

TECHNICAL WHITE PAPER

Design of Experiments at the Concept Stage

In mechanical engineering, concept selection commits most of a part's life cycle cost, yet rarely relies on a systematic comparison of alternatives. This paper examines how design of experiments applied at the concept stage addresses this gap.

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Executive summary

In mechanical design, design of experiments (DoE) is mostly applied at the detailed design stage, once the topology family, the material, the manufacturing process and the mass budget have been fixed. These decisions are therefore taken **without a systematic comparison of alternatives**, largely because the tools available at the concept stage did not allow complete concepts to be generated and evaluated on performance, manufacturability, cost and CO₂ at an acceptable cost.

The consequences are significant because most of a part's cost and environmental impact is committed at that stage. NASA reports that **about 75% of life cycle cost is committed** at the end of design, while about 15% has been spent [1], and the European Commission estimates that **up to 80% of a product's environmental impact** is determined at the design phase [2]. Topology optimization, the usual concept generator for load-bearing parts, converges to a local optimum on a limited number of objectives, and its output must be rebuilt in CAD before manufacturability, cost or CO₂ can be assessed [3, 4].

This paper describes **DoE applied to the concept stage**. The inputs that generate the geometry are sampled systematically, each point of the plan yields a complete concept evaluated on the same KPIs, and **multi-criteria exploration** supports a traceable selection. An implicit geometry engine and a parametric workflow allow each variant to be generated and evaluated without manual intervention, in **minutes of compute instead of hours of engineer time**.

In an industrial case on a steel cantilever bracket, a sweep of the optimizer's inputs produced concepts of similar mass (≈ 180 g) whose **safety factors ranged from 3.79 to 8.71**. A concept about 21% lighter reached a safety factor of 7.20. The branched concept outperformed the sheet-like concept on stress and safety factor but not on stiffness, and the customer retained the sheet. The 30 concepts required about two hours of compute on a local workstation, the duration of a single manual iteration.

Three observations follow:

- **A single optimization run is one sample of the design space**, not a characterization of it.
- **Trade-offs between criteria become visible only when many concepts are compared** on the same KPIs: a small loss on one criterion can correspond to a large gain on another.
- **Visual appearance is a poor predictor of performance**. In this case, the organic-looking concept performed better on stress and worse on stiffness; the appropriate choice depends on the governing requirement.

1 The concept stage today: decisions lock early, exploration stays narrow

Two problems coexist at the concept stage. The first is **economic**: most of a part's cost and impact is determined there, while few concepts are compared. The second is **methodological**: the main concept generators explore the neighborhood of their starting point, on a limited number of criteria.

1.1 Cost, impact and CO₂ are committed before they are spent

Material, manufacturing process, mass, part count and assembly sequence all follow from the selected concept; later phases mainly refine it. The NASA Systems Engineering Handbook indicates that at the end of the design phase about 15% of life cycle cost has been spent, whereas **about 75% has been committed** [1].

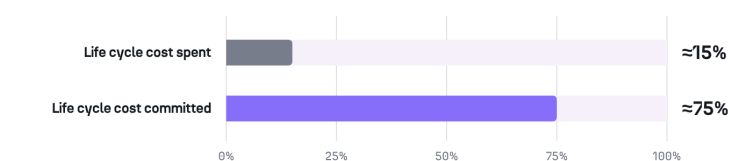
Late changes are costly. A requirements error that costs 1 unit to correct at the requirements phase costs **3 to 8 units in design and 21 to 78 in integration and test** [5]. In a survey of more than 90 Danish engineering companies, engineering changes accounted for **almost one third of R&D capacity** [6].

The same reasoning applies to CO₂. At Airbus, direct emissions and emissions

from purchased energy represented **0.4% of total CO₂ emissions** in 2023, the remainder arising in the value chain [9]; iron and steel production accounts for about 7% of energy-system CO₂ emissions [10]; and the EU Ecodesign Regulation lists carbon footprint among the requirements that may be set for product groups [11]. When cost and CO₂ are estimated after the concept is frozen, they can confirm a choice but **can no longer inform it**.

