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# Multi-objective room acoustics optimization of timber folded plate structure

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## Abstract

This paper investigates the application of multi-objective optimization in the design of timber folded plate structures in the scope of the architectural design process. Considering contrasting objectives of structural displacement, early decay time (EDT), clarity ( $C_{50}$ ) and sound strength (G), the methodology applied in two benchmarks tests, encompasses both structural and acoustic performance when determining folding characteristics and directionality of surfaces in a timber folded plate structure.

**Keywords:** Folded timber plate structures, acoustics, optimization, multi-objective

## 1. Introduction

This paper investigates the potential in the use of computational tools in the architectural design process within the Performance-Aided Design (PAD) framework, proposed at the Master of Science of Architecture and Design at Aalborg University, with the aim of extending a tectonic tradition of architecture through the preparation of the figure of a modern master builder, sitting at the boundary of the disciplines of architecture and engineering (Parigi [12]). Within this frame, this paper aims to benchmark a methodology for designing timber constructions that encompasses an integrated approach where constructions, acoustics and architectural design are combined through multi-objective algorithms.

Other researchers used multi-objective algorithms to achieve good room acoustic performance with compression-only shell structures. Compression-only shells are naturally concave in form, a shape that is generally avoided as unwanted sound concentrations can occur, resulting in negative effects such as echoes. The methodology proposed by Mendez & Block based on multi-objective optimization (Méndez and Block [11]) allows to overcome the intrinsic limitations of concave shapes avoiding sound concentration.

Previous studies aim to fill the gap between architecture and acoustical design by presenting methods for designing and optimizing spaces for acoustical performance, by applying optimization and form finding methods. (Foged *et al.* [7]) (Pignatelli *et al.* [13]) These methods have a shared dependency on a loadbearing substructure, where the acoustically optimized geometry is mounted.

The aim of the paper is to challenge the integration between acoustical optimization and a self-bearing structural principle through the use of multi-objective optimization with timber folded plate structures, for the creation of lightweight, load-bearing acoustic surfaces, eliminating the need for an underlying substructure. Folded plate structures are characterized by a folded geometry of faceted surfaces. The use of these shapes as sound-reflective acoustic surfaces is ideal due to the high level of control they

offer on the directionality and reflectivity of each panel. At the same time folded plate structures provide inherent structural capability. Recent studies demonstrate the potential in the creation of loadbearing folded timber plate structures (Stitic, Robeller and Weinand. [15][16]).

Similar motivations have been presented (Sassone *et al.* [14]), with a basis on a concrete shells, consisting of folded non-planar plates. This paper focuses instead on a timber construction, and therefore planar plate elements. Because the pattern, height, directionality of the folds affect at once the structural and acoustic performance, and because the two objectives could result in being contrasting, the challenge presented within this typology lies in investigating through multi-objective optimization those configurations which are able to provide a suitable solution to both objectives.

## 2. Multi-objective optimization

Opposite to single objective optimization, where a single optimal solution is the goal, a multi objective search can be regarded as a shrinking of the field of feasible solutions, rather than the search of one best solution (Méndez *et al.* [10]). Within an architectural design context, use of multi objective genetic algorithms is closely connected with the concept of the Pareto front. The Pareto front is a set of solutions that cannot be said to be better from each other, but are all optimal solutions with optimized values for multiple contrasting objectives. This allows the designer to choose from a set of solutions without the need to weight the importance of each objective before the search, thus aiding the designer in the process rather than definitely determining the outcome.

When multiple objectives are considered and sought to be satisfied, often two or more objectives will be conflicting. A solution with an optimal value for objective A will have a non-optimal value for objective B, and vice-versa. The difference between single-objective and multi-objective optimization can be explained with the concept of Pareto dominance.

### 2.1. Dominance and Pareto Front

To determine optimal solution in a multi-objective search, one has to look at how solutions mutually dominate each other.

