Two Examples of Integrated Optimization

Evolutionary Computing in Practice
GECCO 2006

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Overview

- Engineering Optimization
  - Requirements
  - Industries
- What it means …
- Requirements for a tool
- Examples
- Is it worth doing it ?

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Engineering Optimization

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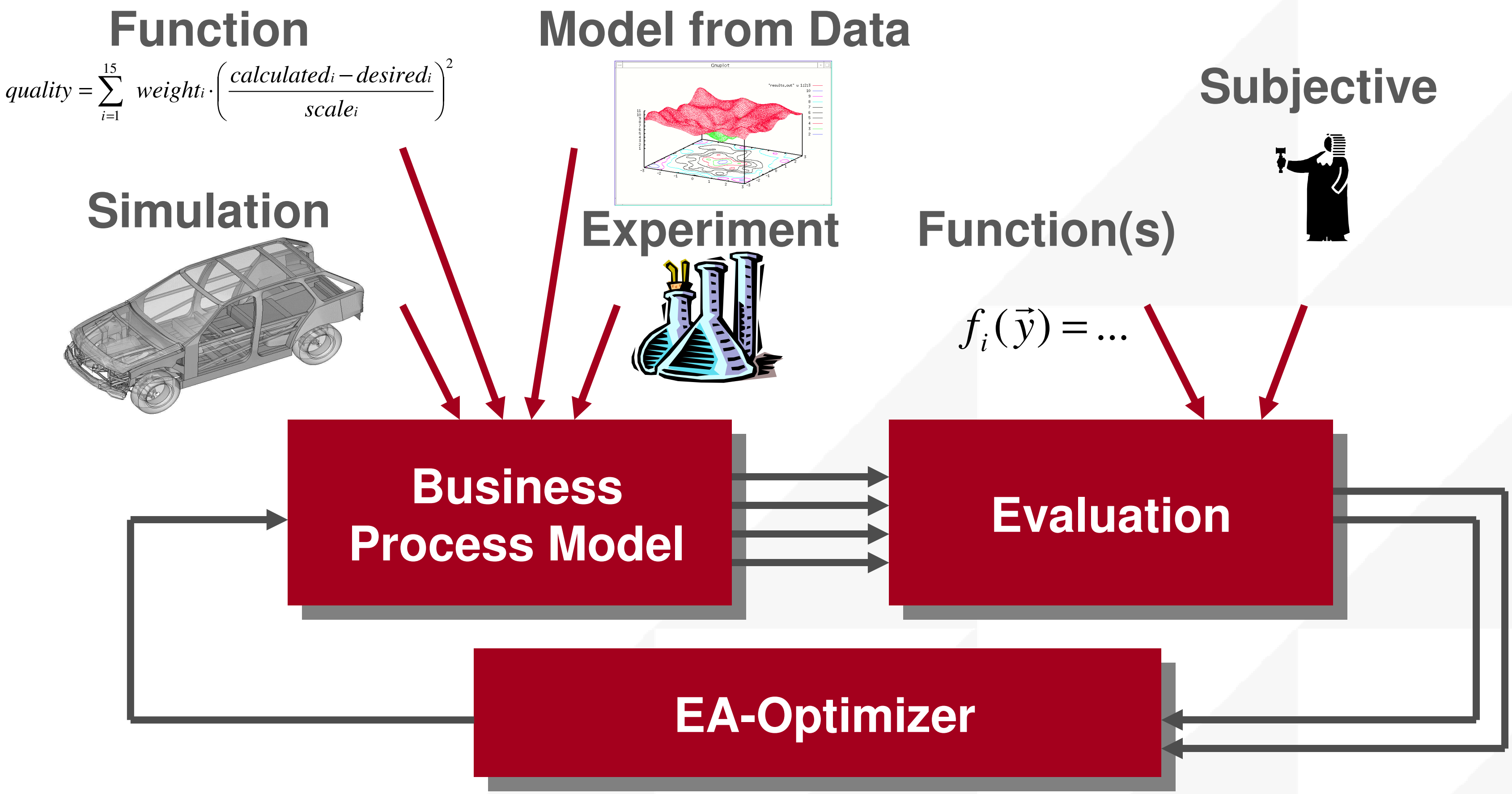
General Aspects