At the end of the design phase

FIG. 1



Source: NASA Systems Engineering Handbook, Rev. 2 (NASA/SP-2016-6105), Fig. 2.5-1. Program level, not a single part.

Fig. 1. Life cycle cost committed vs spent at the end of design. Source: NASA Systems Engineering Handbook, Rev. 2 [1].

1.2 Why so few concepts are compared

The concept stage combines the lowest cost of change with the lowest level of exploration. Three mechanisms contribute to this:

- **Cost per concept.** Each concept must be modeled, meshed, simulated and costed before it can be compared; with a sequential CAD, simulation and manufacturing review loop, only a handful of options are typically assessed.
- **Sequential criteria.** Performance is usually assessed first, manufacturability during detailed design, and cost and CO₂ last. A requirement missed late in development leads to an engineering change, sometimes to a dedicated **weight-saving campaign**. The limiting factor is primarily the tooling: **feature-based CAD** makes it costly to evaluate every KPI on every candidate concept.
- **Design fixation.** Designers tend to remain close to the first concepts they see or produce, independently of skill or experience [7]. Tools that return one shape per run reinforce this tendency.

1.3 The limits of topology optimization and generative design at the concept stage

Topology optimization and the **generative design** methods derived from it are the usual means of generating a first concept for load-bearing parts; generative design returns several outcomes, typically one per material or manufacturing process. Used as concept generators, both present five limitations:

- **Local optimality.** The underlying problem is non-convex: a gradient-based optimizer converges to the nearest local optimum, and level set methods, which move the part boundary described as the zero level of a function, depend strongly on the initial design [3]. Each generative outcome corresponds to one such run.
- **No experimental plan.** Generative design varies the parameters exposed by the tool, such as a material or a process preset. The engineer does not define factors and levels, cannot estimate the effect of each input, and cannot rerun the same plan on another part.
- **Limited objectives.** The standard formulation minimizes compliance for a given volume; cost, CO₂ and manufacturability remain outside it, and multi-objective Pareto fronts require design space sampling to be resolved [8].
- **Geometric post-processing.** Results are dense, faceted geometries; in a survey of 85 users, **49%** cited a feature-based CAD model of the result as their first need [4]. Each concept therefore carries a rebuild cost.
- **Manufacturing constraints outside the loop.** Many processes cannot be expressed as optimization constraints [4], so manufacturability is verified after the fact.

Where an optimizer stops depends on where it starts

FIG. 2

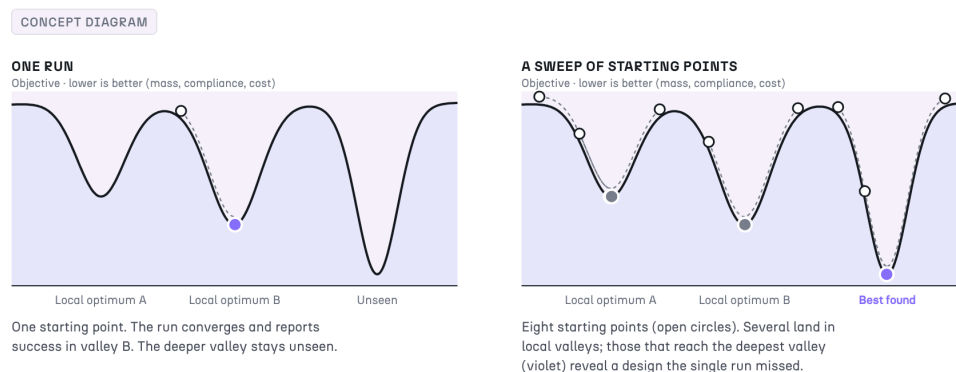


Fig. 2. Where an optimizer stops depends on where it starts. Each point on the horizontal axis stands for a complete design. A real design space has thousands of dimensions, but the behavior is the same: gradient descent finds the bottom of the nearest valley.

At the concept stage, a single run, or a small set of generative outcomes, should therefore be regarded as a sample of the design space rather than as its optimum.

IMPLICATION

The limited exploration observed at the concept stage is better explained by the cost of each evaluation than by engineering practice: when each concept requires hours of modeling, simulation and costing, the decisions that determine most of the cost, mass and CO₂ of a part are taken on the least comparative data of the program.

