Robust design and optimization

Key methods and applications

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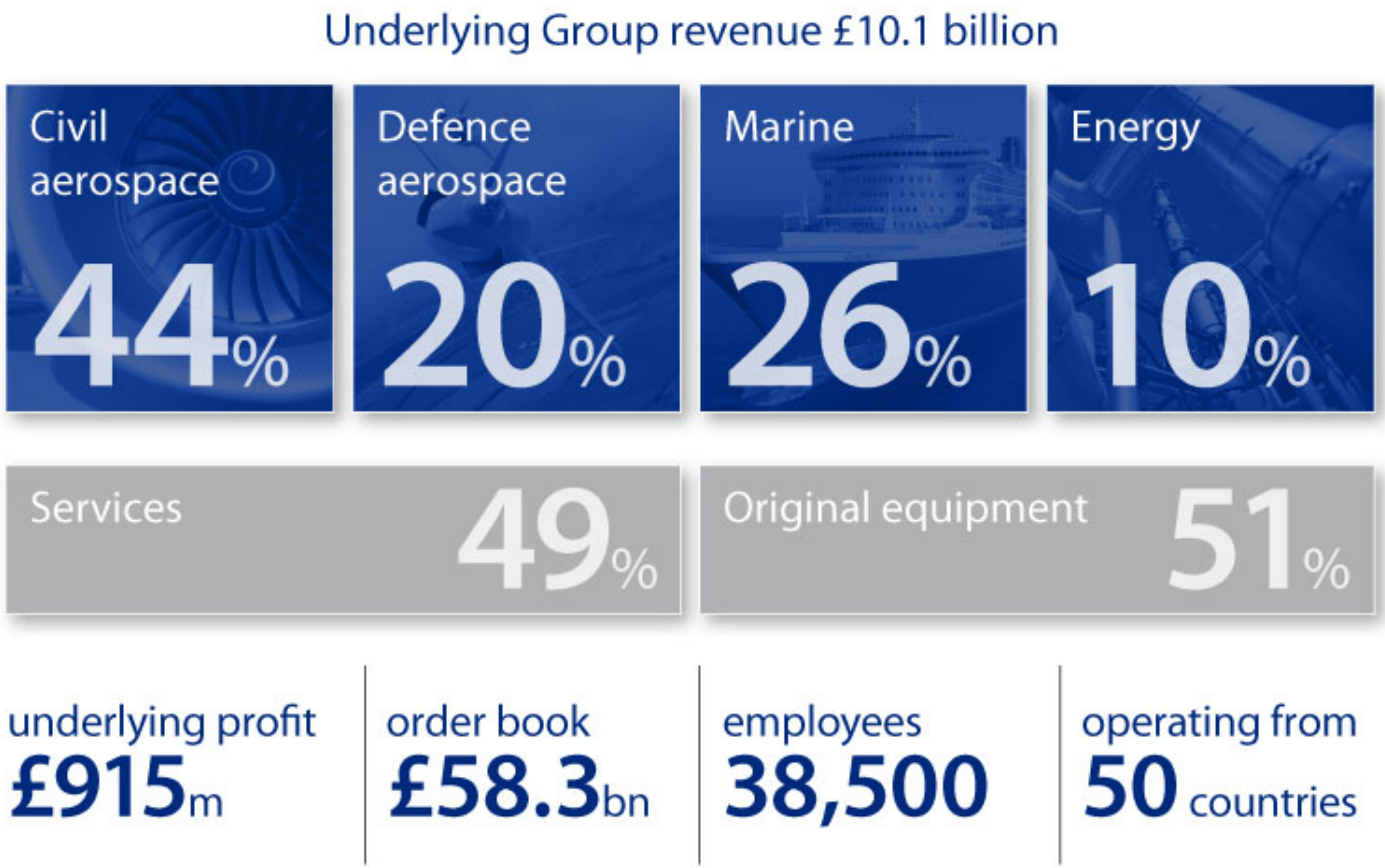
Reliability, integrity, innovation

