Evolution Strategies for Engineering Design Optimization

Evolutionary Computing in Practice
GECCO 2005

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Agenda

- The Task: Automotive Engineering Optimization
- Results
  - BMW Evaluation
  - VW Evaluation
- The Method: Evolution Strategies
- Other Examples

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Engineering Optimization

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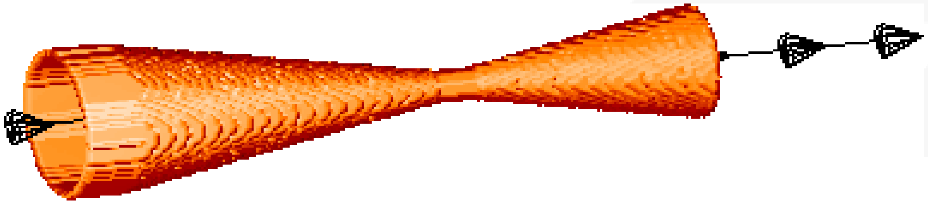
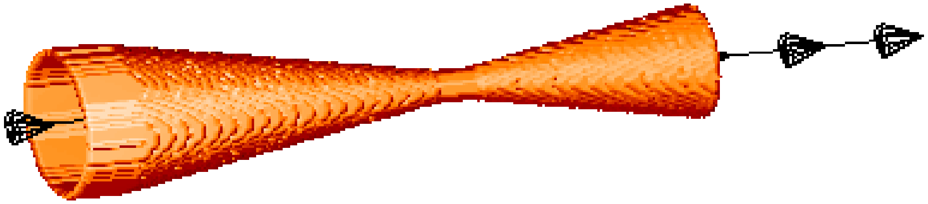
Optimization Creating Innovation

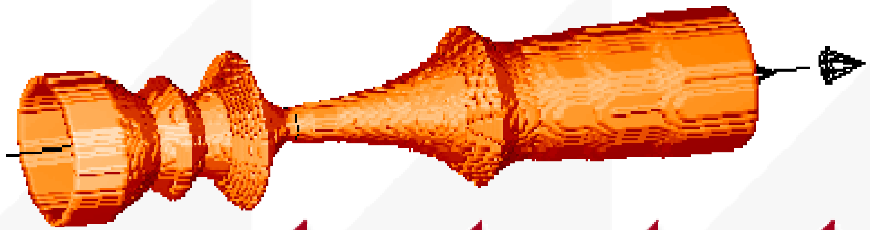
- Illustrative Example: Optimize Efficiency
  - Initial:



  - Evolution:



- 32% Improvement in Efficiency !



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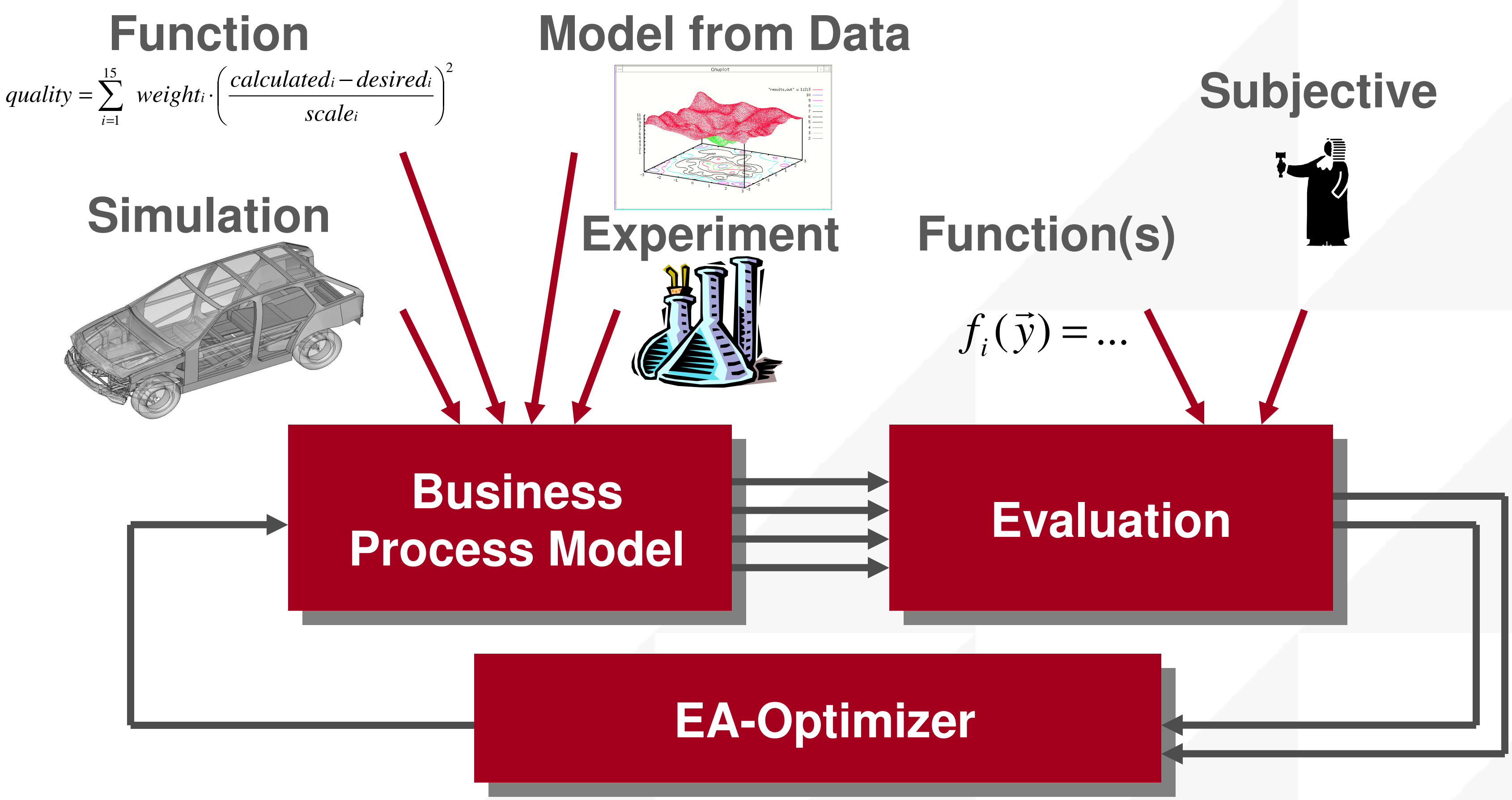
General Aspects



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Safety Optimization – Pilot Study

- Aim: Identification of most appropriate Optimization Algorithm for realistic example!
- Optimizations for 3 test cases and 14 algorithms were performed (28 x 10 = 280 shots)
  - Body MDO Crash / Statics / Dynamics
  - MCO B-Pillar
  - MCO Shape of Engine Mount
- NuTech's ES performed significantly better than Monte-Carlo-scheme, GA, and Simulated Annealing
- Results confirmed by statistical hypothesis testing

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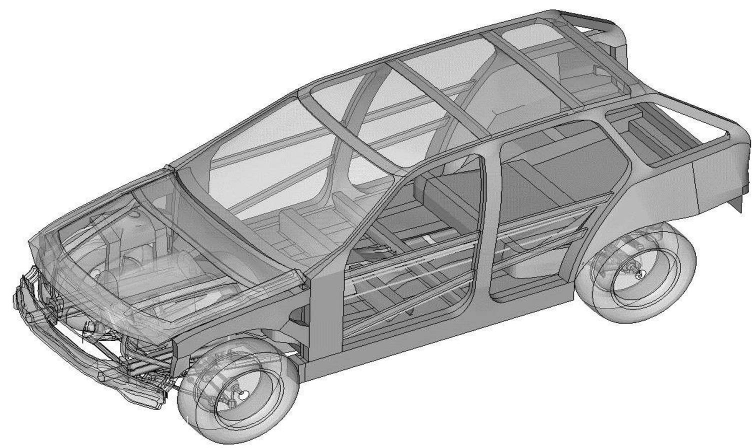
MDO Crash / Statics / Dynamics

- Minimization of body mass
- Finite element mesh
  - Crash ~ 130.000 elements
  - NVH ~ 90.000 elements
- Independent parameters: Thickness of each unit: 109
- Constraints: 18



Algorithm	Avg. reduction (kg)	Max. reduction (kg)	Min. reduction (kg)
Best so far	-6.6	-8.3	-3.3
NuTech ES	-9.0	-13.4	-6.3

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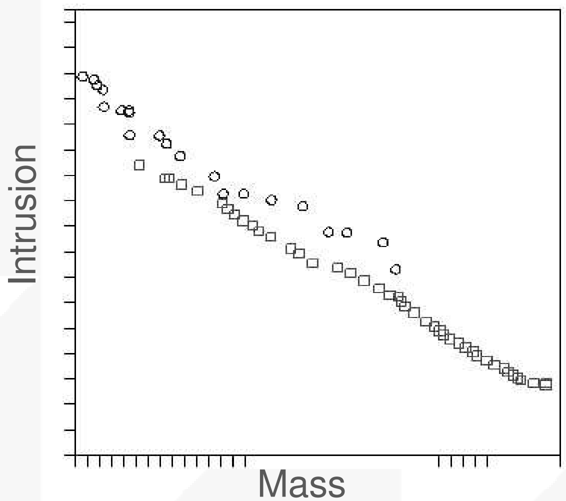
MCO B-Pillar – Side Crash