2 DoE applied to the concept stage

The method consists of sampling the inputs that generate the geometry, generating a complete concept at each point, evaluating every concept on the same criteria, and selecting with the full set in view. The statistical foundations are well established; what changes is **the content of each run** and the technology that allows the plan to run without manual intervention.

2.1 The principle of design of experiments

Design of experiments (DoE) is a family of methods for selecting the combinations of inputs to test, so that a limited number of runs provides as much information as possible on how the inputs affect the outputs [12]:

- **Full factorial** designs test every combination and separate main effects from interactions, but their size grows rapidly: three factors at three levels require 27 runs, five require 243.
- **Fractional factorial** and **Taguchi** designs retain a balanced subset, at the cost of confounding some interactions.
- **Latin hypercube sampling** distributes a fixed number of runs evenly over continuous ranges [13]. Because computer experiments are **deterministic**, replication and randomization are not required.

DoE term	Meaning	At the concept stage
Factor	An input that is varied	Start layout, volume target, filter or smoothing setting, material
Level	A value a factor takes	Start layout off or on; volume fraction 0.25, 0.30, 0.35
Run	One combination of levels	One complete concept, generated then evaluated
Response	A measured output	Mass, stiffness, peak stress, safety factor, manufacturability, cost, CO ₂
Plan	The set of runs	The sweep

2.2 Parametric CAD DoE vs DoE applied to the concept stage

In mechanical engineering, DoE is mostly applied at the detailed design stage: the geometry is frozen in a **parametric CAD model**, and the plan varies a few dimensions to tune it. This practice reflects a tooling limitation rather than a methodological choice: a feature-based CAD model rebuilds reliably only while its topology is unchanged, and each variant requires its own meshing and setup, which makes DoE practical only once the concept is fixed. At the concept stage, **each point of the plan is a complete concept, generated then evaluated**, and two runs may belong to different topology families. The question addressed becomes **which type of part is appropriate**, rather than how much a given dimension matters.

	Parametric CAD DoE	DoE applied to the concept stage
What varies	Dimensions of a frozen geometry	Inputs to geometry generation
What one run produces	A version of the same part	A complete concept, possibly from another topology family
When it is used	Detailed design, tuning	Concept stage, choosing
What is read at the end	Effect of each factor on a response	Trade-offs between criteria across concepts

Parametric CAD DoE vs DoE applied to the concept stage

FIG. 3

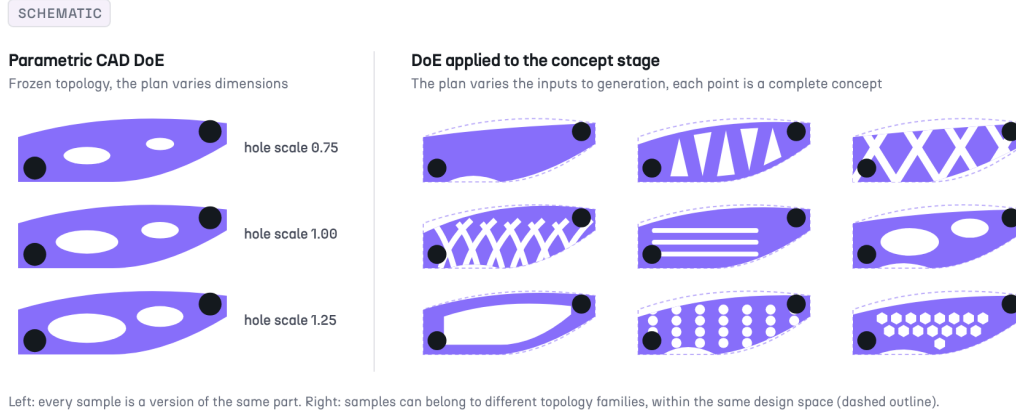


Fig. 3. Parametric CAD DoE vs DoE applied to the concept stage. Left: the topology is fixed and the plan varies dimensions. Right: the plan varies the inputs to generation, so samples can belong to different topology families.