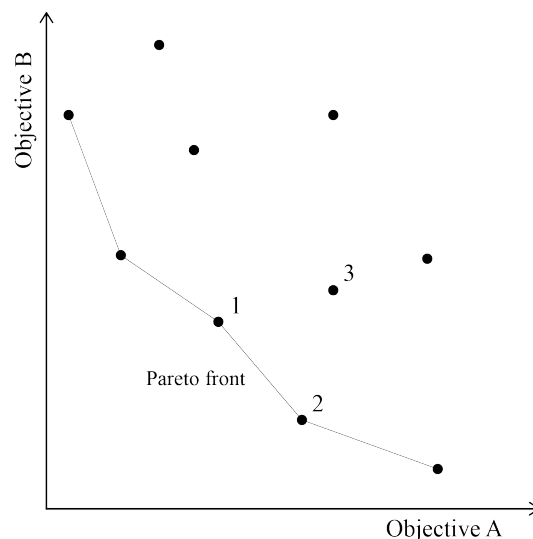


Figure 1: Pareto Front

An objective space where two objectives are sought to be minimized is considered in figure 1. It can be seen that solution 1 is outperforming solution 2 in objective A, but solution 2 is outperforming solution 1 in Objective B. Both solution 1 and 2 are then said to be non-dominated. Solution 3 is said to be dominated by both solution 1 and 2. The set of non-dominated solutions is called the Pareto Front and these solutions are never dominated by others.

### **3. Folding**

Folded plate structures consist of thin structural surfaces that can achieve remarkable spans without constructing single- or double-curves surfaces. An important parameter in folded structural geometry is the angle between adjacent plates (Bechthold [4]) and by extension the height of the fold, as the folding height determines the structural depth of the system.

Folded timber plate structures have the potential to be both architecturally expressive and material efficient. Current research investigates folding patterns known from the art of origami and their structural potential when applied to a timber structure on architectural scale (Stitic and Weinand. [16]). One of these patterns, the Miura Ori pattern is seen in figure 2, will be the basis of the geometry optimization in this paper.

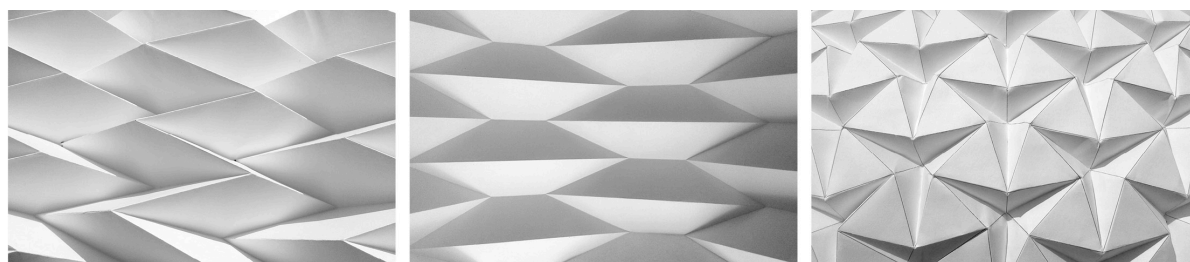


Figure 2: Examples of folding patterns. The Miura Ori pattern is seen to the left

### **4. Methodology**

To exemplify the methodology, it is applied to the design of a roof of a small room. The parametric modelling, acoustic simulation and FEM analysis are all done in Grasshopper for Rhino, a parametric CAD environment, due to its relative ease-of-use in the architectural design process and because it is common practise in many architectural and engineering firms. Likewise also acoustic simulation and structural analysis are done within Grasshopper with the use of the plug-ins Pachyderm by Arthur van der Harten and Karamba by Clemens Preisinger.

The acoustic simulation is done with an average value of the mid frequency range 500, 1000 and 2000 Hz, to obtain a single number for each objective measure to evaluate on. This is commonly done for the objective clarity measure (Barron [2]), but is here extended to the EDT and G measures as well.

#### **4.1. Acoustic**

Numerous experiments in real rooms and in simulated sound fields have resulted in a number of relations between subjective impressions of acoustic parameters with corresponding objective measures (Gade [8]). Subjective parameters have by different authors been described to belong in different categories, but here only the categories: Decay times, clarity measures and sound strength (Bradley [5]), with corresponding objective measures are being included. Optimal values for the objective measures used in this paper are described below.

