionary algorithms are coupled with an in-house parametric FE-Model generation tool, which exhibits an extensive design scope comprising various unconventional stiffener topologies, evaluates buckling modes and obtains composite specific failure criteria according to multiple load cases. This work focuses on multi-criteria optimisation of a lattice-stiffened fuselage panel with novel double-curved stiffeners aiming for minimum weight. The final design is compared to a conventional aircraft stiffener topology with respect to weight and window size.

2. Keywords: Design Optimisation of Composite Panel, Evolutionary Algorithms, Response Surface Models, Automated Fibre Placement, Estimation of Prepreg Tow Gaps

3. Introduction
Increased utilisation of composite materials due to their specific properties such as strength-to-weight ratio, damage tolerance, reduced maintenance costs and flexibility has led to advanced production technologies such as Automated Fibre Placement (AFP) systems. Despite of high positioning accuracy these systems induce manufacturing deviations mainly provoked by geometric complexity of composite structures and restrictions in the structural design space by the dimensions and flexibility of the layup head [1]. Furthermore, unconventional designs adapted to loading conditions can significantly improve efficiency of the stiffened thin-walled structures in terms of weight savings compared to current composite applications in commercial aircrafts. However, increased geometric complexity of composite structure can lead to redesign necessities due to manufacturability requirements and significant production deviations, such as gaps between tows and deviations in fibre orientations by AFP. If not considered, consequently a reduced structural performance would be obtained [2]. Regarding manufacturing deviations of AFP systems, tow gaps have a vital role on mechanical performance of the prepreg laminated composite structures which is precisely presented by [3]. However, AFP induced gaps are most commonly analysed separately after completion structural designs. This may lead to recurring design phases or expansive manufacturing strategies to overcome this issue. Hence, as a solution methodology, especially for unconventional stiffeners, structural optimisation can be coupled with production analysis so that the structure adapts its topology to defined production technology unlikely to process adaptation to the final design to avoid significant material deviations. Thus, a novel optimisation approach is presented that associates structural optimisation with manufacturability of components and restriction of deviations regarding a newly developed AFP system.

4. Panel Concept and Production Phases

Initial concept of the aircraft side panel is based on evolution in biology such as bones or branches that have risen from various loading conditions in their environment. A detailed global topology optimisation of a fuselage barrel presented by [4] exhibits slanted, lattice and intersecting material densities around the window sections. Nevertheless, slanted stiffeners offer increased performance under fuselage regions loaded with shear forces [5] which lead to efficient material usage in terms of weight savings. Stiffener topology of the panel concept consists of a pure grid stiffened region with local stabilisers, so-called stiffener peaks around the windows and conventional stringer frame distribution in upper and lower regions where the slanted grid topology ends. This combination also allows an efficient assembly process in circumferential directions of the fuselage. Advantageous of the machining technologies on foam structures are utilised for serial production of complex sandwich stiffener topologies [6] (see Figure 1).

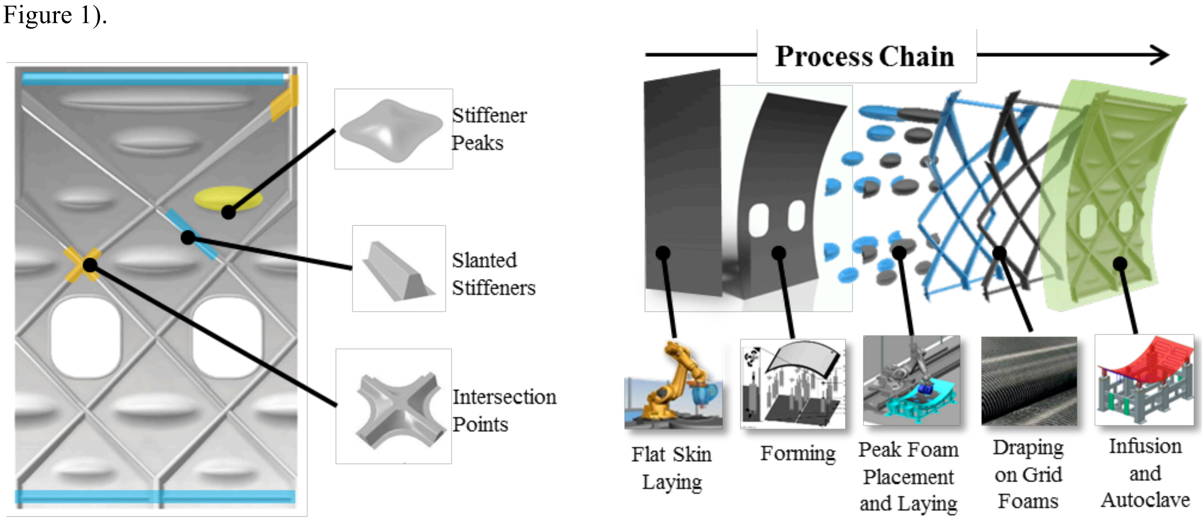

Figure 1: Illustration of concept panel components (left) and the process chain (right)