Key statistics



Our current installed base

Group-wide 54,000 gas turbines in service globally

Civil aerospace

World No.2

650 airlines, freight operators and lease companies

4,000 corporate and utility operators

Defence aerospace

World No.2

160 defence customers

US Department of Defense is largest defence customer

Marine

World No.1

2,000 commercial customers

70 navies served

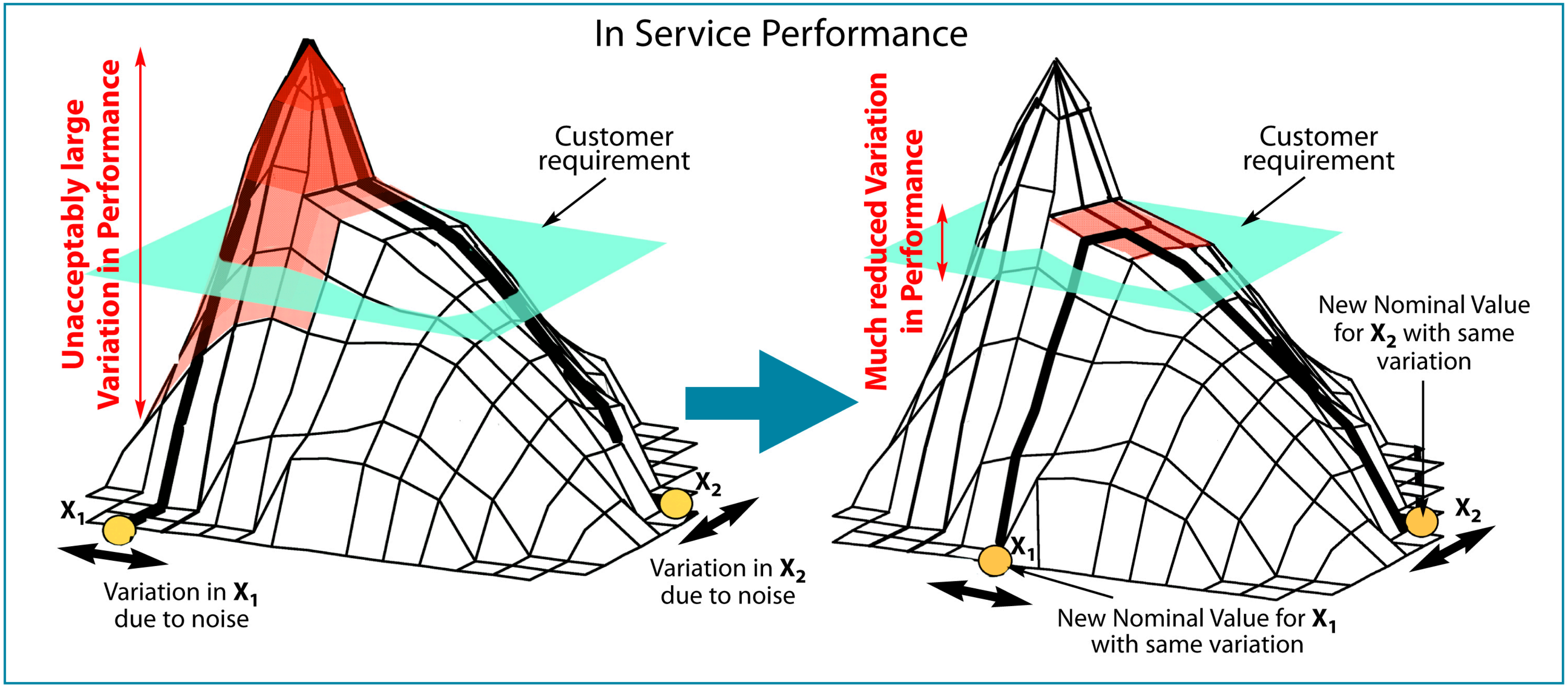
Energy

A substantial position in oil and gas pumping and compression

Customers in over 120 countries

Over 45,000MW of delivered electric power

What is robust design?