Relevant factors include **inputs to generation**, **materials**, **design space and load variants**, and **manufacturing constraint settings**. The sweep is **systematic, not exhaustive**: it covers the ranges defined by the engineer. Manufacturing processes are compared in separate workflows; the DoE does not recommend a process.

2.3 Two technological enablers

A concept-stage DoE is useful only if every run is **automatic, robust, computationally affordable and traceable**; otherwise, the plan reduces in practice to a few concepts. Two building blocks address these requirements:

- **Implicit modeling.** Geometry is represented as a **scalar field over the volume** rather than as surface patches driven by a feature history [14]. Boolean operations and blends remain valid on organic shapes, holes and branches can appear or merge, and every concept is a closed volume that can be evaluated directly, without CAD reconstruction.
- **Parametric design workflow.** The chain from inputs to KPIs (geometry, analysis, manufacturability, cost and CO₂) is **defined once** and executed at every point of the plan. All concepts are evaluated identically, the plan runs unattended, each result is traceable, and the workflow can be reused for other parts of the same family.

Two technological enablers for a concept-stage DoE

FIG. 4

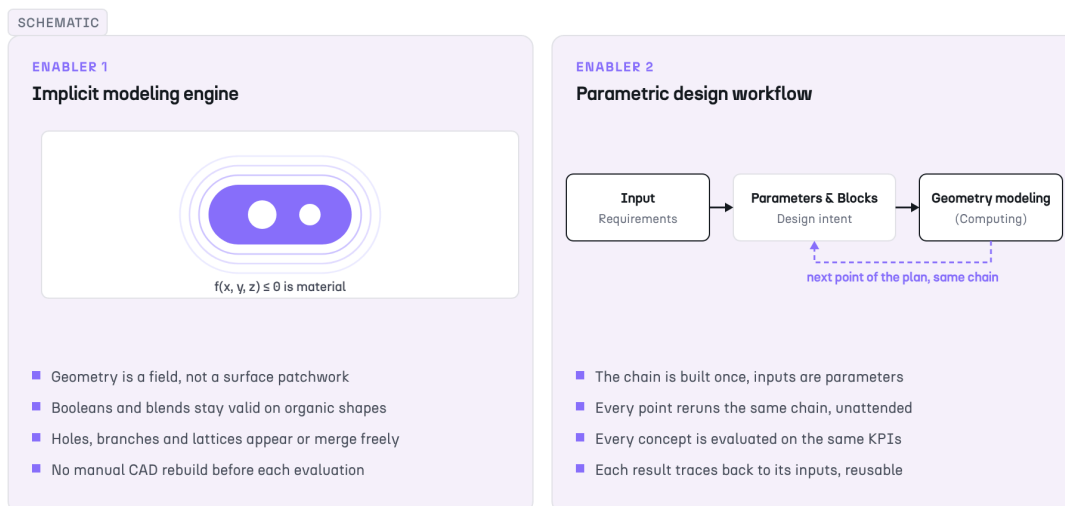


Fig. 4. Two technological enablers for a concept-stage DoE: geometry as a field (left) and a workflow built once and rerun for every point of the plan (right).

2.4 The bottleneck moves from engineer hours to compute time

In a manual loop, effort grows in proportion to the number of concepts. In a concept-stage DoE, each variant requires **minutes of compute** and can run in parallel, while the engineer's effort (setup before the sweep, review after it) remains **nearly constant** whether the plan contains 8 concepts or 80. The appropriate fidelity is the one that **ranks concepts correctly**; detailed validation follows the selection.

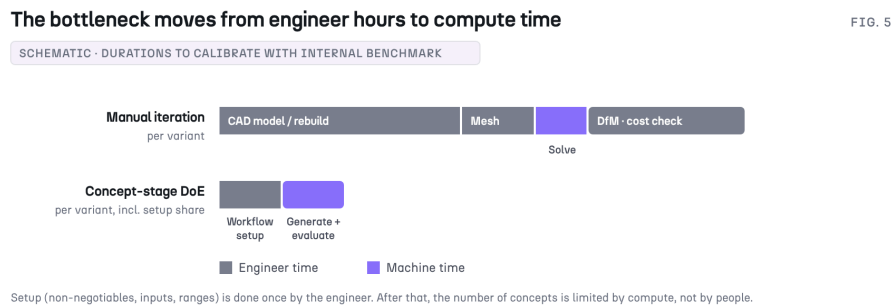


Fig. 5. The bottleneck moves from engineer hours to compute time (schematic). Measured durations for the case are given in Section 4.