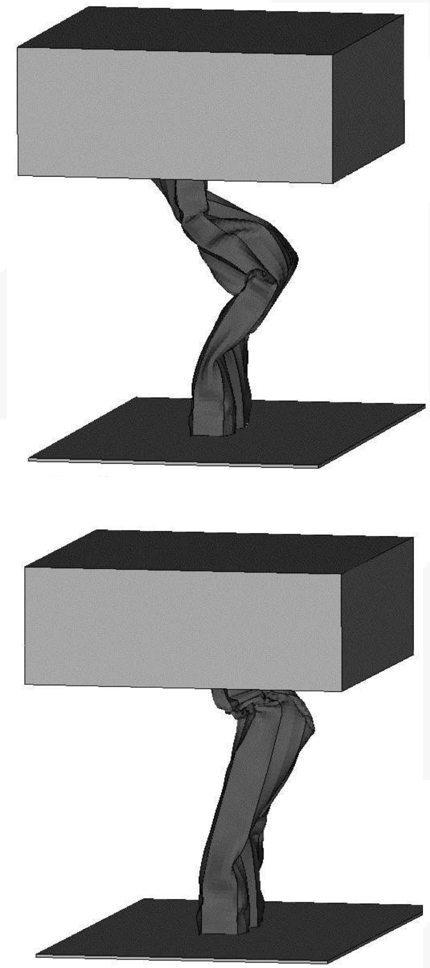
- Minimization of mass & displacement
- Finite element mesh
  - ~ 300.000 elements
- Independent parameters: Thickness of 10 units
- Constraints: 0

- ES successfully developed Pareto front



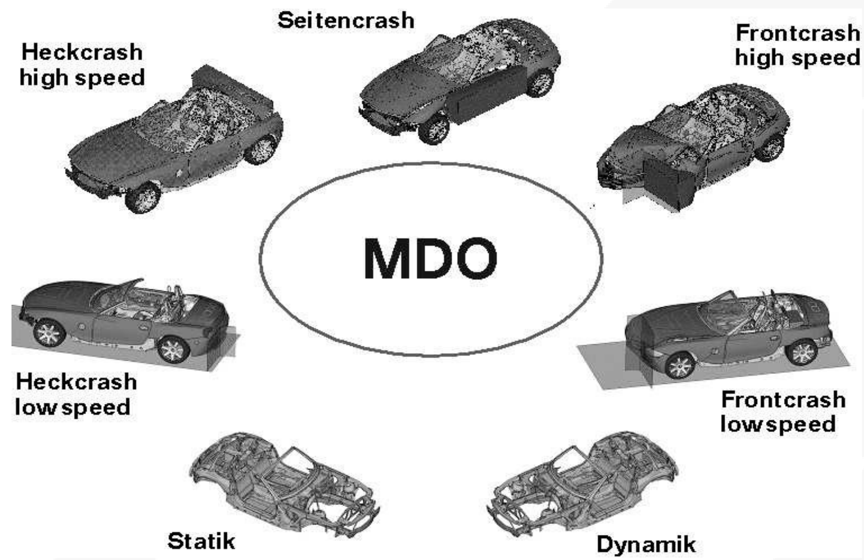
MCO Shape of Engine Mount

- Mass minimal shape with axial load > 90 kN
- Finite element mesh
  - ~ 5000 elements
- Independent parameters: 9 geometry variables
- Dependent parameters: 7
- Constraints: 3
- ES optimized mount
  - less weight than mount optimized with best so far method
  - geometrically better deformation

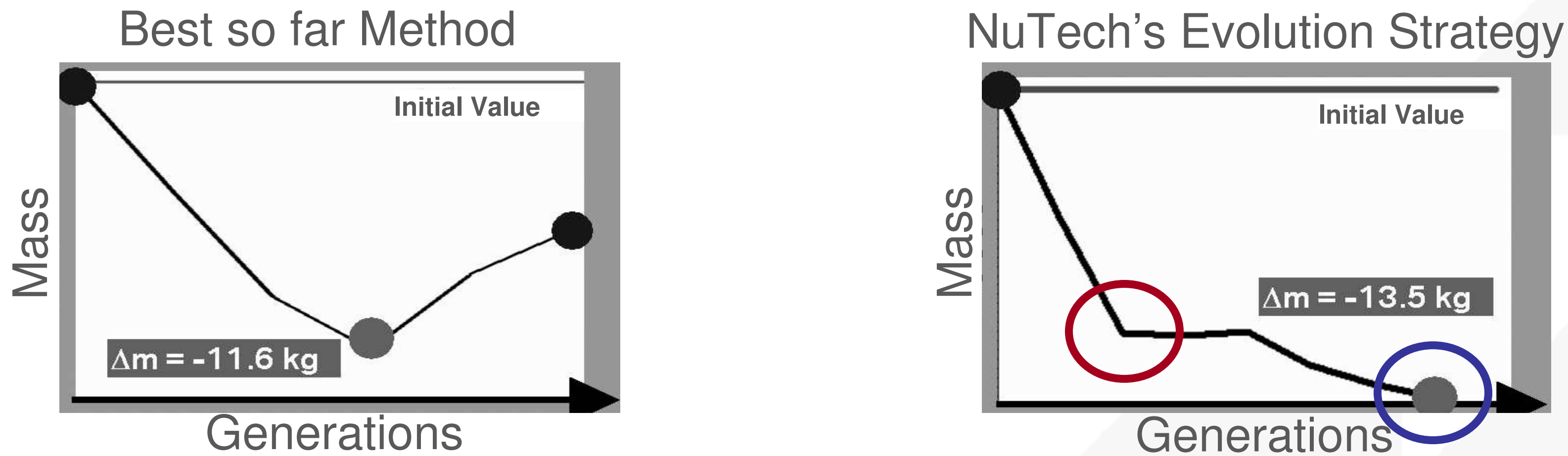


Safety Optimization – Example of use

- Production Run !
- Minimization of body mass
- Finite element mesh
  - Crash ~ 1.000.000 elements
  - NVH ~ 300.000 elements
- Independent parameters:
  - Thickness of each unit: 136
- Constraints: 47, resulting from various loading cases
- 180 (10 x 18) shots ~ 12 days
- No statistical evaluation due to problem complexity



Safety Optimization – Example of use



- 13,5 kg weight reduction by NuTech's ES
- ~ 2 kg more mass reduction than Best so far method
- Typically higher convergence velocity of ES
  ~ 45% less time (~ 3 days saving) for comparable quality needed
- Still potential of improvements after 180 shots.
- Reduction of development time from 5 to 2 weeks allows for process integration

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MDO Body – Concept Phase

- **Goal:** Mass minimization
- **Constraints:**
  - **Statics:** Torsional stiffness, diagonal measures, max. bending
  - **Dynamics:** Eigenfrequency of torsion-, bending- and crossbending-modulus
  - **Frontal crash:** Intrusions
  - **Side crash:** Intrusions and velocities at predetermined points in time
- **Additionally:** Symmetry of metal thicknesses

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MDO – Optimization Parameters

- Metal thicknesses in 3 sub-assemblies:
  - Roof system (26 laminations)
  - Frontal platform (25 laminations)
  - Back platform (15 laminations)
- Total: 66 Optimization parameters
- 56 Constraints from various load cases
- Variation of metal thicknesses within [0,65mm-2,5mm] range
  - 6 laminations have slightly different bounds

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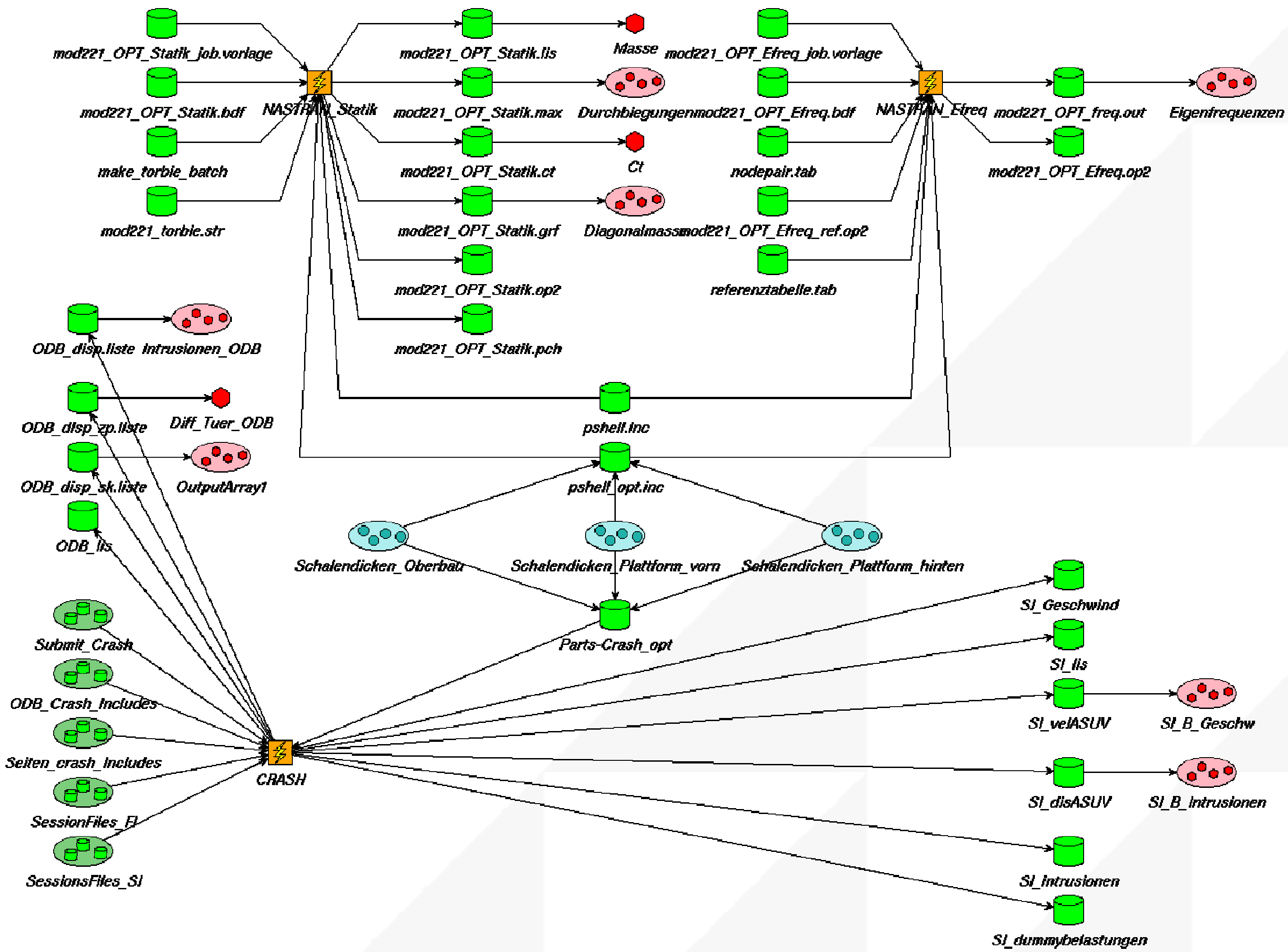
MDO - Optimus Workflow