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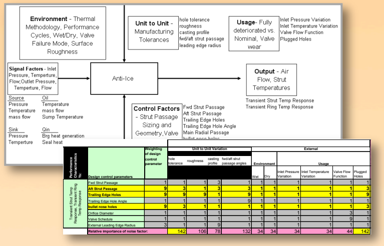
Robust design methodology

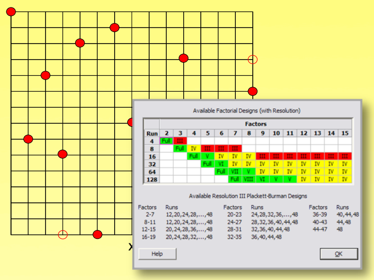
Define

- Understand what is important to the customer and translate into engineering language
- Choose design concepts with variation in mind



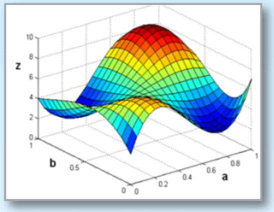
Characterize

- Generate measurable Critical-to-Quality (CTQ's) criteria for each level
- For each CTQ:
  -Understand the sources of variation
  -Measure the effects of variation



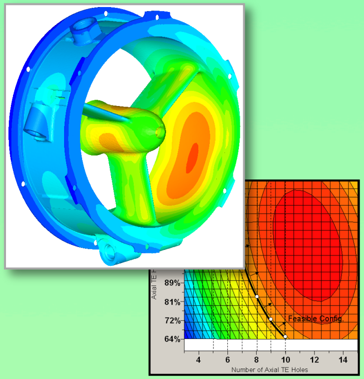
Optimize

- For each CTQ:
  - Choose and implement a strategy to reduce the effects of variation



Verify

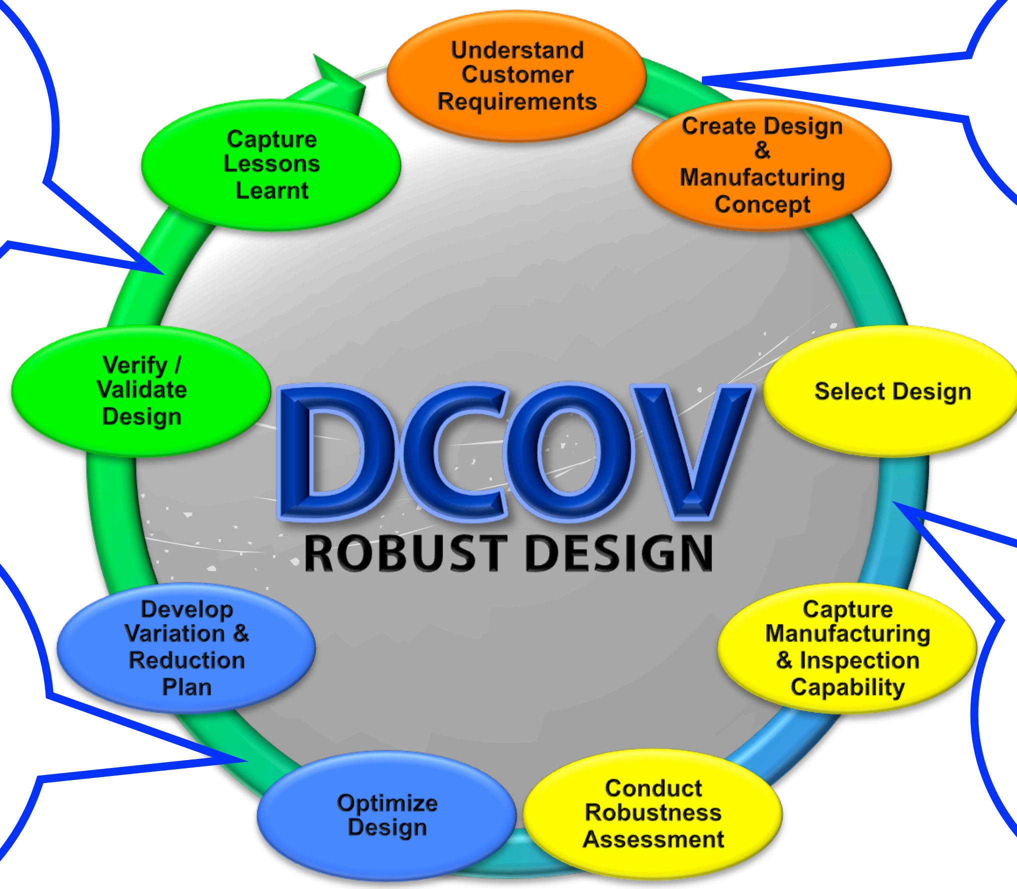
- Use knowledge of variation and its effects in construction and design verification plan