IMPLICATION

For engineering management, the relevant variable is no longer the number of concepts a team can afford to model, but the number of concept decisions taken without a comparison of alternatives. When a variant costs minutes of compute, limiting the comparison to the first converged concept is no longer imposed by the tools.

3 From a set of concepts to a decision: multi-criteria exploration

A sweep yields a set of concepts and their KPIs rather than a design. Reading that set and selecting a concept constitute **multi-criteria exploration**; the DoE itself does not select the design. Fig. 6 summarizes the method in seven steps.

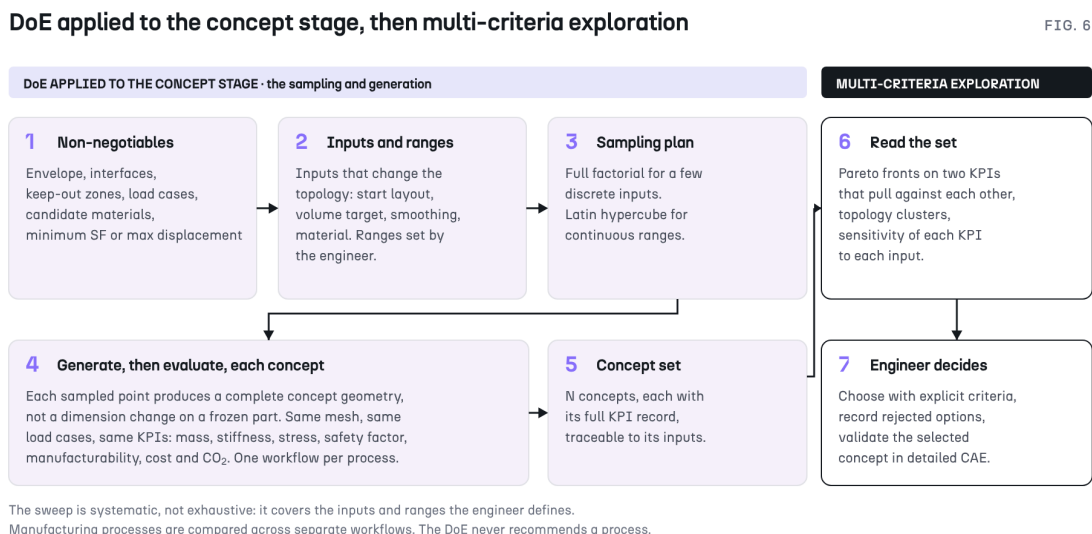


Fig. 6. Method flow: DoE applied to the concept stage (sampling and generation), then multi-criteria exploration (reading the set and deciding).

Before the sweep. The engineer first defines the **fixed requirements**: envelope, interfaces, keep-out zones, load cases, candidate materials, and a minimum safety factor or maximum displacement. The inputs that may change the topology, and their ranges, are defined next. These choices determine what the set can contain and therefore warrant more attention than the sweep itself.

After the sweep. For high-performance parts, KPIs are typically in conflict, and a set of 50 concepts described by six KPIs cannot be ranked visually. Three analyses provide most of the information:

- **Pareto fronts on two conflicting KPIs**, such as mass and safety factor, identify the concepts that cannot be improved on one criterion without degradation on the other, and the regions where a small concession yields a large gain.
- **Topology clusters** indicate whether high-performing concepts belong to one family or to several, which informs the robustness of the selection.
- **Sensitivity of each KPI to each input** identifies the influential settings and those that can be fixed for subsequent parts.

Selection and documentation. The selection is made on explicit criteria, rejected options are recorded with the reasons for rejection, and the selected concept is validated with detailed CAE. This record makes the decision auditable in later design reviews.