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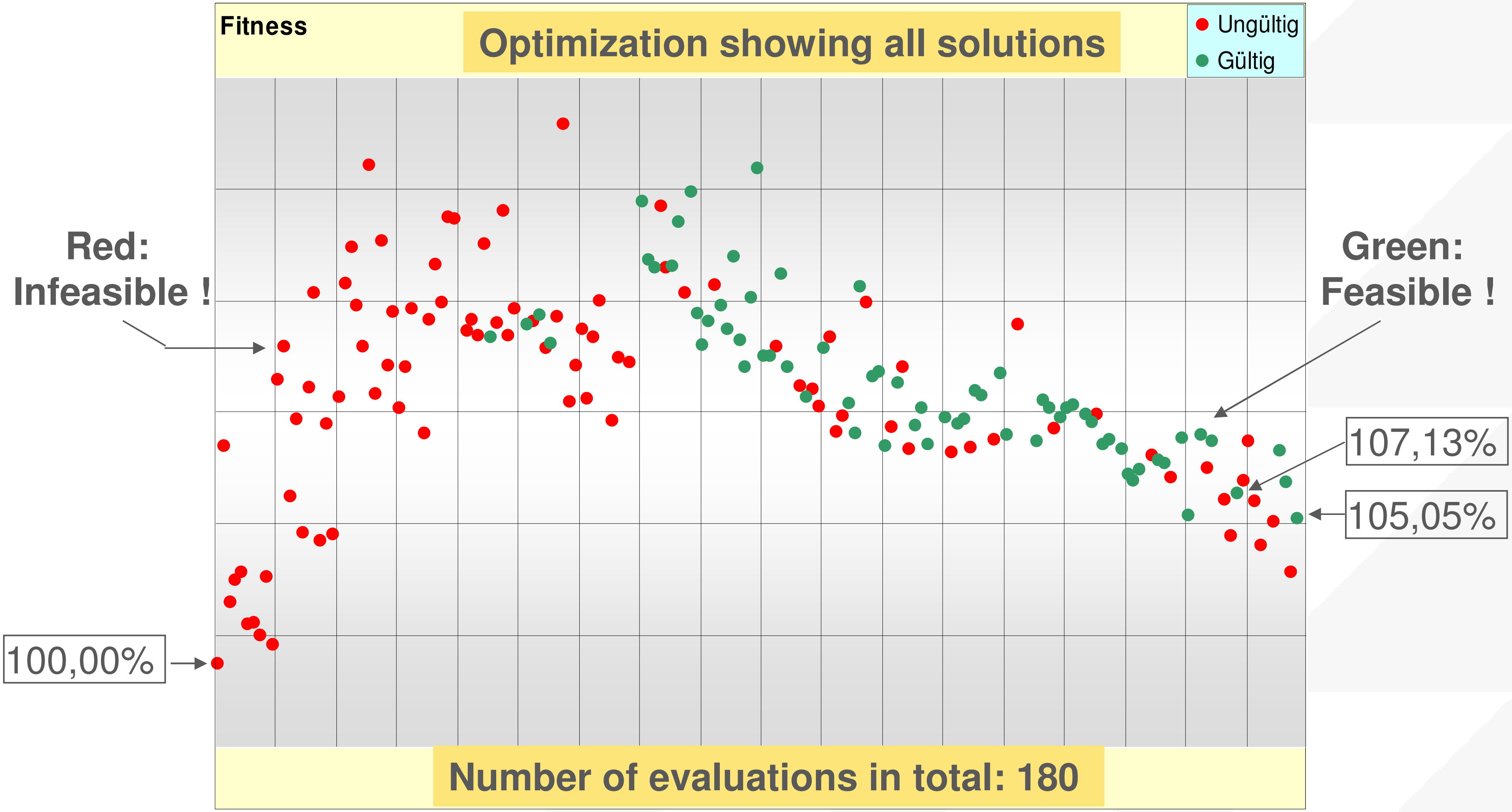
MDO – Optimization Run



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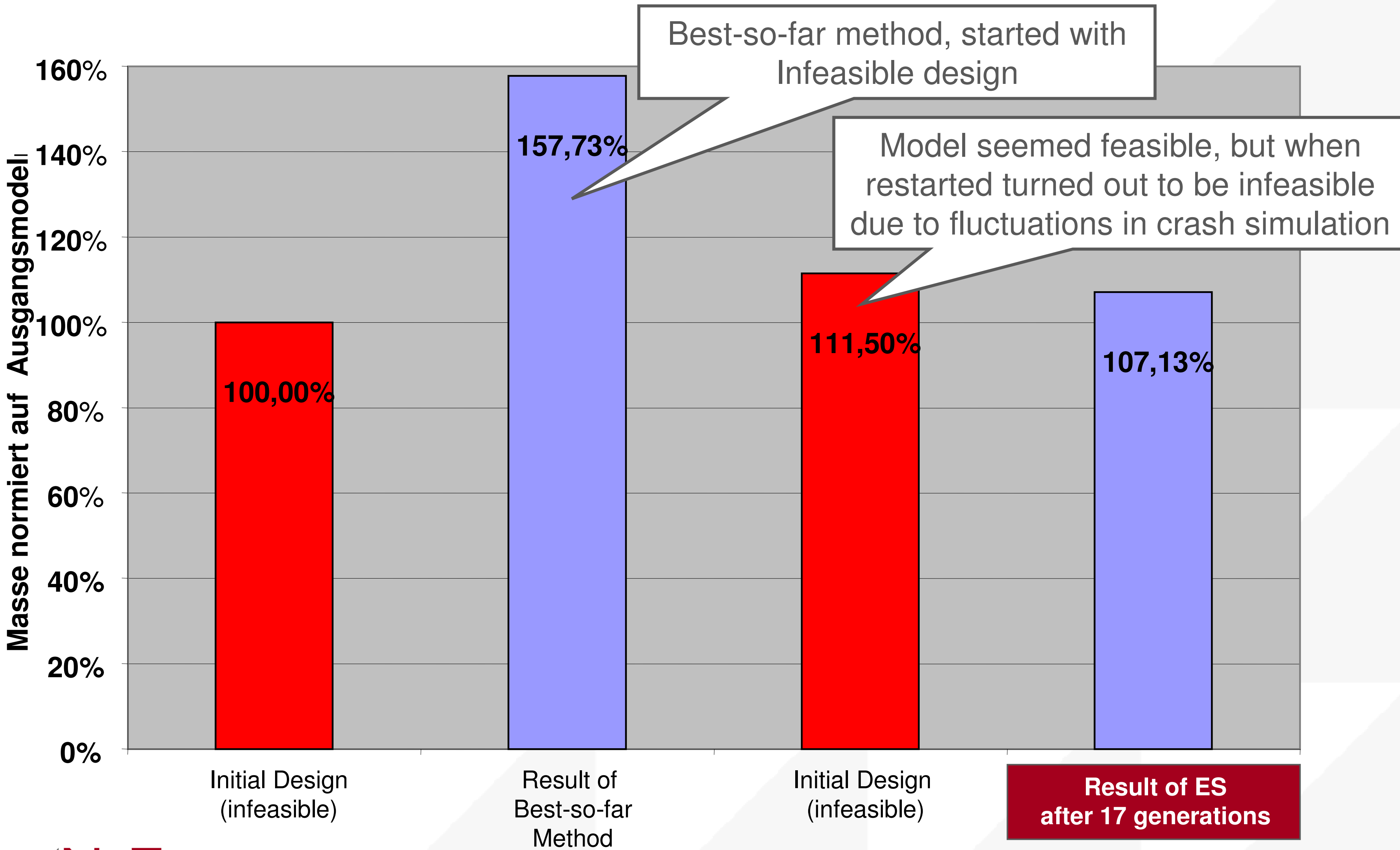
Results after 17 (18) Generations



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Evolution Strategies

Evolution Strategies

- Real-valued / discrete / mixed-integer search spaces.
- Emphasis on mutation: n-dimensional, normally distributed, expectation zero.
- Different recombination operators.
- Deterministic selection: (μ,λ) , $(\mu+\lambda)$
- Creation of offspring surplus, i.e., $\lambda >> \mu$.
- Self-adaptation of strategy parameters.