Robust design and the design process

Testing
Statistical process control
Reliability analysis
Hypothesis testing
Service feedback

Quality function deployment
Function means analysis
Design failure mode and effects analysis

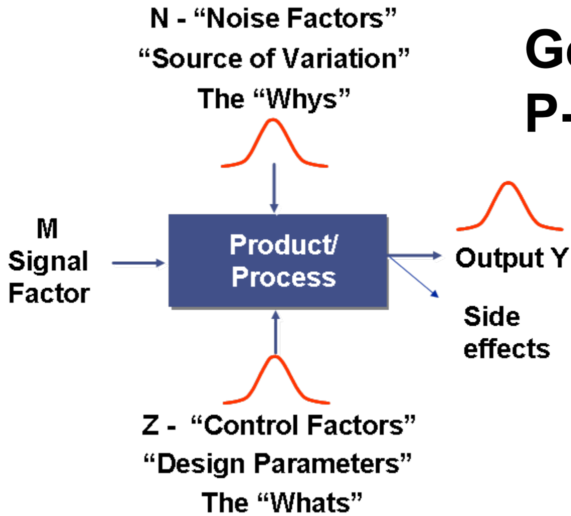


Parameter and tolerance design
Design of experiments
Response surface methods
Process failure modes and effects analysis

Parameter diagrams
Design of experiments
Manufacturing process capability
Robustness metrics
Surrogate modeling
Monte-Carlo simulation

DCOV methodology used as design framework

Basic principles of parameter and tolerance design as part of robust design



Generic P-diagram

Provided the inputs (x' s) are statistically independent, the Taylor series expansion gives the

Variation transmission equation

$$\sigma_Y^2 \approx \sigma_{X_1}^2 \left(\left. \frac{\partial Y}{\partial X_1} \right|_{x_1 = \mu_{x_1}} \right)^2 + \sigma_{X_2}^2 \left(\left. \frac{\partial Y}{\partial X_2} \right|_{x_2 = \mu_{x_2}} \right)^2 + \ldots = \sum_{j=1}^{k} \sigma_j^2 \left(\left. \frac{\partial y}{\partial x_j} \right|_{x_j = \mu_{x_j}} \right)^2$$

Tolerance design **Parameter design**

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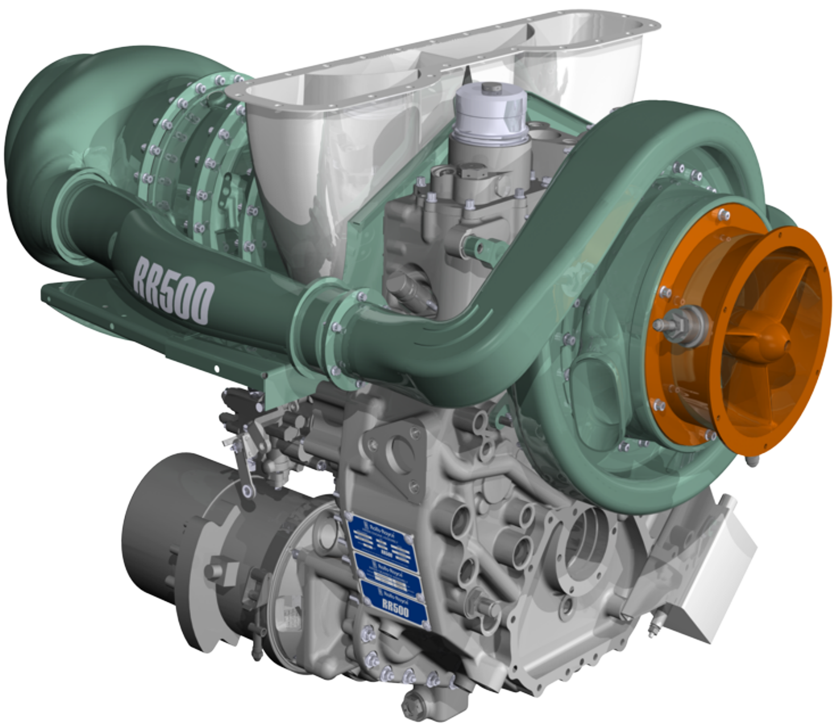
Case study: RR500 front support anti-ice system