#### 4.1.1. Objective measures

Early Decay Time, EDT, measures the rate of sound decay, evaluated from 0 to -10dB extrapolated to -60dB. Below  $t_{-10}$  denotes the time when the sound have decayed to 10dB below its start value (Gade [8]).

$$EDT = 60dB \frac{t_{-10}}{10dB} \quad (1)$$

Clarity,  $C_{50}$ , describes the ratio between the total energy in the impulse response before and after 50ms. Higher values of  $C_{50}$  means the early arriving sound to the listener dominates the later reverberant sound. Below  $p(t)$  denotes the instantaneous sound pressure of the impulse response (Barron [2]).

$$C_{50} = 10 \log \left( \frac{\int_0^{50} p^2(t) dt}{\int_{50}^{\infty} p^2(t) dt} \right) \quad (2)$$

Sound Strength,  $G$ , is the ratio between the total energy of the impulse responses and the energy of the direct sound, the latter measured 10m from the sound source (Gade [8]).

$$G = 10 \log \left( \frac{\int_0^{\infty} p^2(t) dt}{\int_0^{\infty} p_{10}^2(t) dt} \right) \quad (3)$$

#### 4.1.2. Acoustic quality distribution

Local conditions at different listening position in a room have a considerable influence on acoustic quality at the specific position. The large variances are caused by different distances to the sound source, vicinity to sidewalls, balcony overhangs etc. As a consequence it is relevant to include the spatial differences in the overall fitness value for the optimization search. An approach to this issue is adopted from another author (Méndez [9]).

A weighted average for the objective measure for all listening positions determines an overall distribution score  $D$ . In the weighting, measures further away from a predefined optimal value is weighted higher in the summation than a value close to the optimal. An optimal  $D$ -score is equal to 0. For a more extensive description of the approach see (Méndez [9]).

$$D_i = \frac{1}{n} * \sum_{i=1}^n |x_{i,n}|^{3/2} \quad (4)$$

Where  $x_i$  differs for different objective measures and  $n$  is the number of listening positions. Below  $EDT_{opt}$ ,  $C_{50,opt}$  and  $G_{min}$  denotes the values set as the goal to reach in the optimization search and  $EDT$ ,  $C_{50}$  and  $G_{min}$  denotes the measures values at a specific listening position.

Table 1: x-values for each objective acoustic measure

$x_1$	Early Decay Time, EDT	$\log(EDT/EDT_{opt})$
$x_2$	Clarity, $C_{50}$	$C_{50} - C_{50,opt}$
$x_3$	Sounds strength, $G$	$G - G_{min}$

#### 4.2. GA inputs and fitness values

A specific Multi-Objective Genetic Algorithm, the HypE algorithm (Bader and Zitzler [1]) is employed. The algorithm is implemented via the Grasshopper plug-in Octopus by Robert Vierlinger with the settings stated below.

Table 2: HypE algorithm settings

Elitism	0,5
Mutation probability	0,1
Mutation rate	0,5
Crossover rate	0,8

Optimal values for each search objective is stated below. Optimal values for acoustic objectives are decided with inspiration from Barron [2] [3].

Table 3: Optimal objective values for optimization algorithm

Search objective	Optimal Value
Displacement (m)	0
Early Decay Time, EDT (s)	1
Clarity, $C_{50}$ (dB)	0
Sounds strength, G (dB)	Barron's min G curve

## 5. Benchmarks

### 5.1 Setup

The search process is applied to two simple benchmark tests. The subject of the studies is a roof construction of an 8 by 10-meter room as seen in figure 3. In both tests, the geometry is constrained to be symmetric down the longitudinal axis of the room and 6 listening points are evenly spread out in one half of the room. Floor, wall and roof are modelled as a wooden material and the audience is modelled as a simple box, both with appropriate absorption and scattering coefficients.