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ES: Mutation

- Creation of a new solution: $x_i' = x_i + \sigma_i' \cdot N_i(0,1)$
- σ-adaptation by means of
  - 1/5-success rule.
  - **Self-adaptation.**
- More complex / powerful strategies:
  - Individual step sizes σ_i.
  - Covariances.
- Convergence speed:

  ⇒ Ca. 5 · n down to 2 · n is possible.

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ES: Self-Adaptation

- Learning while searching: Intelligent Method.
- Different algorithmic approaches, e.g:
  - Pure self-adaptation (Schwefel):

$$\sigma_i' = \sigma_i \cdot \exp(\tau' \cdot N(0,1) + \tau \cdot N_i(0,1))$$
$$x_i' = x_i + \sigma_i' \cdot N_i(0,1)$$

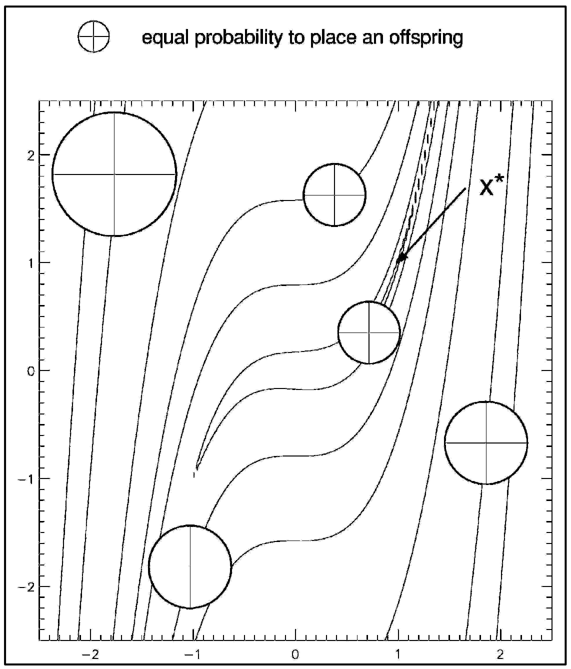
  - Mutational step size control (Rechenberg):

$$\sigma' = \begin{cases} \sigma \cdot \alpha \ , & \text{if } u \approx U(0,1) \le 1/2 \\ \sigma / \alpha \ , & \text{if } u \approx U(0,1) > 1/2 \end{cases} \qquad x_i' = x_i + \sigma_i' \cdot N_i(0,1)$$

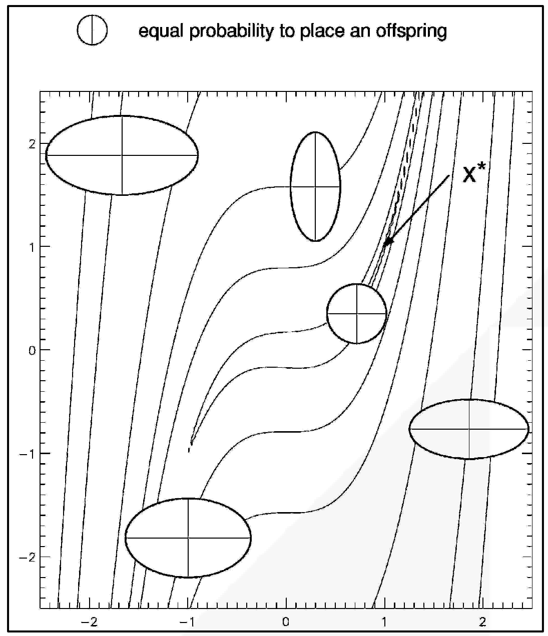
  - Derandomized, CMA

ES: Self-Adaptive Mutation

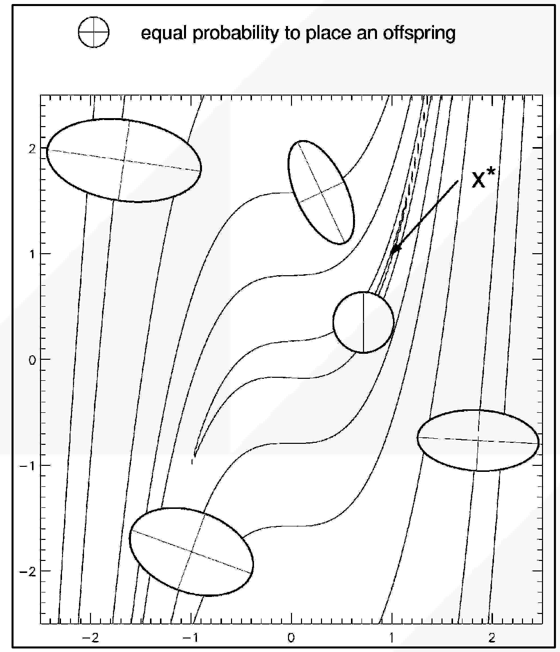
- Visualization of the Principle



$n = 2, n_\sigma = 1, n_\alpha = 0$



$n = 2, n_\sigma = 2, n_\alpha = 0$



$n = 2, n_\sigma = 2, n_\alpha = 1$

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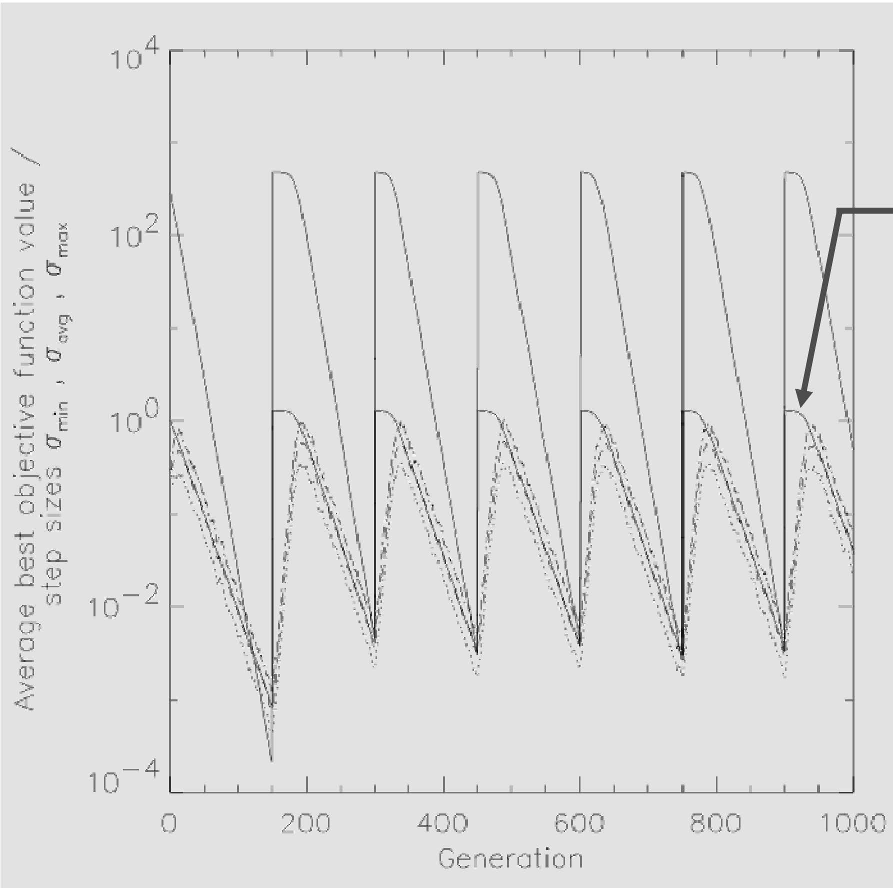
ES: Self-Adaptation: Dynamic Sphere



- Optimum σ:

$$\sigma_{opt} = c_{\mu,\lambda} \frac{R}{n}$$

- Transition time proportionate to n.
- Optimum σ learned by self-adaptation.

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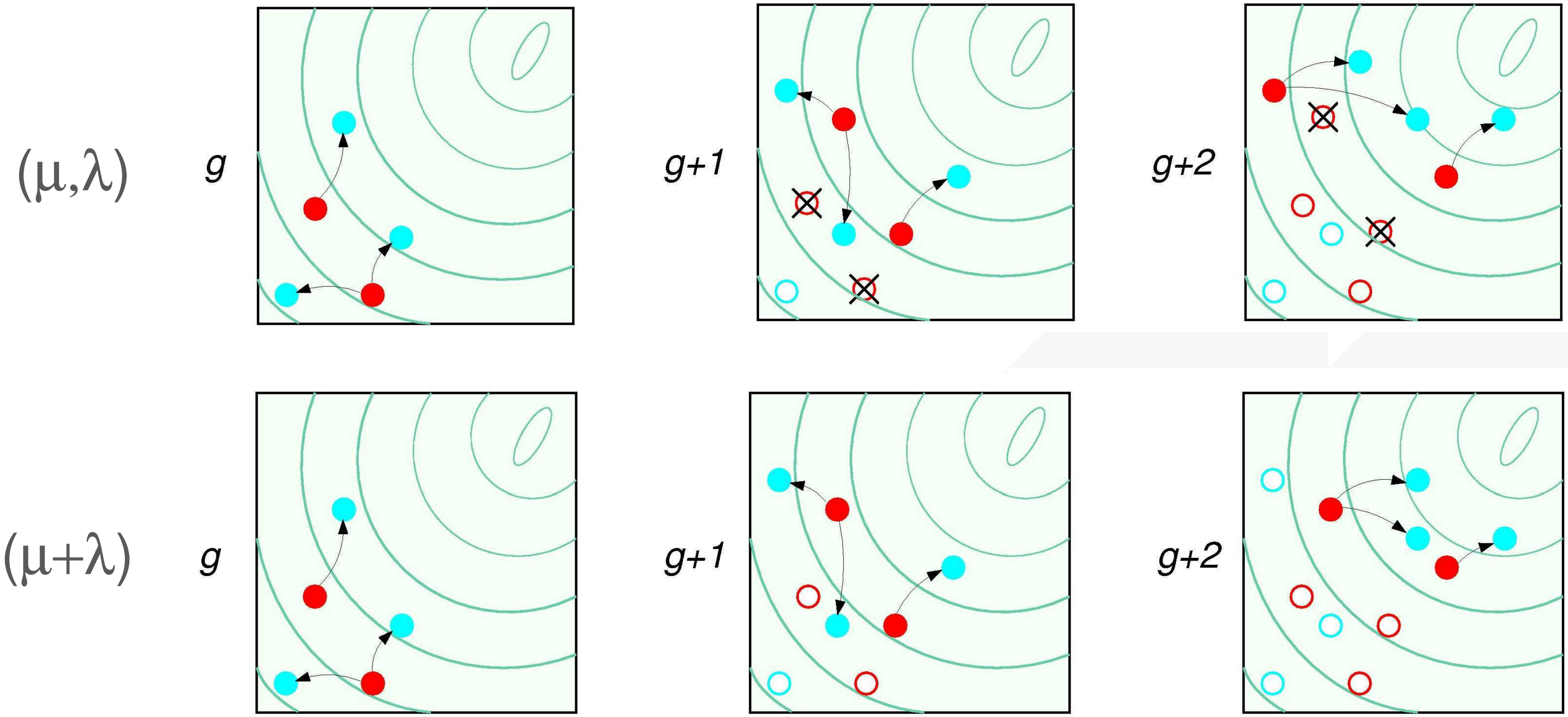
ES: Selection