- **Purpose**
  - To increase the metal temperature of the RR500 front support to prevent the build up of ice in extreme climates
- **Challenges**
  - Determining the best anti-ice configuration for both cost and performance
- **Goal**
  - Use robust design tools and methodology to minimize anti-ice air flow rate and manufacturing cost while satisfying product requirements



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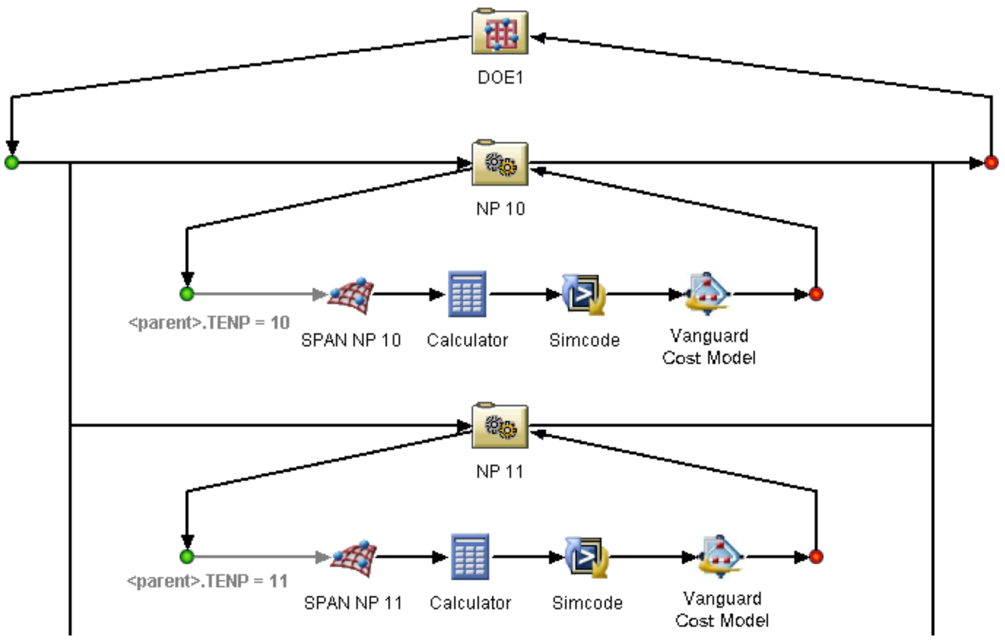
Analysis workflow