4 Field evidence: a steel cantilever bracket, explored in several batches

Context. A Japanese industrial equipment manufacturer optimized the same steel cantilever bracket with a density-based solver (SIMP, in which the material density of each element is a design variable) and with the level set method implemented in Cognitive Design, and obtained **two markedly different shapes**. A concept-stage DoE, run in Cognitive Design, was used to explain the difference.

Role of the initial layout. Level set methods move the boundary of the part and rarely nucleate new holes, so **the final topology depends on the initial design** [15]. The **Start Design** function seeds a grid of holes before optimization, which allows branches to form.

Setup. All runs used the same load case, material and settings, except for the swept inputs:

Held constant	Value	Swept	Levels
Method; material	Level set topology optimization; structural steel	Start Design (seeded holes)	Off / On (Cartesian grid, 10 mm spacing, Z direction)
Volume fraction; resolution	0.30; 100,000 cells	Smoothing frequency	0 / 3
Refinement level; max. iterations	0.20; 45	Further batches	Other optimizer settings

The sweep produced **30 concepts** in several batches, at about **4 minutes of compute per concept** on a local workstation. The complete sweep therefore required about two hours, which the CDS application team estimates as the duration of a single manual iteration on a comparable part; 30 manual iterations would have required about **60 hours of engineer time**.

Observation 1: an organic shape does not imply better performance. With identical settings, activating Start Design changed the **topology family** from a sheet to a branched structure. The branched concept shows **8.1% lower**

peak stress and an **8.9% higher safety factor** for 1.2% more mass, while the sheet deflects 4.4% less, consistent with published results on stiffness-optimal layouts [16].

Same settings, different start layout, different part

FIG. 7

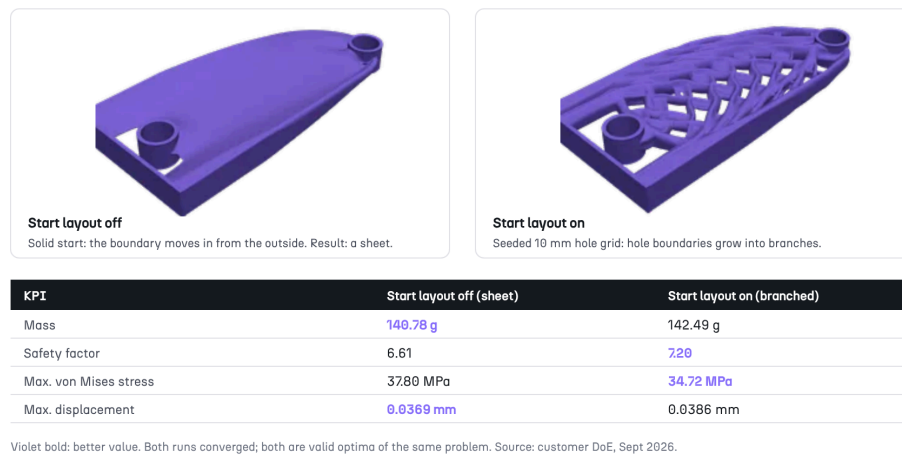


Fig. 7. Same settings, different start layout, different part. Violet: better value for each KPI.

Observation 2: mass alone does not rank concepts. At about 180 g, the **safety factor ranges from 3.79 to 8.71**. The branched concept reaches 7.20 at 142.5 g, **21% lighter** than the stiffest concept of that group. Whether the additional 37 g is justified depends on whether stiffness or strength governs the design.