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ES: Possible Selection Operators

- (1+1)-strategy: one parent, one offspring.
- (1,λ)-strategies: one parent, λ offspring.
  - Example: (1,10)-strategy.
  - Derandomized / self-adaptive / mutative step size control.
- (μ,λ)-strategies: μ>1 parents, λ>μ offspring
  - Example: (2,15)-strategy.
  - Includes recombination.
  - Can overcome local optima.
- (μ+λ)-strategies: elitist strategies.

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Advantages of Evolution Strategies

- Faster than other optimizers (incl. GAs)[1]
- Better solutions in less Time !
- Easy to parameterize due to self-adaptive parameter control
- Configures itself to problem at hand
- Scales well with problem dimensionality ($\sqrt{n}$)
- Multi-Criteria & Mixed-Integer variants available

[1]See: H.-P. Schwefel (1995): *Evolution and Optimum Seeking*, Wiley, NY.
Th. Bäck (1996): *Evolutionary Algorithms in Theory and Practice*, Oxford University Press, NY.

Other Aspects

- Optimization Using Distributed Resources
- Robustness against Client / Server Failures
- Constraint Handling
- Multiple Criteria
- Robust Design
- Meta-Learning (RSA)
- Easy to Use !

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Other Examples

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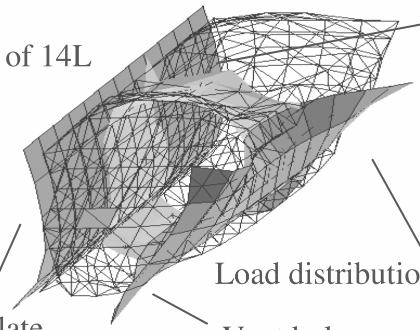
Inflatable Knee Bolster

Objective: Minimize $P_{combined}$

Subject to: Left Femur load ≤ 7000
Right Femur load ≤ 7000

deployed knee bag (unit only)



MAZDA Picture

Design Variable
IKB center offset x
IKB center offset y
KB venting area ratio
KB mass inflow ratio
DB venting area ratio
DB high output mass inflow ratio
DB low output mass inflow ratio
DB firing time
DB strap length ratio
Load of load limiter (N)
Performance Response
HIC
CG
Left foot load
Right foot load
P combined (Quality)

Design	$P_{combined}$	# Simulations
Base	13.69	--
Hooke Jeeves	8.89	160
GA (Ford)	7.29	155
ES	6.77	122

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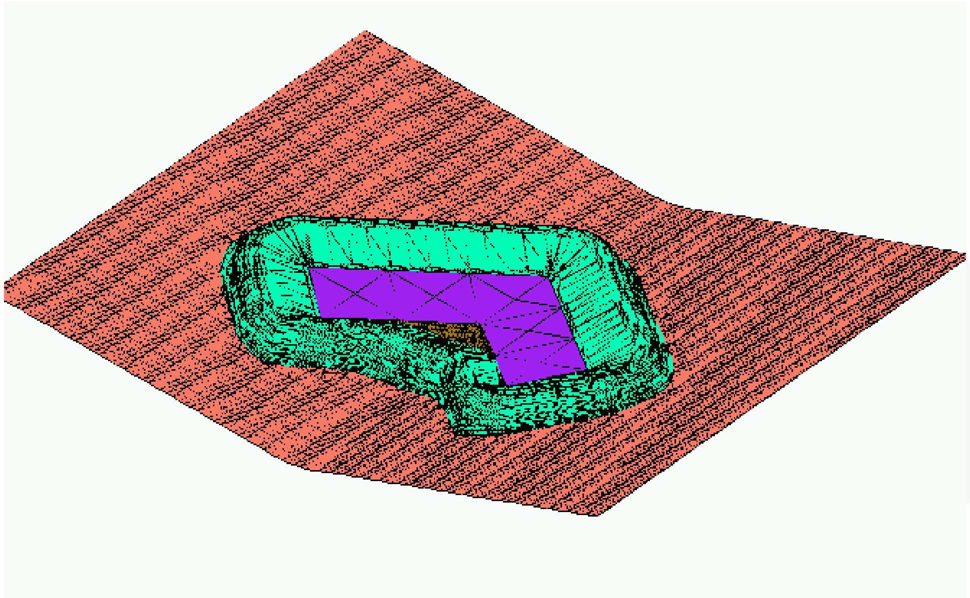
Optimization of metal stamping process



- **Objective:** Minimization of defects in the produced parts.
- **Variables:** Geometric parameters and forces.
- ES finds very good results in short time
- Computationally expensive simulation

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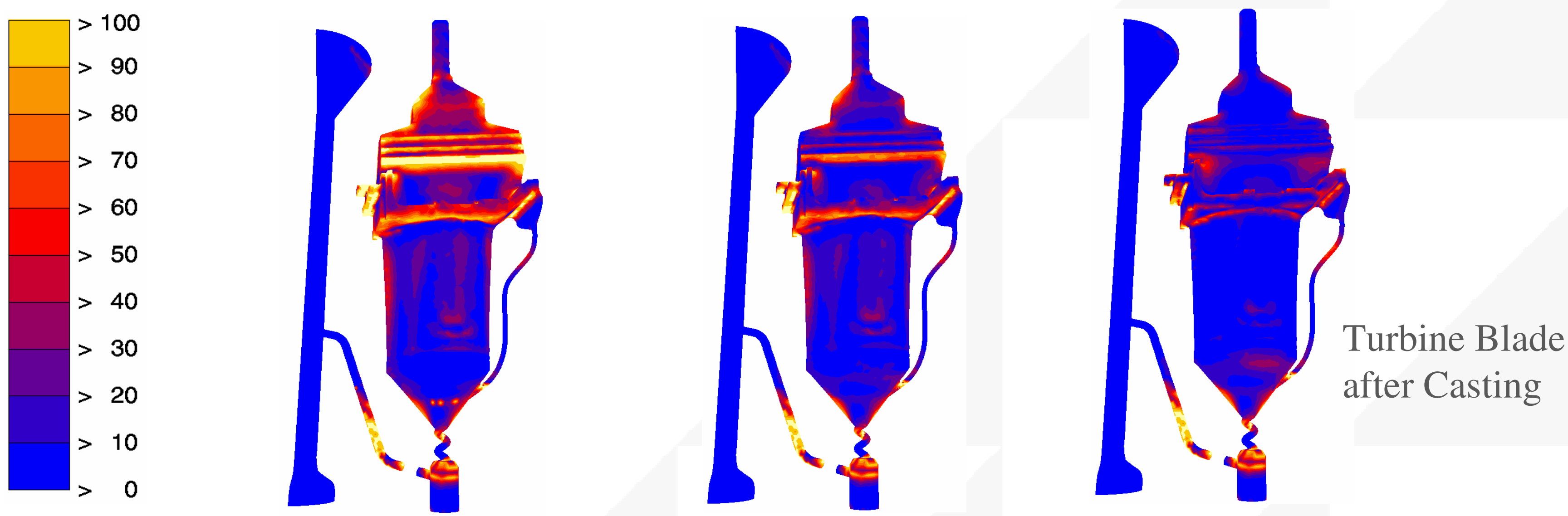
Bridgeman Casting Process

- Objective: Max. homogeneity of workpiece after Casting Process
- Variables: 18 continuous speed variables for Casting Schedule
- Computationally expensive simulation (up to 32h simulation time)