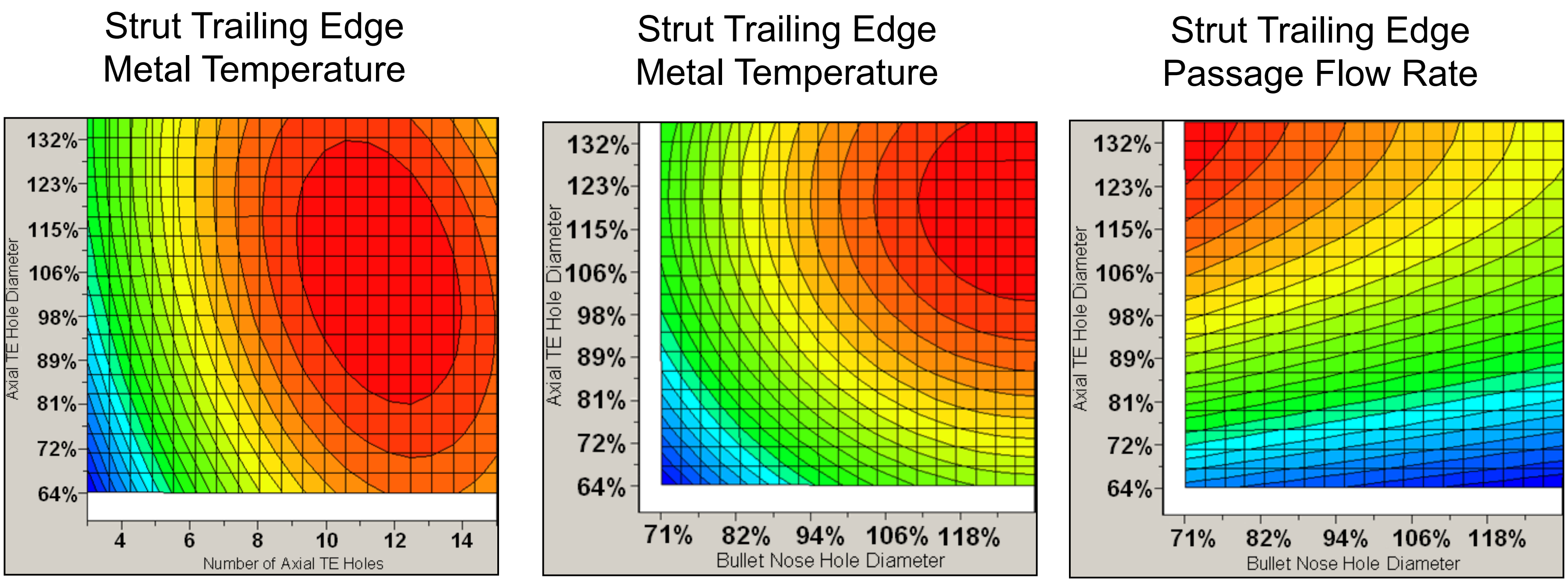
- Automated process includes:
  - 1-D flow solver
  - 3-D thermal finite element analysis
  - Manufacturing cost model



→ **Response surface models to describe the relationship between customer requirements and key input variables**

Assessing the design space

Main customer requirements:
metal temperature at key locations and required air flow rate



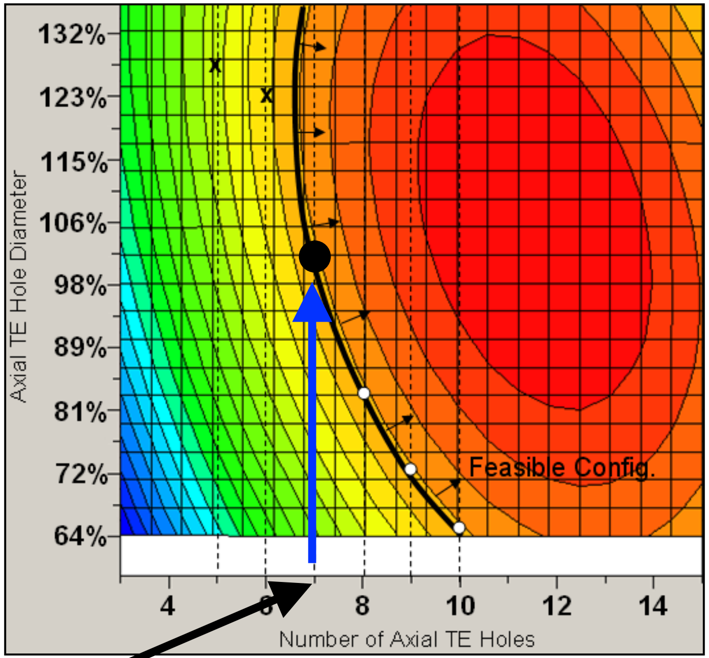
Axis values are key input parameters identified in the first steps of the robust design process (normalized with an arbitrary reference value)

Initial design selection

- **Optimization methodology applied to surrogate responses to generate optimal design configuration**
  - **Bullet nose holes: 94% dia. min**
  - **Radial aft passage: 96% dia. min**
  - **Axial TE holes: 102% dia. min**
  - **Number of axial TE holes: 7**