Every concept in the DoE, by stiffness and mass

FIG. 8

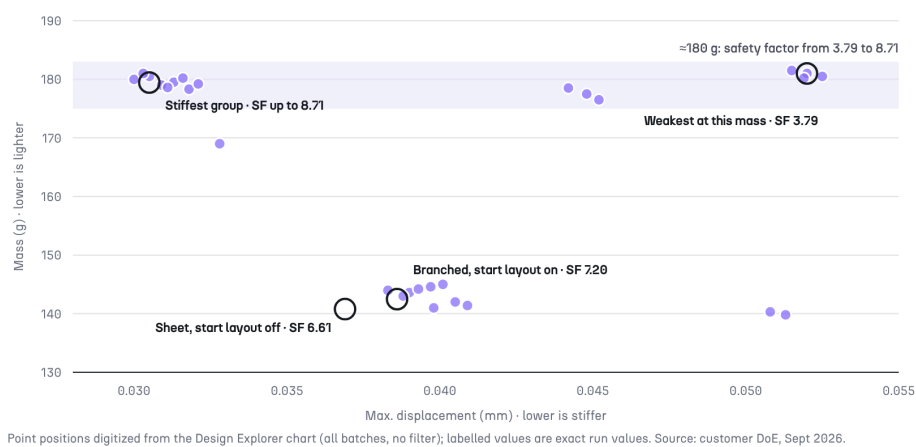


Fig. 8. Every concept in the DoE, by stiffness and mass. Point positions digitized from the Design Explorer chart (all batches, no filter); labeled values are exact run values.

Observation 3: the initial layout selects the family; smoothing adjusts within it. In a 2×2 full factorial (Fig. A3), Start Design increases the safety factor by **0.59 to 1.10**, whereas smoothing increases it by 0.52 without Start Design and by 0.01 with it. These effects are specific to this bracket and should not be generalized.

Cost and selection. Mass is a first-order proxy for material cost; a **cost and CO₂ model** can be added once the process is known. The customer retained the **sheet concept generated without Start Design**, which is lighter and stiffer than the branched concept, and validated it with its usual FEA tool. **Concept-stage fidelity serves selection; detailed CAE serves sign-off.**

5 Conclusion: moving the DoE upstream

Two observations coexist in most design offices. Most of a part's cost, mass and CO₂ is fixed at the concept stage, and the concept stage is where the fewest alternatives are compared. Topology optimization and generative design produce concepts one run at a time, mostly on few criteria. Design of experiments, the method developed to compare alternatives systematically, is applied only once the concept is frozen, to tune dimensions on a parametric CAD model.

This sequence was rational. As long as each concept-stage variant required hours of rebuild, meshing and checks, a systematic plan was out of reach, and engineering effort was concentrated where the geometry was stable. That constraint is now being lifted. When generating and evaluating a complete concept becomes a matter of compute rather than engineer time, the economics of the concept stage change: exploring several families of concepts costs less than correcting an inappropriate choice later, and the design office can document why a concept was selected, not only that it meets its requirements. A comparison that was previously implicit, based on individual judgment and a few criteria, can become explicit, systematic and traceable. The relevant question is then no longer which optimizer performs best, but **when the comparison takes place, and on how many criteria.**

Three questions help a team assess its current practice:

1. How many complete concepts were compared before the concept review?
2. Were they compared on performance, manufacturability, cost and CO₂, or on performance alone?
3. Could the team explain, six months later, why the selected concept was chosen?

Answers such as "a few," "performance only" and "not with certainty" indicate that the comparison takes place after the decisions it should inform.

From method to practice. Cognitive Design, developed by Cognitive Design Systems, is designed for this approach. Engineers chain generative design, design for manufacturing, simulation, and cost and CO₂ estimation in one parametric workflow, run it as a DoE on a robust implicit geometry engine, and compare every concept in an interactive results explorer that keeps each concept linked to its inputs and KPIs, so the set can be filtered and ranked on several criteria at once. It is used during the concept phase in aerospace, space, defense, automotive and industrial machinery.

Talk to an expert. To discuss how a concept-stage DoE could apply to one of your parts, request a conversation with a Cognitive Design Systems application engineer. [Contact link]