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Requirements I

- Very few function evaluations!
  - Simulator run times often many hours
- Tight business constraints on runtime
  - E.g., 2 weeks maximum (time pressure)
- Workflow support required
  - Coupling with simulators
  - Analysis of results
  - Great graphical user interface needed

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Requirements II

- Optimizer requirements
  - Easy to use
  - $n > 100$, but number of evaluations often ~150
  - Many nonlinear constraints
  - Multiobjective needed
  - Robustness analysis needed
  - Mixed-integer needed
  - …

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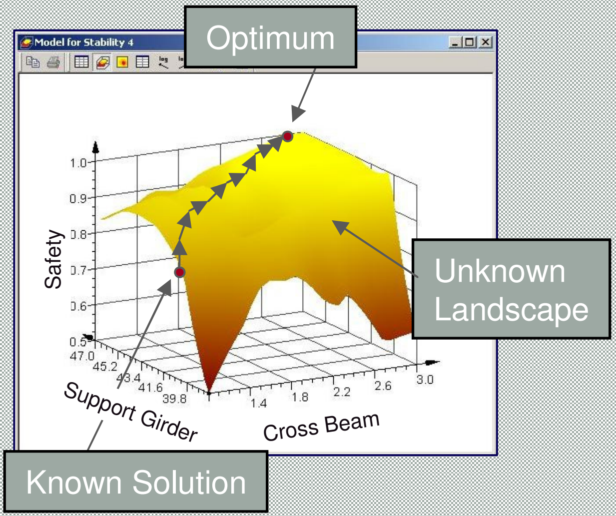
Industries

- Automotive
- Aerospace
- Chemistry
- Engines, Turbines
- …

A Solution for ...

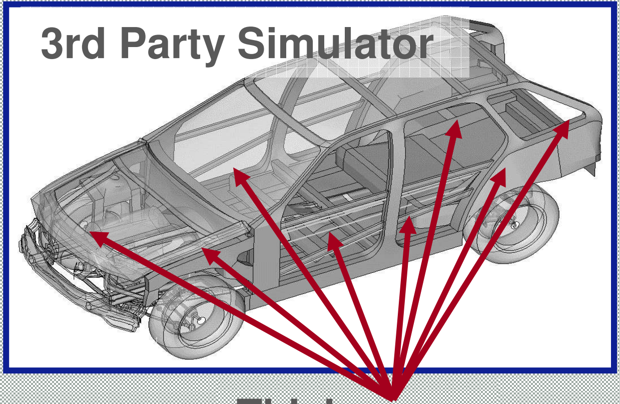
Intelligent Computing ◄ Intelligent Computing | (Expensive) Computer Experiments

A Challenging Example: Car Body Design



Global Optimization ◄

Finite Element Mesh of 130,000; Runtime: ~ 1 day



Thickness of 109 Units

Two Must-Haves ...

... to accomplish such complex tasks:

- the most efficient algorithms

&

- a robust and fail-safe environment

Requirements for a Tool

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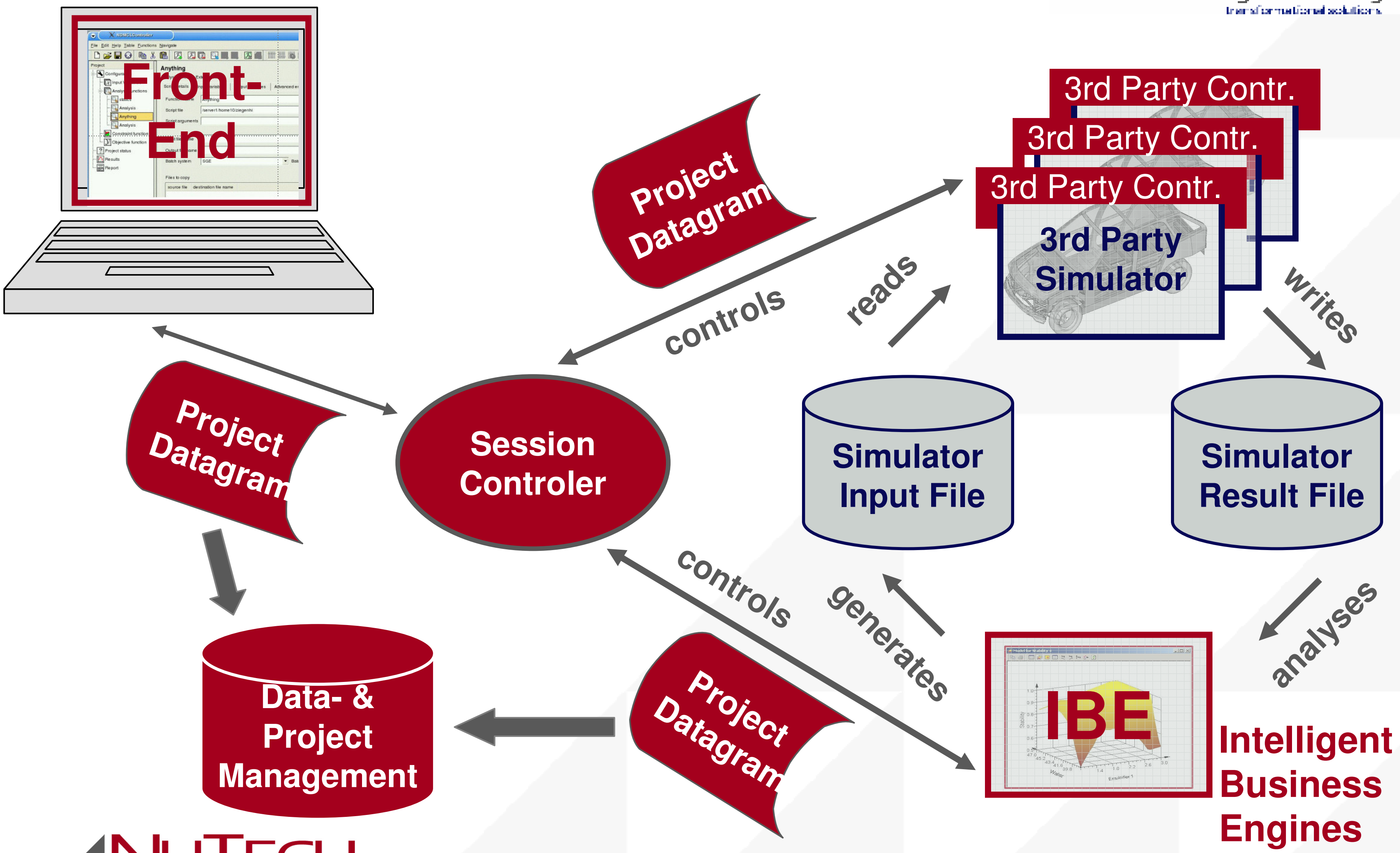
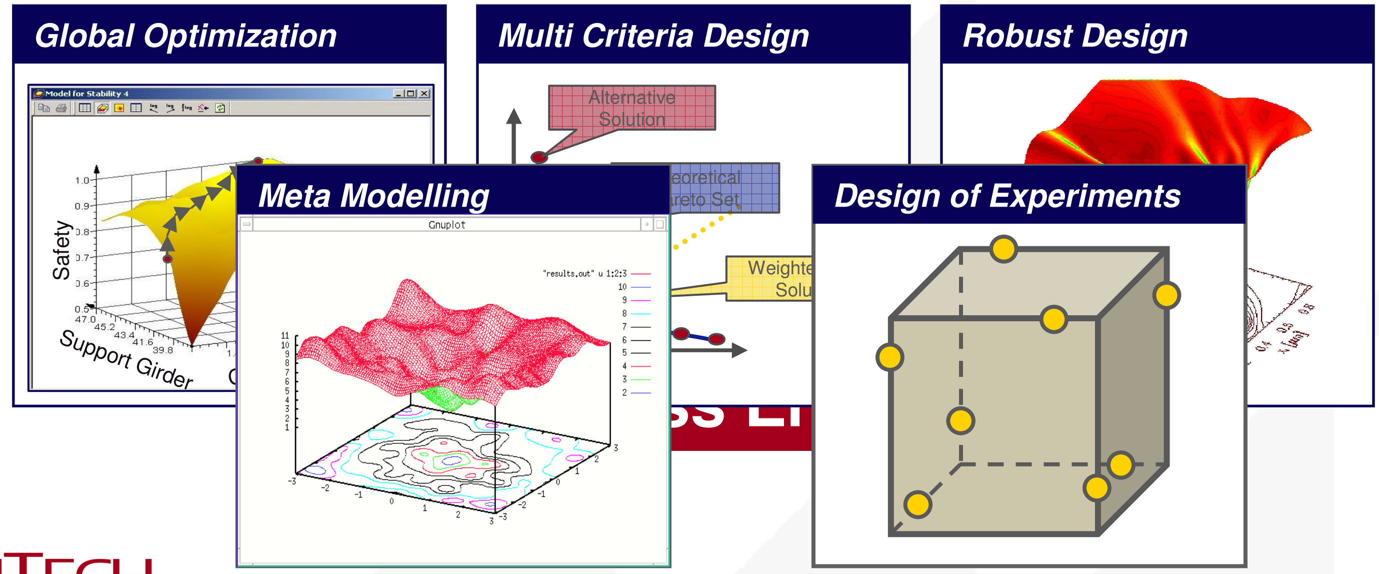
How it Works