Strut Trailing Edge Metal Temperature

Minimum value needs to be achieved



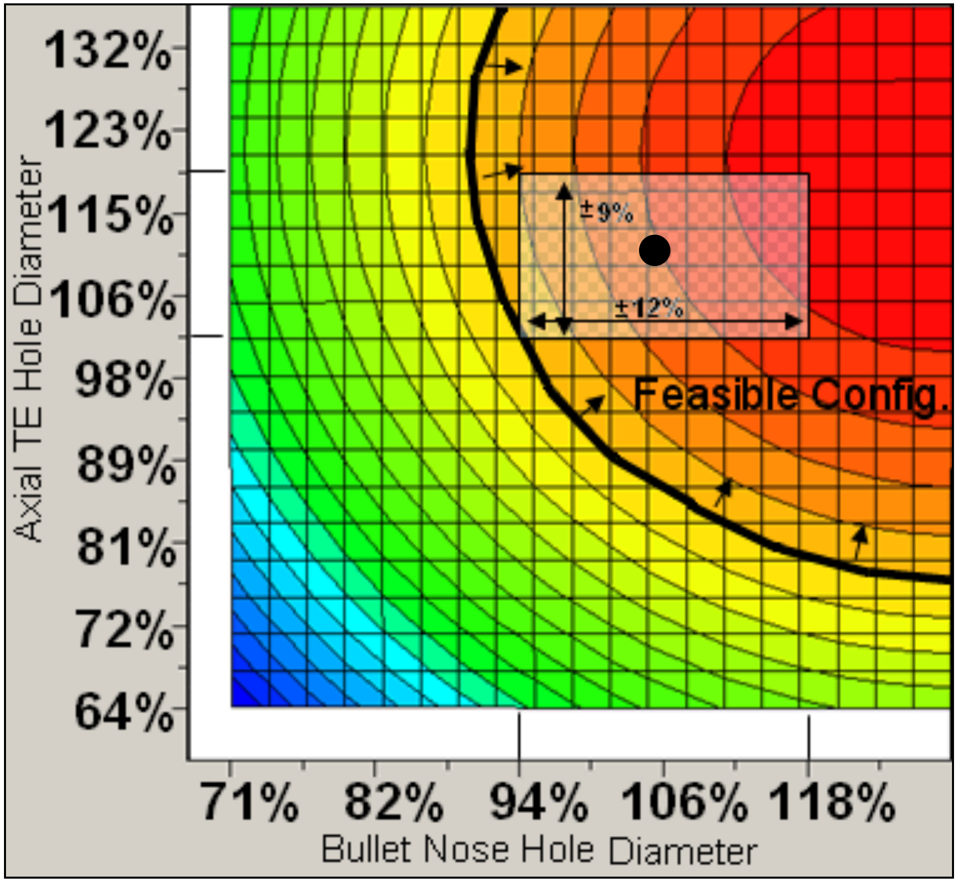
Sample visualization of optimization process:

Step 3: use other response surface models to determine the other parameters

Step 2: select axial TE hole diameter to satisfy temperature requirement

Step 1: Determine number of axial TE holes (least number of TE holes and lowest L/D minimizes manufacturing cost)

Assessing the design robustness and selecting a nominal design



- **Step 1: Collect manufacturing data and map onto the response model outputs (grey rectangle)**
- **Step 2: Ensure that the whole range is in the feasible area**
- **Step 3: Select the nominal design to sit in the middle of the manufacturing variation range (black dot)**

Summary

- Optimization and automated design help achieving better design by focusing the work on the key levers
- Simulation driven design allows a thorough design assessment early in a development program
- Robust design allows the consideration of variation in the design process and the appropriate selection of the nominal design point

Outlook

- Process integration, automation and robust design will be growing rapidly in the next few years
- Further developments and improvements in the available integration and optimization tools and methods will support this trend
  - The software and methods must be usable by the end user and not just by specialized methods and tool development areas.
  - The software and methods must offer a simple integration of key tools (CAD, FEA, cost, post processing, meshing, statistics, etc) used in industry
  - The software and methods must integrate with the emerging simulation data management tools to extend the principles currently used in the geometry world (data storage, versioning, workflows, etc.) into the analysis and simulation world