Initial (DoE) | GCM (Commercial Gradient Based Method) | Evolution Strategy

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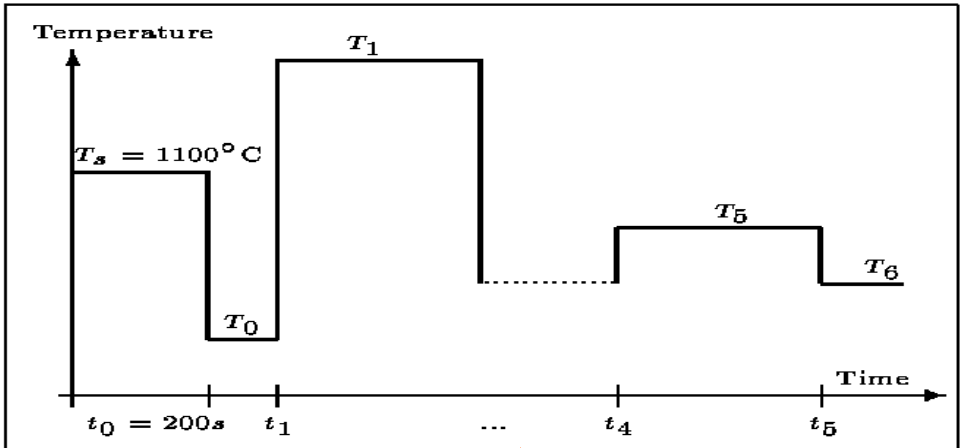
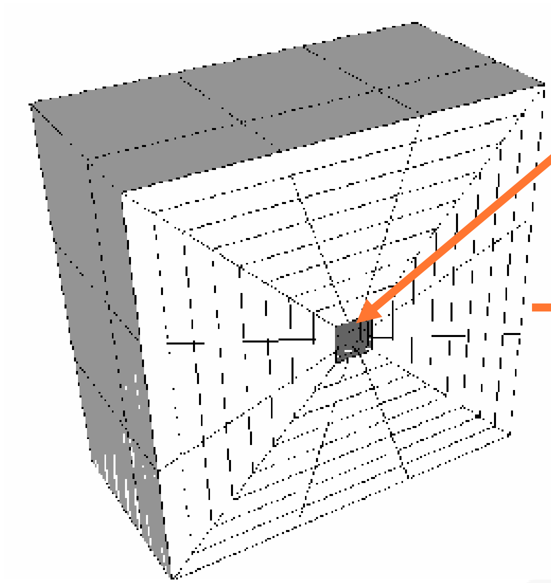
Steel Cube Temperature Control

Minimize the deviation of temperture at the cube´s Surface to 1000℃ !



Input: Temperature Profile (12 Variables 7 Temperatures and 5 Time-Steps)



$$\Delta T_{max}$$

Algorithm	100 OFE	200 OFE	1000 OFE
SQP	148	67.7	59
Conjugate directions	135	135	135
Pattern search	157	147	48
DSCP/Rosenbrock	88	38	29
Complex strategy	152	152	111
(1,3)-DES	91	67	67
(1,5)-DES	53	48	48
(1,7)-DES	110	58	58
(1,10)-DES	152	80	28
MAES	122	65	12

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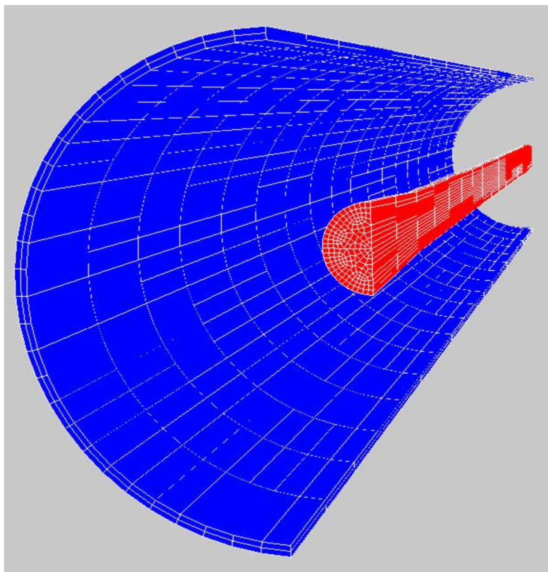
Access Materials + Processes
RWTH AACHEN RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Siemens C Reactor

- Maximisation of growth speed
- Minimisation of diameter differences



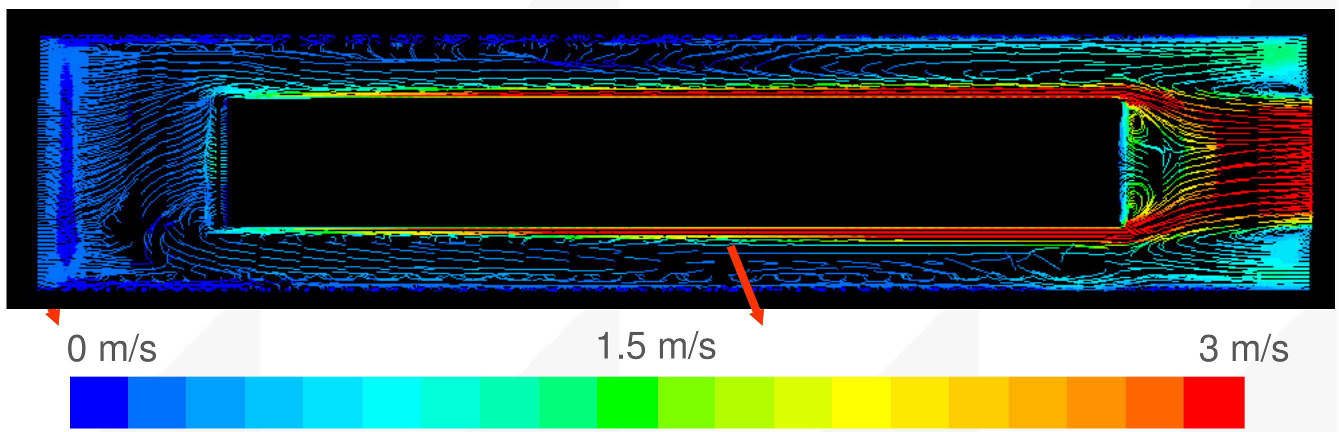
FLUENT: Simulation of fluid flow
CASTS: Calculation of Temperature and concentration field

Optimsation of 15 process parameters:

Production time 35 hours → 30 hours

Reaction Gas TCS

Growing High Purity Silicon Rod



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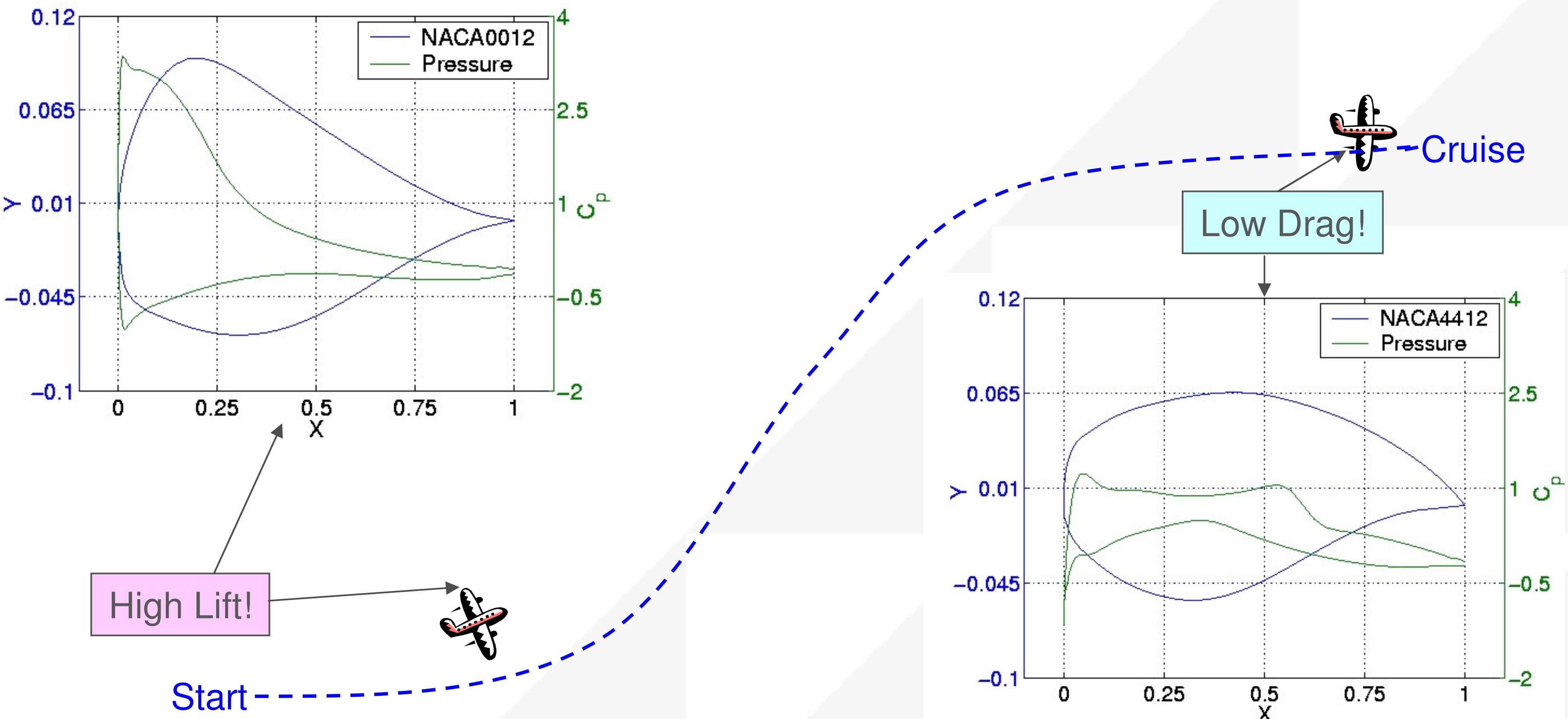
Multipoint Airfoil Optimiziation