Front-End
Project Datagram
controls
reads
3rd Party Contr.
3rd Party Contr.
3rd Party Contr.
3rd Party Simulator
writes
Project Datagram
Session Controler
Simulator Input File
Simulator Result File
Data- & Project Management
controls
generates
Project Datagram
IBE
analyses
Intelligent Business Engines

How it Works / IBEs

Computer Experiments

New Experiments



Experimental Results

Features and Architecture

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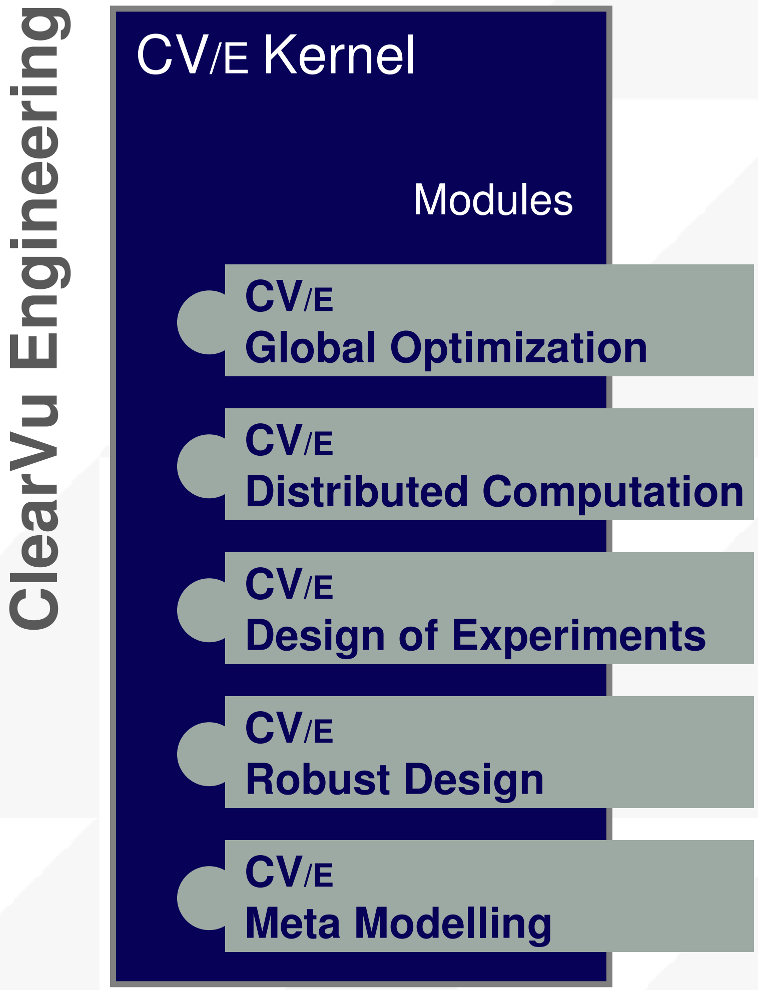
Unique Features:

- Extensible XML-based Architecture
- Platform independend
- Runs 24/7 --- Hot-Plug Update
- Fast Adaptive Search
- Multi Criteria Design
- Thin Redundant Master
- ...