The manufacturing process starts with the prepreg-skin being placed on a 2D surface by AFP and then being transformed into 3D by a flexible forming process. Foam of stiffener peaks are placed and processed as well in AFP followed by the placement of the more complex grid-stiffeners. Draping process on lattice stiffeners and intersection points using innovative textile-concept is carried out and afterwards slanted stiffeners are infused and bonded to prepreg skin via co-curing process in autoclave. The production concept yields a significant reduction in manufacturing costs due to a single bonding of all panel components.

5. Automated Fibre Placement System

Main advantages of the in-house system are increased laying velocity around 3 m/s and form flexible compaction device with a decreased minimal tape length compared to state of the art. Hence, the layup head design not only allows for manufacturing geometric complex structures but also for placing slit tapes on plane fuselage skin with high productivity. To adapt to different surface conditions like stiff metal moulds or the more elastic foams, the compaction device is separated in four force-controlled compaction segments, allowing an additional radial displacement. The geometric characteristics are presented in Figure 2, and as well as the most important criteria for design optimisation regarding restrictions of the compaction device.

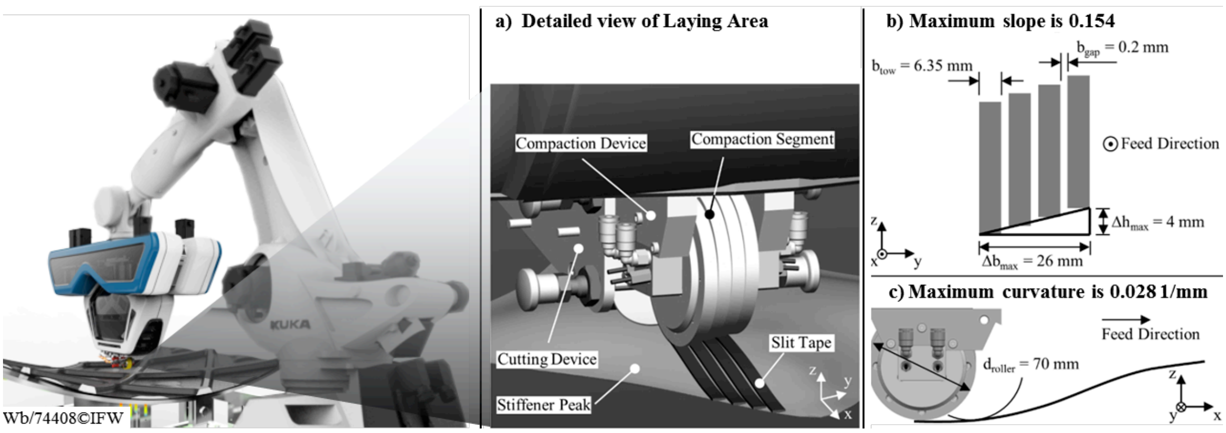

Figure 2: Illustration of newly developed modular layup head at left and manufacturability criteria at right

The newly developed layup head processes 1/4" (6.35 mm) slit tape. Between each tow and compaction segment a gap of 0.2 mm exists because of tow guidance. Each segment is able to perform a radial displacement to adapt curved surfaces of up to 4 mm. With an overall width of 26 mm the resulting maximum slope of the compaction device is 0.154 across feed direction (b). Another criterion derived from the compaction device is the curvature (c). The segment diameter of 70 mm allows a maximum curvature of 0.028 1/mm for concave arched surfaces. These three criteria, the gap, the maximum slope and the maximum curvature are taken into account within the optimisation procedure.