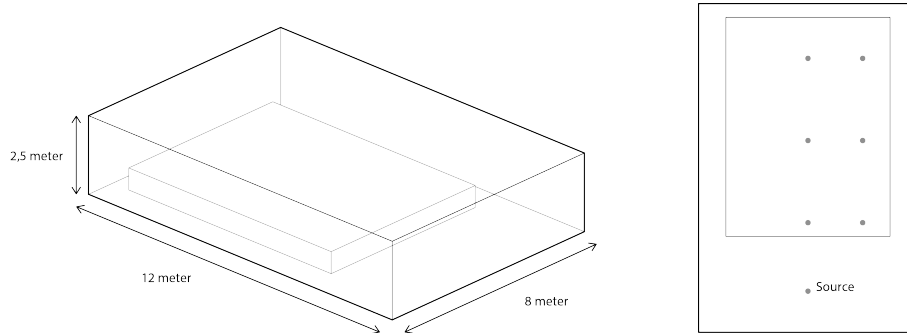


Figure 3: benchmark setup

### 5.2. Benchmark 1

To get a deeper understanding of the nature of contrasting objectives and the Pareto front, a study of a simple 1-directional folding was done. The setup includes two parameters; height of folding and slanting of folds, while number of folds are fixed to 6, and two objectives; displacement and the distribution score of EDT, see table 4 and figure 4. Because the parameter space is small, an exhaustive search was done rather than applying the optimization algorithm.

Table 4: Parameters of benchmark 1

Parameters		Domain
$f_1$	Number of folds in y direction	6
$h$	Height of folds	0,1 to 1,0
$s$	Slanting of folds	0,0 to 1,0

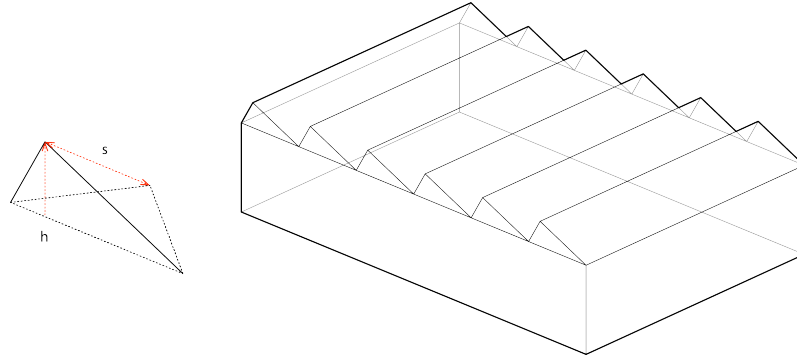


Figure 4: Benchmark 1

Figure 5 shows the complete solution set (grey) plotted in relation to distribution scores of the EDT and G measures ( $D_{EDT}$  and  $D_G$ ), with the Pareto set highlighted (black) and the profile shapes of the relating roof geometries shown to the right. It is clear from the Pareto front that the EDT and G measures are contrasting objectives, which, as mentioned above, is necessary for the search process to result in set of optimal solutions. The Pareto set seems to organise itself into four groups of geometrically similar solutions; {A, B, C, D, E}, {F, G, H}, {I, J, K} and {L, M}, that are also organised in relation to EDT and G performance, from solutions characterised by low  $D_{EDT}$  scores (A to E) to solutions with medium performance in both  $D_{EDT}$  and  $D_G$  (F to H) and to solutions characterised by low  $D_G$  scores (I to M).

In figure 6 the Pareto solutions are projected onto the fitness landscapes of the EDT and G distributions scores. On the left it can be seen that solutions with higher folds and slanting ratios around 0,2 (A to E) achieve the best performing  $D_{EDT}$  score, while on the right the opposite is true, with solution with better G values are concentrated around parameter configurations with low folding height and low folding ratio (I to M). Comparing solution G and I it is worth noting that while having similar performance in both acoustical objectives, there are geometrically quite different, see table 5.