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Architecture

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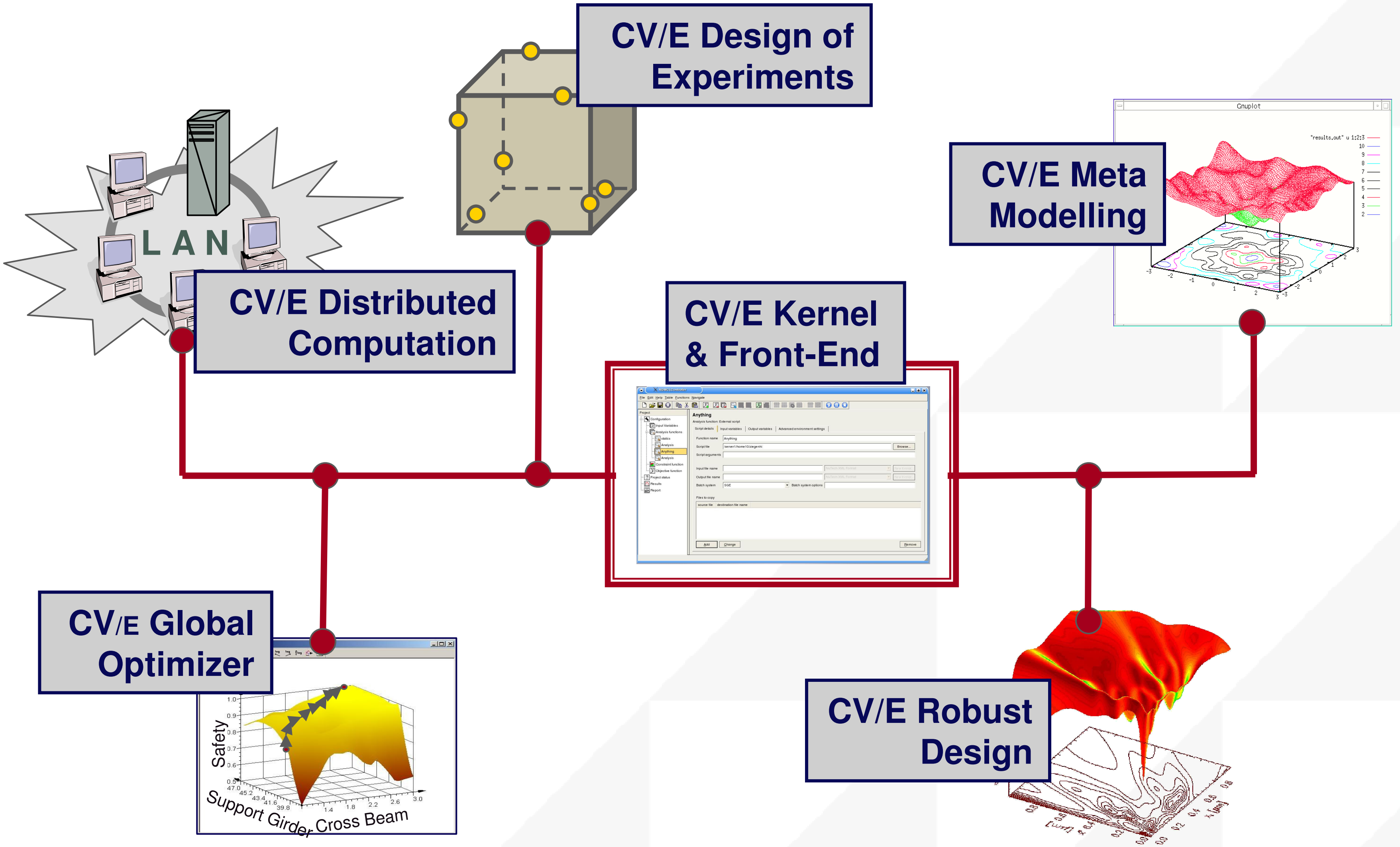

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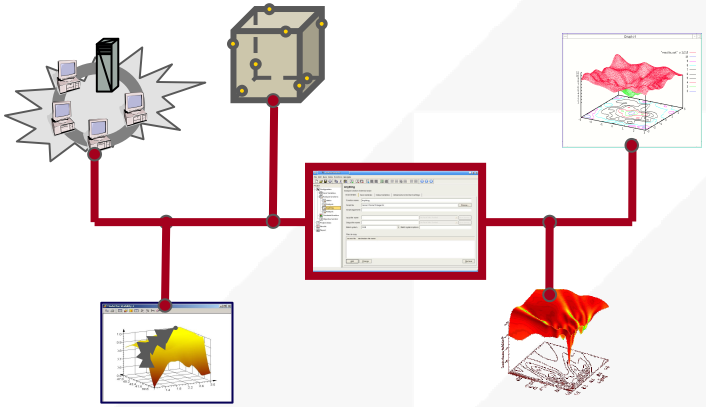
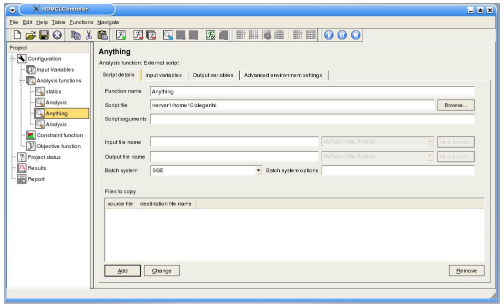