6. Estimation of Manufacturability

The manufacturability analyses focus on the production of the double curved stiffener peaks presented in Figure 1. Due to geometric complexity, during the optimisation, manufacturability analysis has to be carried out in order to adapt the structural surface to machine restrictions shown in Figure 2. This analysis is automatically performed with an AFP-interface-algorithm within the in-house parametric simulation tool. Computations of surface slopes and curvatures are performed by projecting partitioning lines on the stiffener peak according to the global fibre placement direction. Distances between lines are set to two tow widths including segmentation spacing of the compaction roller. By this means, the neutral fibre lines can be obtained between two partitioning lines representing projected fibre path borders. Ascending surface slopes are computed along the vertical direction of neutral fibre paths (Figure 3 left). Allowable curvature and minimum radius are iteratively computed regarding the neutral fibre line information.

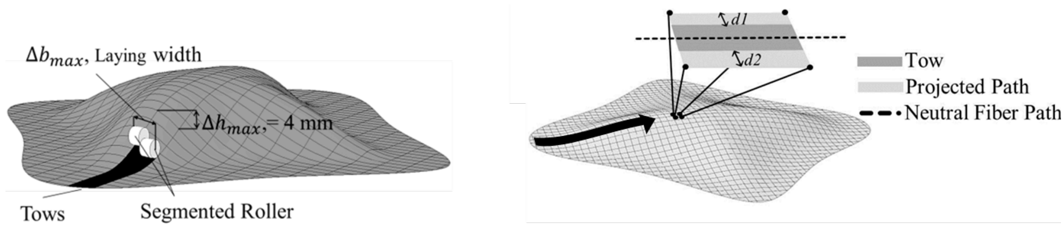

Figure 3: Computation of allowable surface slopes in layup direction (left), geometric gap analysis (right)

Based on the same methodology, partial geometric gaps, *d1*, *d2* (in Figure 3 right) are analysed at the points that are lying on the intersection of vertical partitioning lines and projected borders of tows with assumption of infinitesimal material strains vertical to fibre direction. The maximum gap value is calculated iteratively on each cell with summation of partial gap values of neighbour cells as follows:

$$\max(d1_i + d2_{i-1}, d1_{i+1} + d2_i),\ i = \text{number of the parallel neighbour cells} \qquad (1)$$

The estimation of the gaps will be larger than experimental values due to missing material behaviour during the compaction. However, this assumption will affect the mechanical performance in a positive way since the gaps are also minimized more than expected values which lead to increased fibre volume fraction in gap regions.

7. Surrogate Models of Manufacturability Outputs

In order to increase optimisation efficiency in terms of computation time, a response surface generation of the manufacturability output of stiffener peaks is carried out using radial basis function, artificial neural networks (RBF-ANN) that are based on biological process of neurons [7]. This methodology offers a faster approximation method by creating an output of linear combinations of weighted radial basis functions, in this case Gaussian functions, to get sufficient non-linear approximation models.

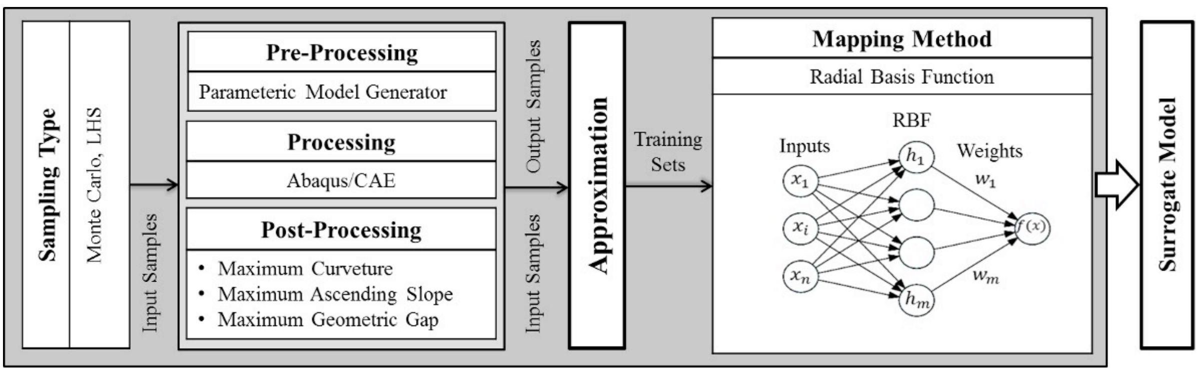

Figure 4: Response surface generation of manufacturability output of stiffener peaks

The Latin hypercube sampling method is chosen to generate input samples. The surrogate model generation represented in Figure 4 is carried out according to training data sets that contain input samples regarding optimisation parameters of the FE panel model and corresponding output sets containing maximum tow gaps, ascending slope, and curvature information of peak topology. Since the lay-up orientations are restricted to 0°, +45°, −45°, 90°, other orientations are not necessary to be included during computation of maximum gap, slope and curvature information.