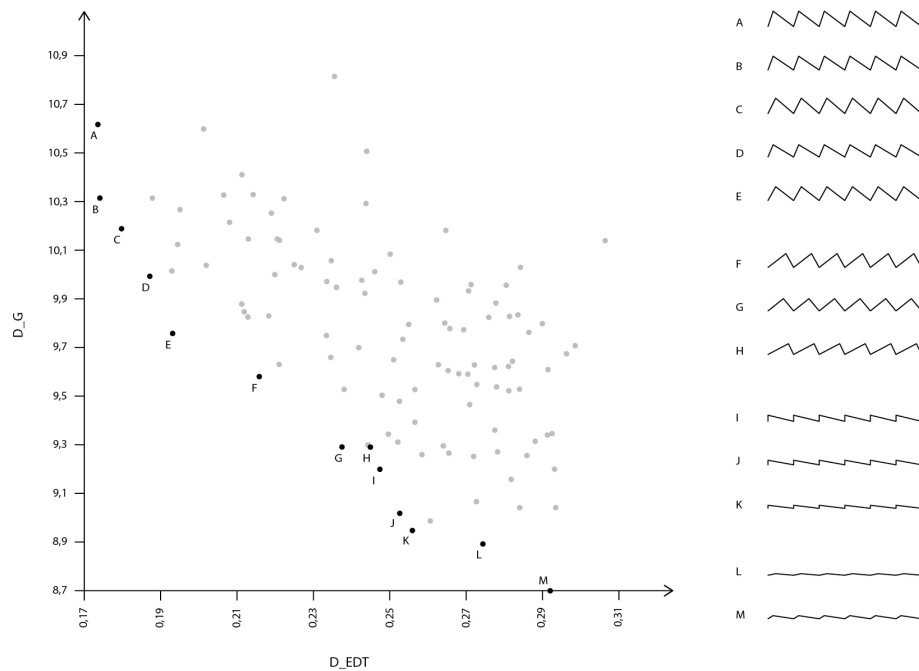


Figure 5: Pareto front of benchmark 1 and relating optimised geometry

Table 5: Examples of Pareto solutions

Solution	C	G	I	M
$f_1$	6	6	6	6
$h$	1,0	0,8	0,4	0,2
$s$	0,3	0,6	0	0,2
Objective values				
$D_{EDT}$ (s)	0,18	0,24	0,25	0,29
$D_G$ (dB)	10,19	9,29	9,20	8,70

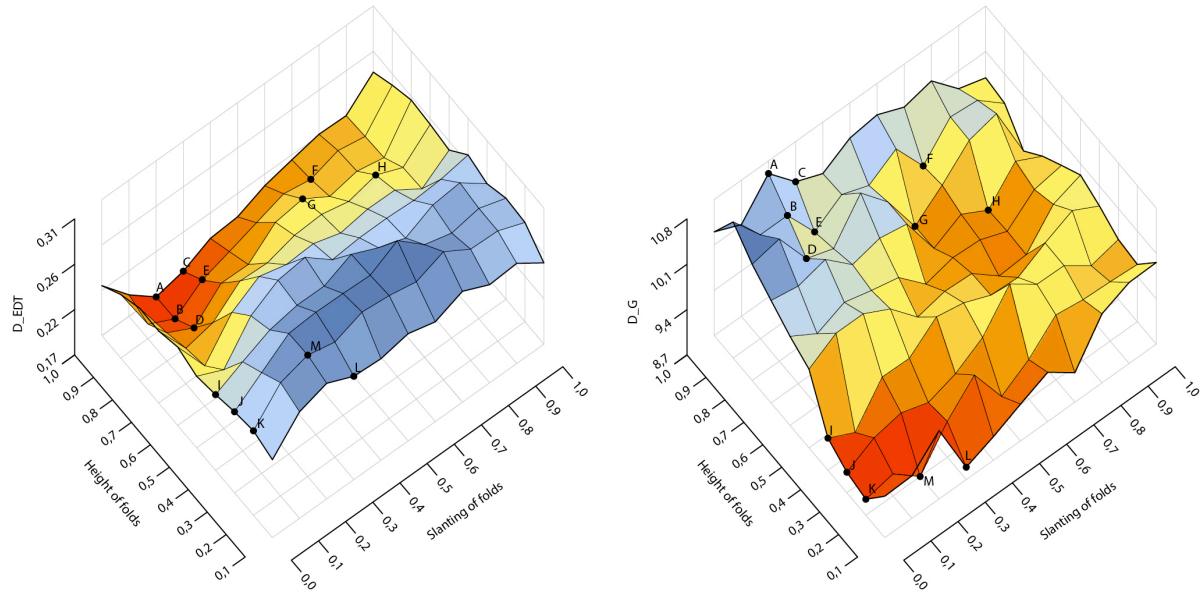


Figure 6: Fitness landscapes of benchmark 1.

### 5.3. Benchmark 2

For the second benchmark the full methodology is implemented in the optimization of a more complex geometry. A folding based on the before mentioned Miura Ori pattern is defined with 4 parameters giving a parameter space far too large for an exhaustive search. 2 parameters are the same as in benchmark 1, while 2 new parameters are introduced, see table 6 and figure 7.