The CV/E Kernel



Features:

- Modular Extensible Architecture
- Open to Integrate 3rd-Party Algorithms
- XML-Based Interfacing and API
- Simple to Use Graphical User Interface
  (& Optional Text Console)
- Different Levels of User Skills and Permissions
- Project Templates Supporting Team Work
- Advanced Postprocessing†

† available with release 2.2

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Graphical User Interface

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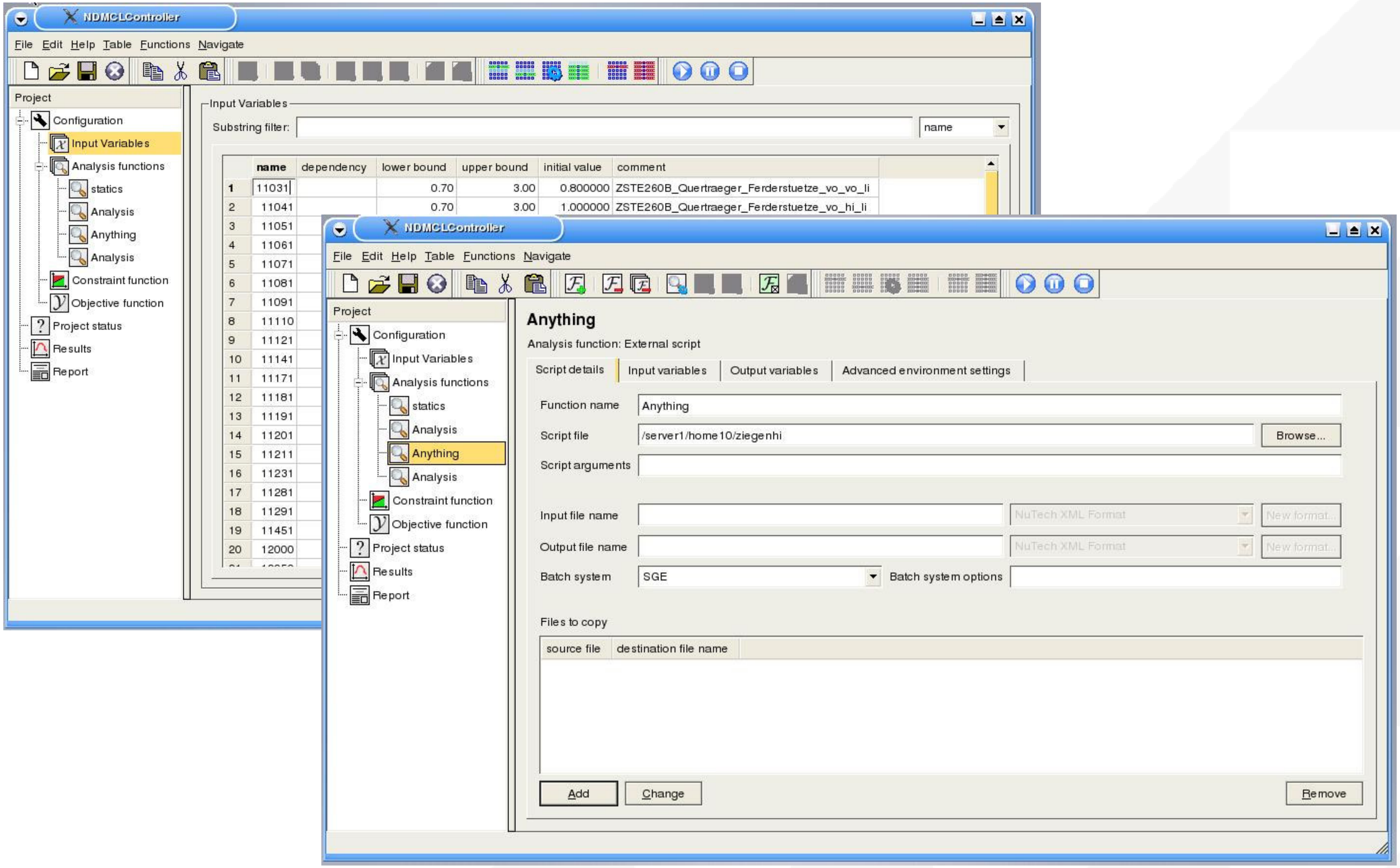