8. Multi-criteria Optimisation

The objective of the multi-criteria optimisation is formulated to reach minimum weight goal based on a conventional reference panel, under structural and manufacturability constraints of stiffener peaks. Evolutionary strategies based on selection, recombination and mutation operators are used to minimise fitness value consisting of approximated manufacturing outputs, structural responses and weight of the panel. The optimisation framework combines manufacturability outputs from surrogate models with FE analysis by adding and weighting mapping functions of objective C^{opt} and mapping functions of constraints $C_l^{=/<}$. Summation is the fitness evaluation, C, of each individual represented in equation (2) where X presents the system parameters, also $F(X_i)$ and $f(X_l)$ are representing respectively, the weight objective and the constraints.

$$minimise \quad \left\{ C(F(X_i), f(X_i)) = w_0 C^{opt}(F(X_i)) + \sum_{l=1}^{n_=+n_<} w_l C_l^{=/<}(f_l(X_i)) \right\} \quad \begin{matrix} i = number\ of\ design\ variables \\ l = number\ of\ constraints \end{matrix} \qquad (2)$$

8.1 Design Variables and loading conditions

As presented in Figure 5, an optimisation model is automatically generated by an in-house parametric panel generation tool which is written in Python. Window cut out topology can also be varied during the optimisation and can be changed from oval to lozenge shape. The object oriented structure of the panel generation tool automatically enables FE models of different kind of stiffener topologies and profiles to expand the design scope with large number of design parameters.

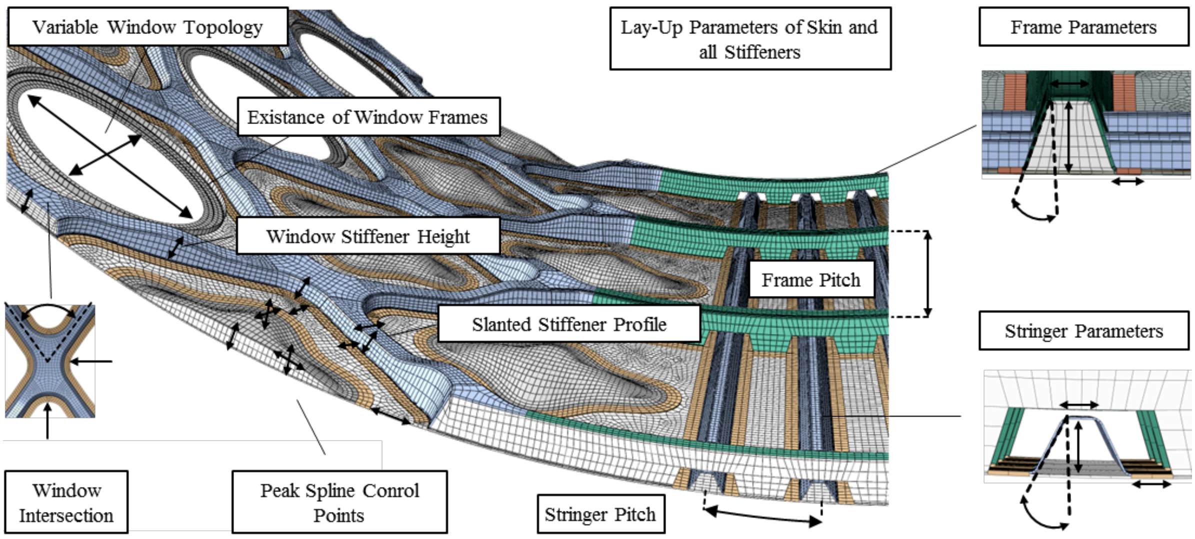

Figure 5: Design variables of newly developed fuselage side panel

Automated design of producible lay-ups and thickness adjustments on overlapping zones or sections of different textile topologies are handled with composite module and production module (AFP and draping) within the panel generation tool. The layup parameters are optimised with an interface to the table of allowable layups consisting of combinations of all possible stacking sequences based on number of layers, orientations (+45, −45, 90, 0) and production requirements in [8], such as symmetry and balance condition where at least 8 % of fibres have same orientation, not more than four plies having the same direction could be stacked in a sequence and orientation of the outermost layers are restraint to +45 or −45 in order to minimise impact effects. Within this strategy all layup parameters such as number and orientations of the layups are reduced to only one index variable of the allowable layup table.