Table 6: Parameters of benchmark 2

Parameters		Domain
$f_1$	Number of folds in y direction	6
$f_2$	Number of folds in x direction	2 to 5
$h$	Height of folds	0,1 to 1,0
$s$	Slanting of folds	0,0 to 1,0
$d_{revfold}$	Depth of the reverse fold	-1,0 to 1,0



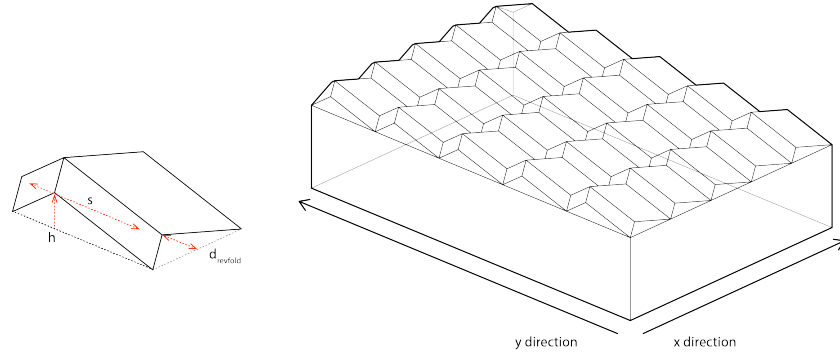


Figure 7: Benchmark 2

With more than 3 objectives in the optimisation search, an issue arises when plotting the Pareto front in objective space. In this case the objective space is 4-dimensional and simply plotting solutions along three objective axes and getting a clear and understandable Pareto front is unlikely. The issue can be seen in figure 8 on the left, where the complete Pareto set is plotted in a 2D objective space, according to  $D_{EDT}$  and  $D_G$ . The Pareto front consist of all these solutions, but it does not look as clearly defined as described in figure 1. This is because even if some solutions appear to be dominated in a 2d (or 3d) plot, dominance is evaluated according to the ‘hidden’ objectives as well, so they are in fact non-dominated when considering the  $D_{C50}$  measure and displacement not shown in the plot. In figure 9, the  $D_{C50}$  measure is excluded from the plot of the Pareto front in the objective space, because both  $C_{50}$  and EDT relates to the relationship between early and late sound and are in this study non-contrasting objectives, as it can be seen in figure 8 on the right.

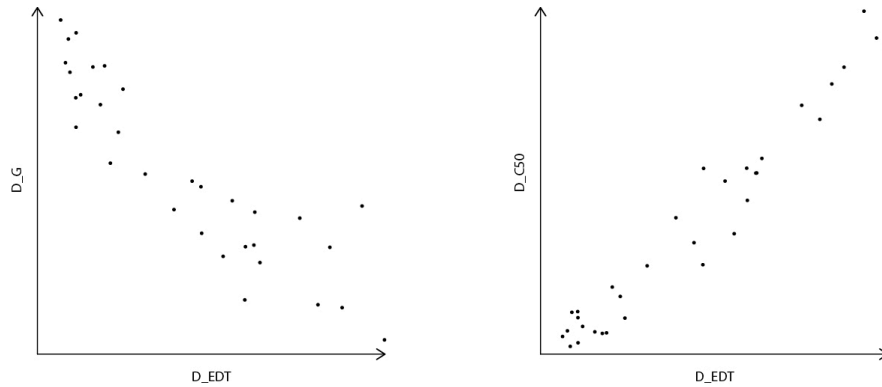


Figure 8: Complete Pareto set plotted in 2D objective space

Table 7: Examples of Pareto solutions

Parameter values	A	B	C	D	E	F
$f_1$	6	6	6	6	6	6
$f_2$	3	5	4	3	3	3
$h$	1,0	1,0	1,0	0,6	0,8	0,3
$s$	0,2	0,3	0,3	0,1	0,2	0,1
$d_{revfold}$	0,9	1,1	1,1	1,6	0,3	0,6
Objective values	A	B	C	D	E	F
Displacement (m)	0,0008	0,0008	0,0008	0,0025	0,0016	0,0071
$D_{C50}$ (dB)	5,73	6,66	11,82	7,66	8,79	11,14
$D_{EDT}$ (s)	0,17	0,19	0,29	0,24	0,25	0,30
$D_G$ (dB)	10,61	9,62	9,32	9,36	9,05	8,40