- **Objective:** Find **pressure** profiles that are a **compromise** between two given **target pressure** distributions under two given flow conditions!
- **Variables:** 12 to 18 Bezier points for the airfoil



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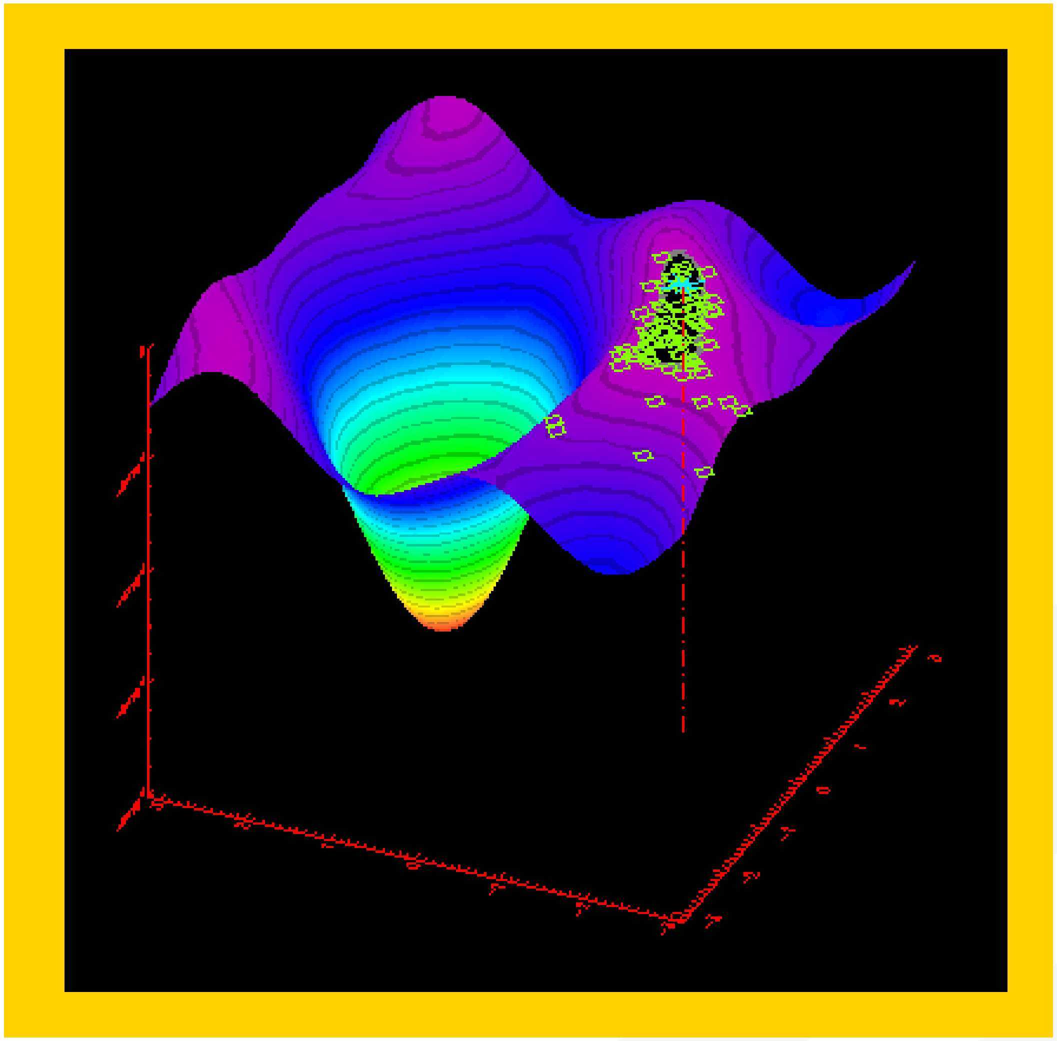
Optimum tracking of an ES



- Dynamic function
- 30-dimensional
- 3D-projection

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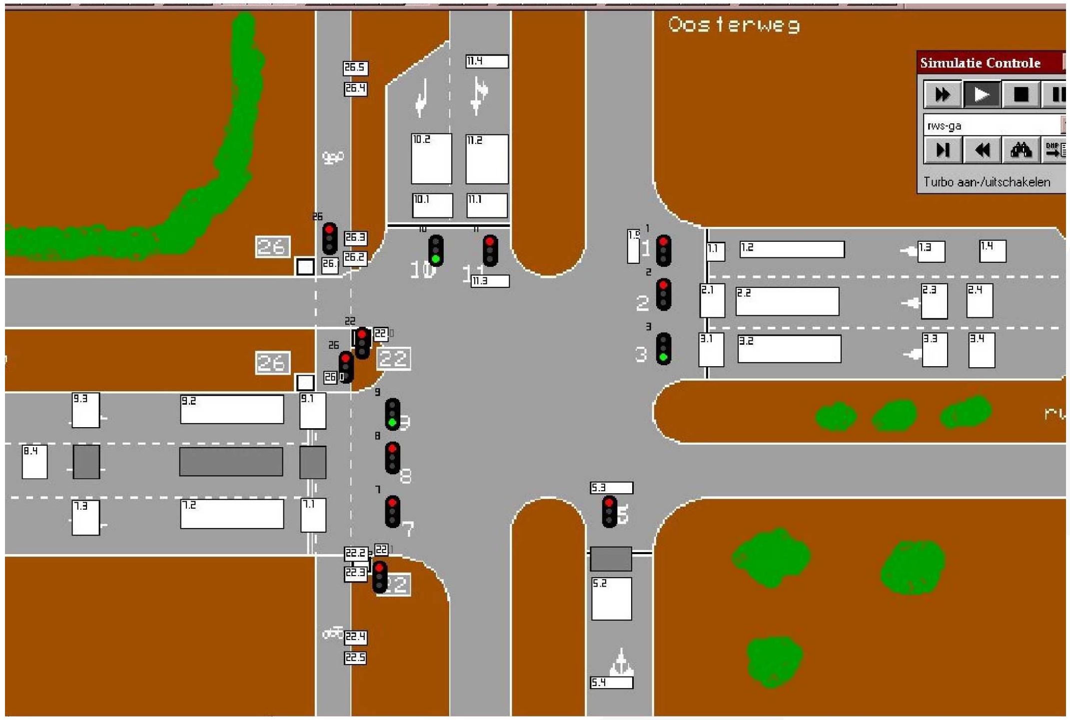
Traffic Light Control Optimization



- **Objective:** Minimization of total delay / number of stops
- **Variables:** Green times for next switching schedule
- **Dynamic optimization**, depending on actual traffic
- Better results (3-5%)
- Higher flexibility than with traditional controllers

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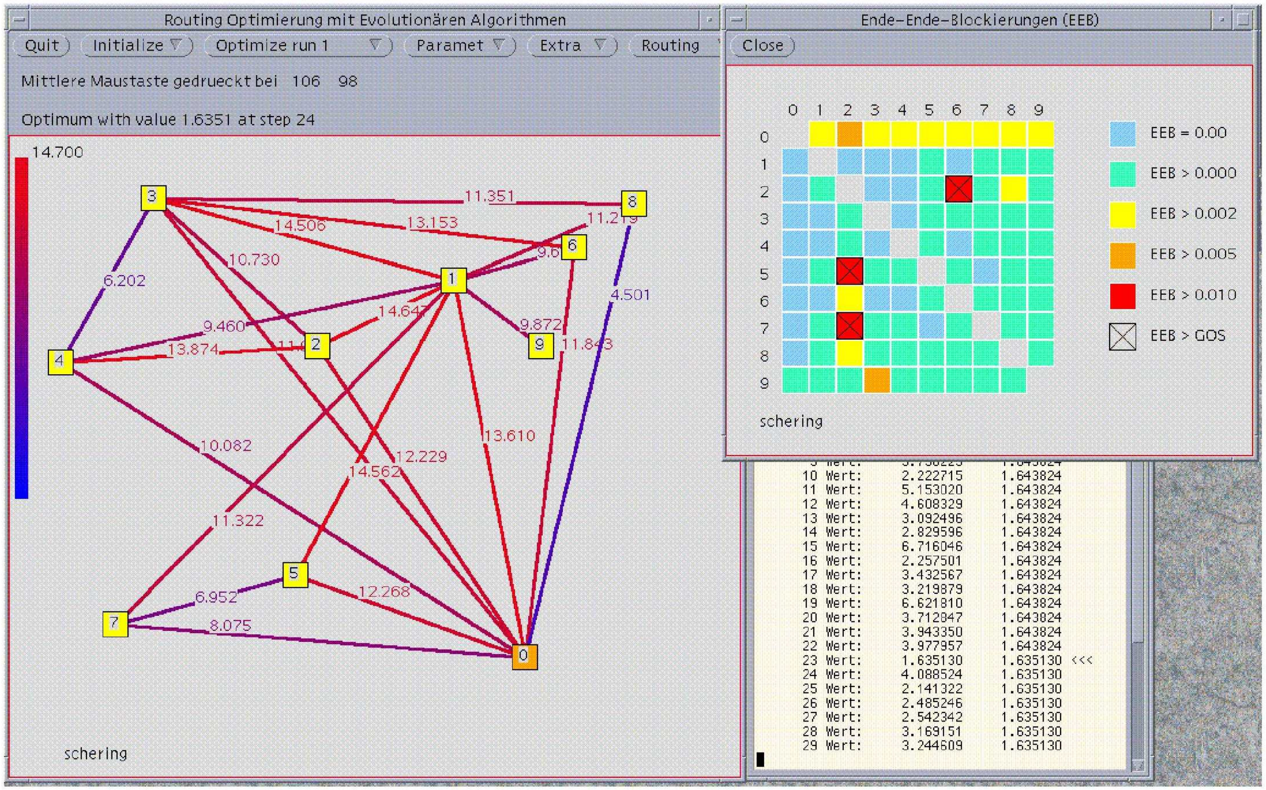
Ministerie van Verkeer en Waterstaat

Optimization of elevator control

- Minimization of passenger waiting times.
- Better results (~10%) than with traditional controller.
- **Dynamic optimization**, depending on actual traffic.