In order to realise aircraft fuselage deformations on the panel level, periodic boundary conditions are applied at the edges of the FE model. Different loading scenarios stated in Table 1 and corresponding failure analyses are automatically performed during the optimisation.

Table 1: Load cases and origins of loading conditions with corresponding analysis type in optimisation process

Load Case	Loading Type	Analysis Type	Cabin Pressure [mbar]	Axial Loading, $n_{x,x}$ [N/mm]	Shear Loading, $n_{x,\theta}$ [N/mm]
1	Cabin Pressure	Static	1200	120.0	-
2	Manoeuvre	Static	600	60.0	−86
3	Lateral Gust	Static	600	197.0	−1.0
4	Lateral Gust	Static, Buckle	-	-	−86
5	Manoeuvre	Static, Buckle	-	−137.0	−67.0

8.2 Structural and Mechanical Constraints

The damage tolerance requirement of the panel is satisfied by the maximum strain condition ε_{max} in each load case (see Table 1). Due to the positive effect of the cabin pressure, only load cases 4 and 5 are considered for buckling. Furthermore, out of plane deformations are not allowed around the windows in order to prevent faster delamination in weak regions and sustain damage tolerance. Manufacturability constraints (5, 6 and 7 in Table 2) are assigned according to the requirements illustrated in Figure 2 and approximated by the response surface method. Manufacturability of the stiffener peaks is handled as upper restriction and the outputs under upper limit constraints are ranked equally since secondary influences such as machine speed in terms of laying rate are not considered.

Table 2: Structural Constraints 1–4 and manufacturability constraints 5–7 with source of computations

No	Constraint Type	Constraints	Source
1	Allowable Strain in each Load Case, ε	$\varepsilon < \varepsilon_{max}$	*FEM – Abaqus®*
2	No Buckling Forms Around Windows, Load Cases 2, 4, 5	$U_r < U_{min}$	*FEM – Abaqus®*
3	Reserve Factor Load Case 4, RF_1	$RF_1 > 1$	*FEM – Abaqus®*
4	Reserve Factor Load Case 5, RF_2	$RF_2 > 1$	*FEM – Abaqus®*
5	Maximum Ascending Slope, m	$m < 0.154$	*Response Suface*
6	Maximum Curvature, k	$k < 0.028$ 1/mm	*Response Suface*
7	Maximum Tow Gaps, d	$d \leq 0.55$ mm	*Response Suface*

9. Results and conclusions

The evolution parameters of the panel are set to 30 populations with 80 offspring per generation and infinite lifespan in the optimisation environment. Convergence of the multi-criteria problem is observed at 27th generation after approx. 2600 structural evaluations, with static and buckling analysis in conjunction with response surface approximation of AFP manufacturability analysis. Lozenge shape of window cut-outs adapted to stiffener layout around the window is one of the significant outcomes of the optimisation. Even though the objective is to reach minimum weight based on reference value, panel offers 12 % larger windows compared to optimised reference composite panel under same loading conditions and constraints (Figure 6). Oval shapes of the windows are restricting the intersection angles to lower degrees in order to satisfy allowable window sizes. Significantly increased stability is observed on pure shear loading (*RF1*) due to lattice topology and adaptation of intersection angles and material properties to the dominant loading condition (*RF2,* combined shear and compression loading).