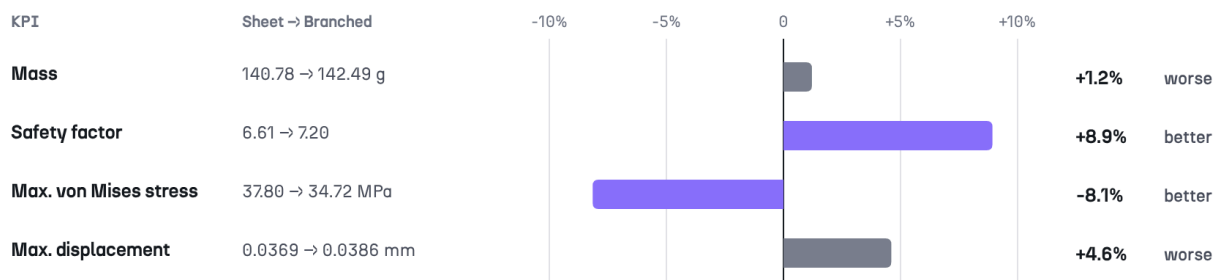
Annex A. Bracket case data

Run	Start Design	Smoothing	Mass (g)	Safety factor	Max. von Mises (MPa)	Max. displacement (mm)
Factorial 1	Off	3	140.78	6.61	37.80	0.0369
Factorial 2	Off	0	140.46	6.09	41.05	≈0.040 (read from chart)
Factorial 3	On	3	142.49	7.20	34.72	0.0386
Factorial 4	On	0	143.33	7.19	34.78	0.0390
Batch_2_004			179.45	8.71	28.70	≈0.030 (read from chart)
Batch_2_037			≈177 to 182	5.46		
Batch_2_068			≈177 to 182	3.79	65.88	≈0.052 (read from chart)
Batch_3_003			140.36	6.09		≈0.050 (read from chart)

Common settings: level set topology optimization, structural steel, volume fraction 0.30, 100,000 cells, refinement level 0.20, 45 iterations, strength 1.00. Values marked "read from chart" are digitized from the Design Explorer view and given to two significant figures.

Branched vs sheet: one input changed, four KPIs

FIG. A1



Steel cantilever bracket, level set topology optimization, volume fraction 0.30, smoothing 3.
 Start layout off (sheet) vs 10 mm seeded hole grid (branched). Violet: better value for that KPI. Grey: worse.
 Source: customer DoE, CDS Design Explorer data, Sept 2026.

Fig. A1. Change in each KPI from the sheet concept to the branched concept.

Mass alone does not rank concepts

FIG. A2

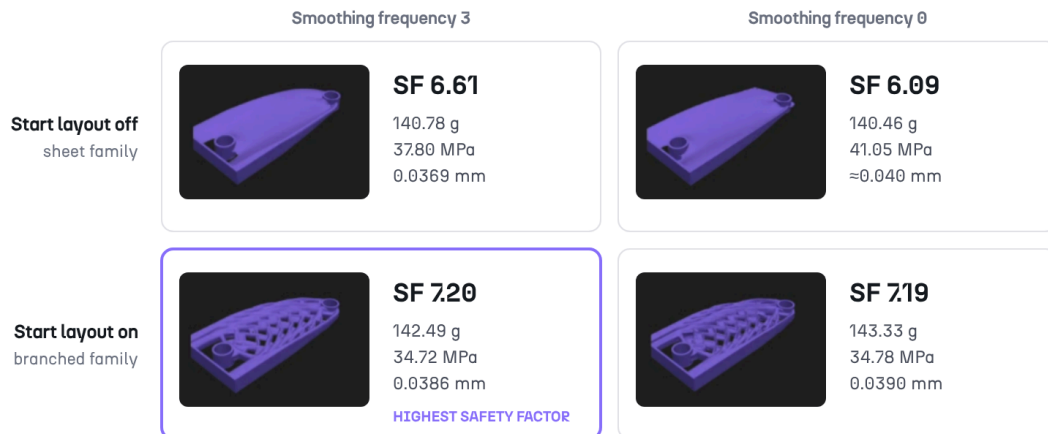


Fig. A2. Safety factor against mass for the four factorial runs and the ≈180 g group.

Two inputs, four runs: what drives the result

FIG. A3

2 × 2 FULL FACTORIAL



Effect on safety factor: start layout +0.59 to +1.10; smoothing +0.52 with the layout off, +0.01 with it on.

The start layout selects the topology family; smoothing tunes the result inside it. A result of this DoE on this part, not a universal recipe. Displacement for the run without start layout and smoothing 0 is read from the chart. Source: customer DoE, Sept 2026.

Fig. A3. Two inputs, four runs: what drives the result.

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Case data: customer DoE run in Cognitive Design, September 2026, published anonymized [customer agreement to confirm].