Optimization of network routing

SIEMENS



- Minimization of end-to-end-blockings under service constraints.
- Optimization of routing tables for existing, hard-wired networks.
- 10%-1000% improvement.

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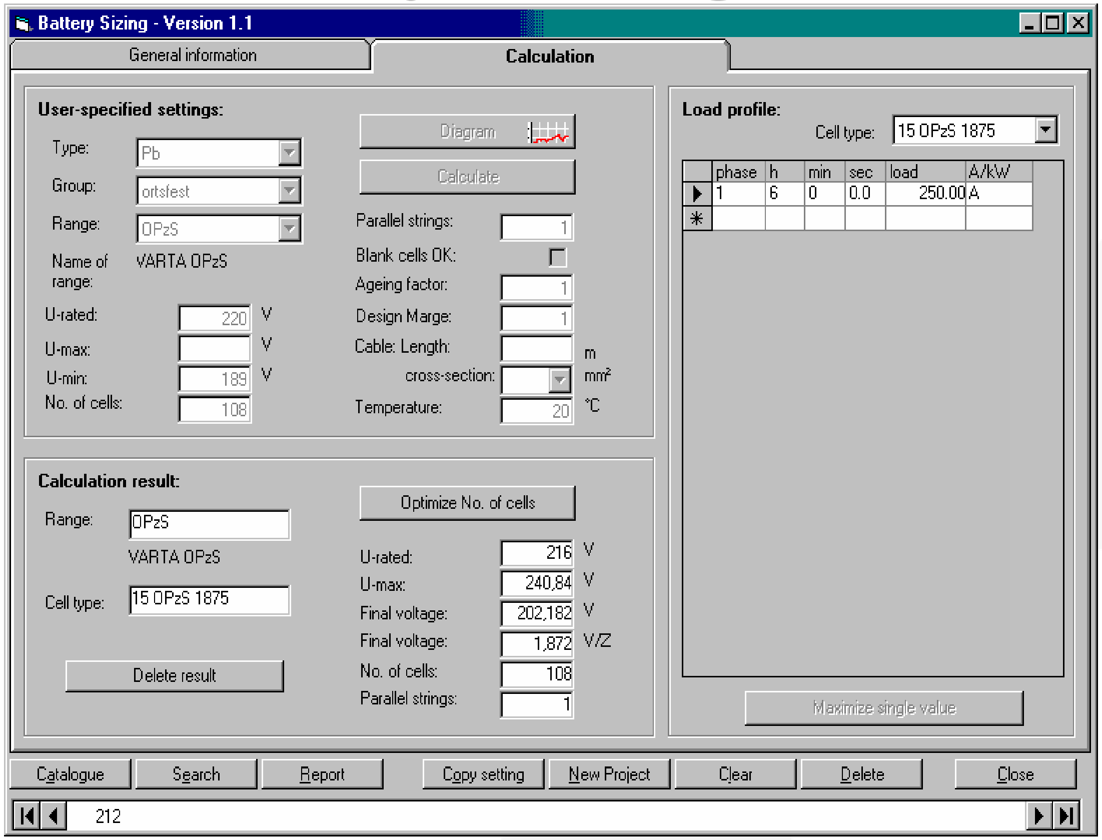
Automatic battery configuration



- Configuration and optimization of industry batteries.
- Based on user specifications, given to the system.
- Internet-Configurator (Baan, Hawker, NuTech).

HAWKER BATTERIEN Standby Batteries Germany

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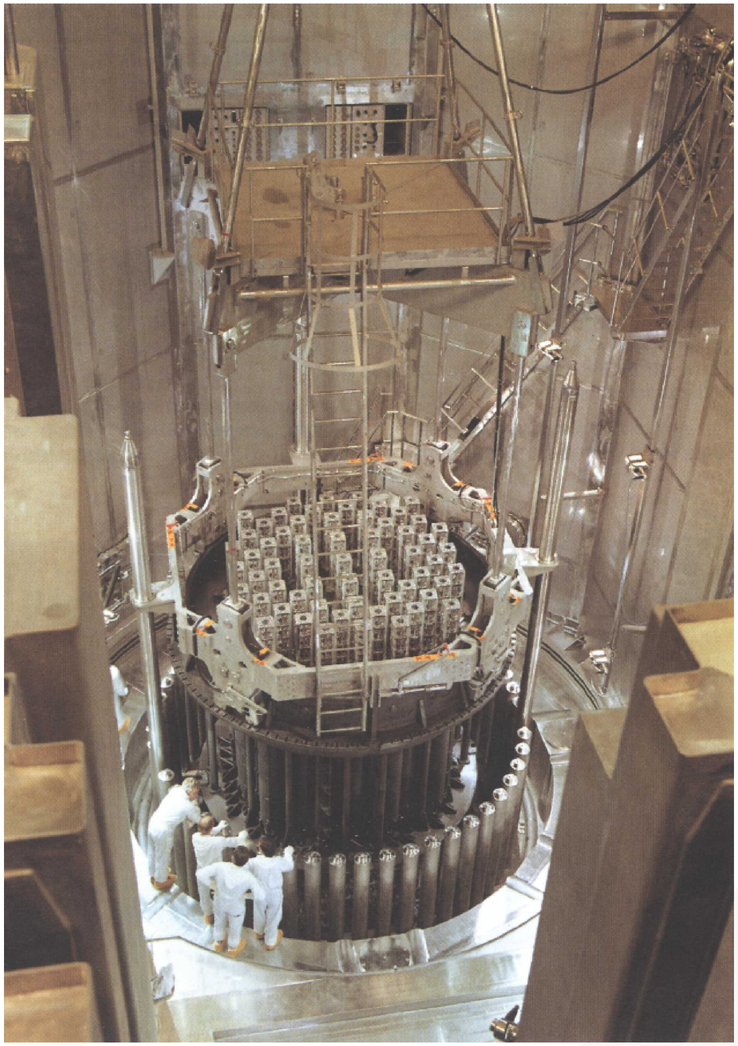
Optimization of reactor fueling.

SIEMENS



- Minimization of total costs.
- Creates new fuel assembly reload patterns.
- Clear improvements (1%-5%) of existing expert solutions.
- Huge cost saving.

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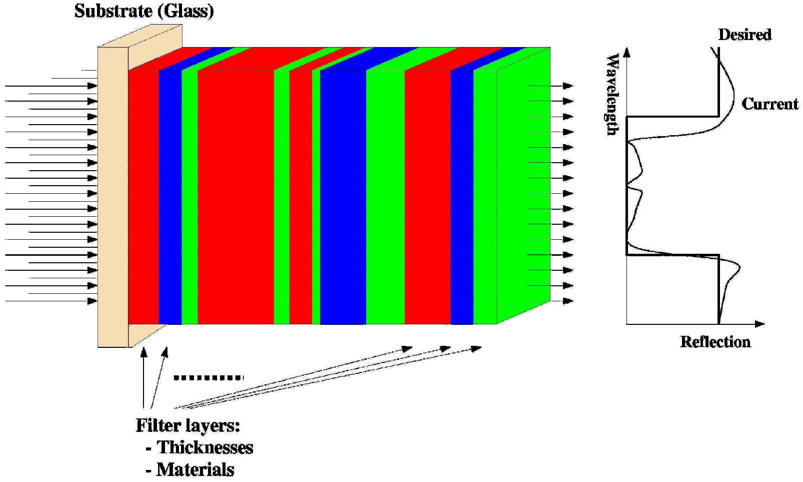
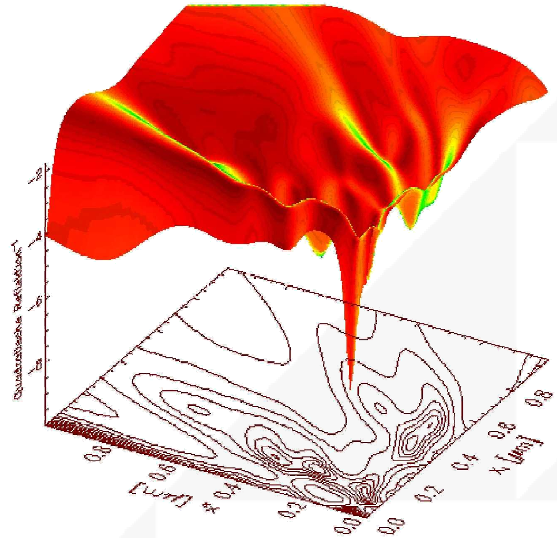
Optical Coatings: Design Optimization





- Nonlinear mixed-integer problem, variable dimensionality.
- Minimize deviation from desired reflection behaviour.
- Excellent synthesis method; robust and reliable results.
- MOC-Problems: anti-reflection coating, dialetric filters
- Robust design: Sharp peaks vs. Robust peaks

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CORNING Discovering Beyond Imagination

Final Remarks

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Final Remarks

- Would not work without continuously improving ES
- Have not published results for 6 years
- If challenging problems can be handled, clients have more challenging ones
- See www.nutechsolutions.com

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Partnership

ANALYSIS

SOFTWARE

ENGINEERING

....

- Evolution Strategy Module for Optimus available.
- Distribution D, A, CH by FE Design.
- Effective as of April 2005.

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Thank you for your Attention !

Questions ?

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