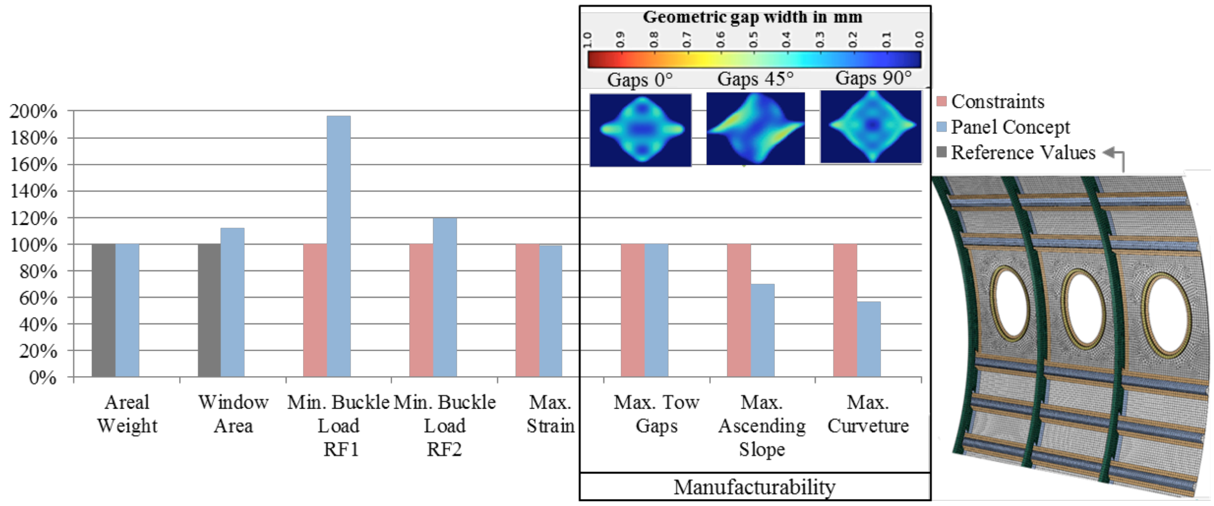

Figure 6: Optimisation result with constraints and reference panel (right) and true geometric gap fields on peaks

Therefore, buckling values in load case 5 (compression and shear loading) are significantly reduced in all parameter combinations of oval shapes. Besides, configurations offering smaller window size than the reference panel are not included and ranked in the structural evolution. Additionally as presented in Figure 7, an efficient convergence is obtained for the layup index parameters of the allowable layup array, which comprises thousands of allowable stacking sequences sorted by ascending layer numbers.

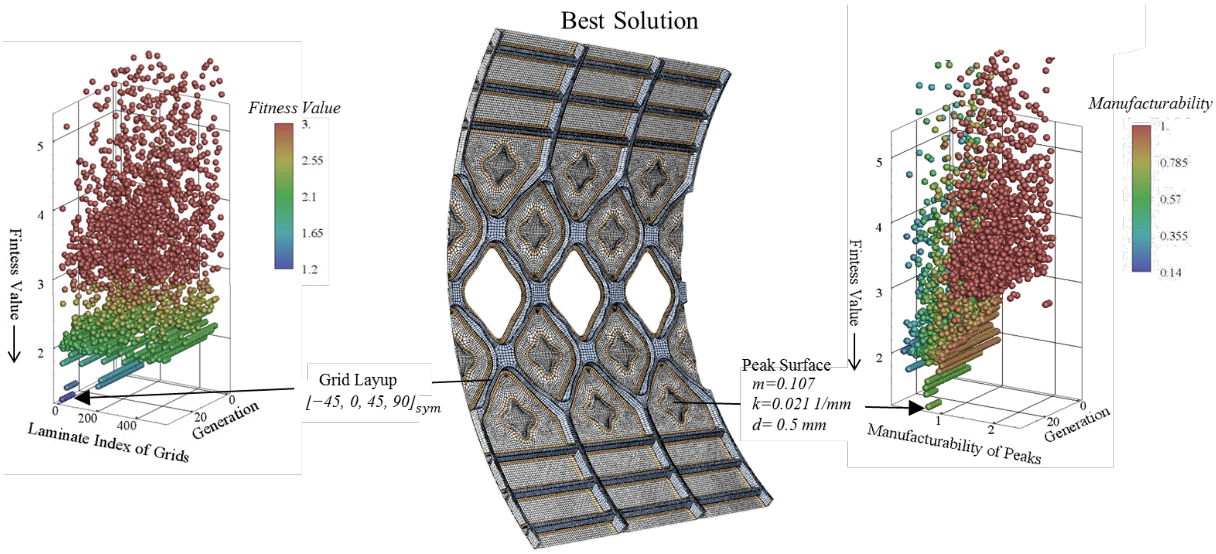

Figure 7: Best stiffener and window topology, convergence of grid laminate and manufacturability parameters

The obtained peak configuration satisfies all requirements regarding production quality. Within this methodology, an automated structural evolution together with production quality can be obtained simultaneously without any requirements such as complex path programming to avoid large gaps between tows. To effectively improve manufacturing quality, gap information will in future be used to monitor the layup process continuously and to feedback data about real material behaviour in the optimisation framework. The alternative design and methodology can be improved even further by integrating influences of the draping process and other loading conditions in the structural evolution.

10. Acknowledgements
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