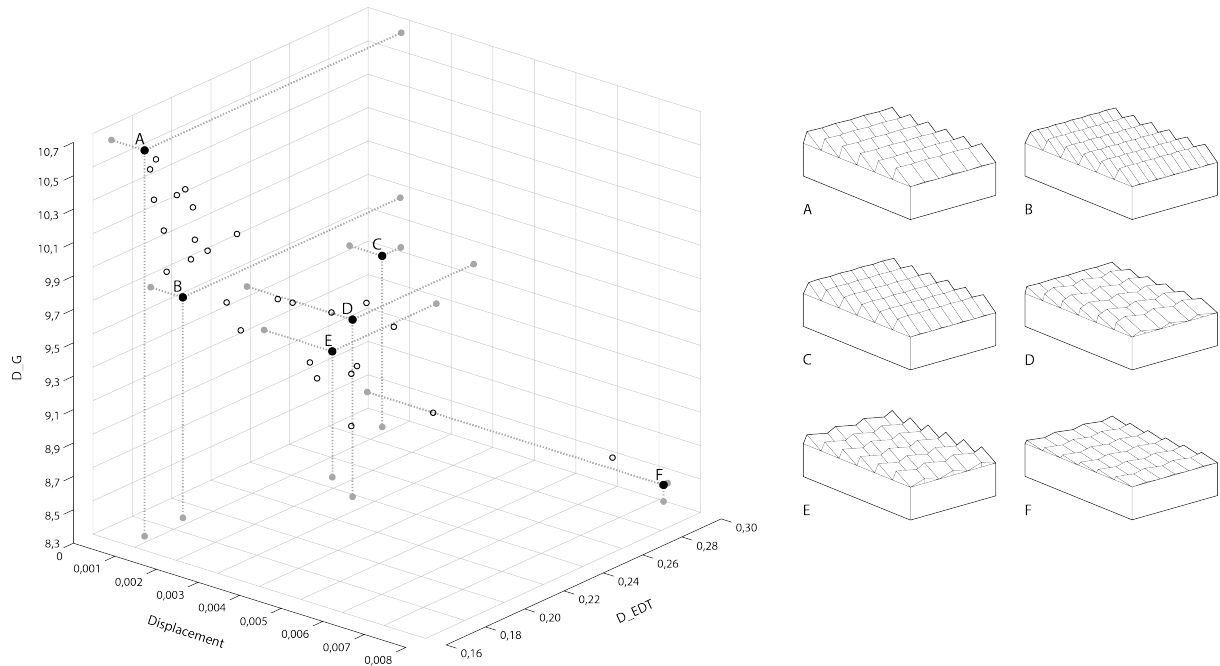


Figure 9: Pareto front of benchmark 2 with highlighted solutions

In figure 9 the Pareto set is plotted in objective space, with 6 highlighted solutions also projected into 2-dimensional objectives spaces for clearer understanding of their positions in relation to each other in the 3D plot. The 6 highlighted solutions, see also table 7, illustrates two qualities of the optimised solution set that are very relevant to the architectural design process. The Solutions A, B and C demonstrate that solutions with very similar geometrical traits can have quite different acoustical performance, while solutions D and E demonstrate the opposite; very different geometries with similar acoustical performance. Solution F is highlighted as well to present the diversity of the resulting set of solutions that all can be said to have optimised performance regarding the chosen fitness functions.

## 6. Conclusion and future work

The two benchmarks demonstrates the potentials in applying multi-objective optimization in the design of folded plate structures in relation to structural and acoustic performance by controlling directionality of panels in a folded plate structure. The search process results in a set of optimised solution, where no solution can be said to be better than others on the basis on the chosen fitness functions. In context of the architectural design process, it is clear that the final decision making of the designer is necessary. The search process shrinks the field of feasible design solutions, but subsequent decision for boundary conditions for the fitness functions, weighting of importance of each objective and general architectural qualities are entirely in the hands of the designer, and thus the methodology acts as an aid to the designer rather than determining the outcome.

The benchmarks done in this paper are of parametric models of geometries with global parameters only, so a single parameter value is applied to all folds in the geometry. Further studies into generating and optimizing folded geometries where true local variation of the folded panels are possible will be interesting, possibly within the framework of applying this method to a case study of a specific building design.

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