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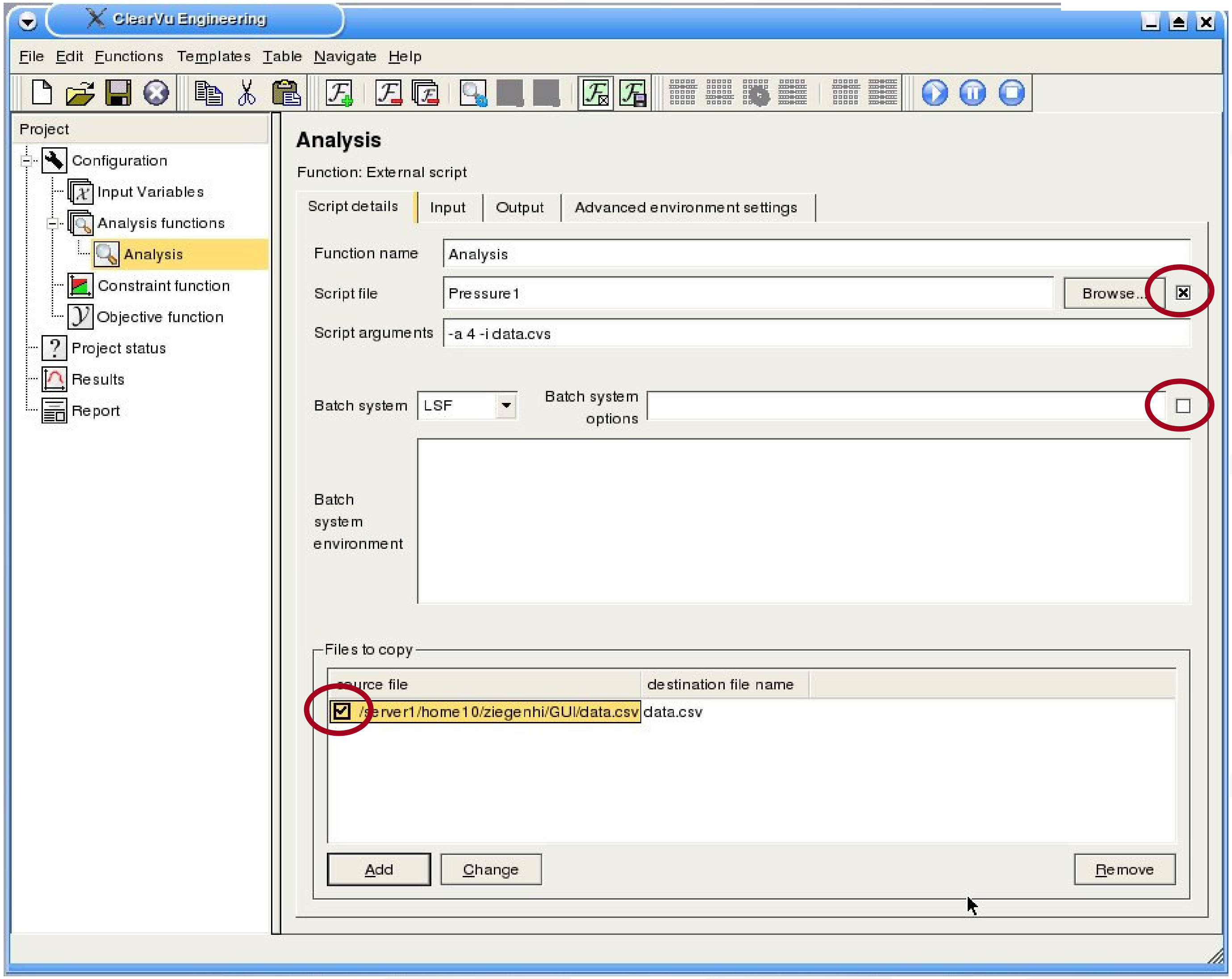
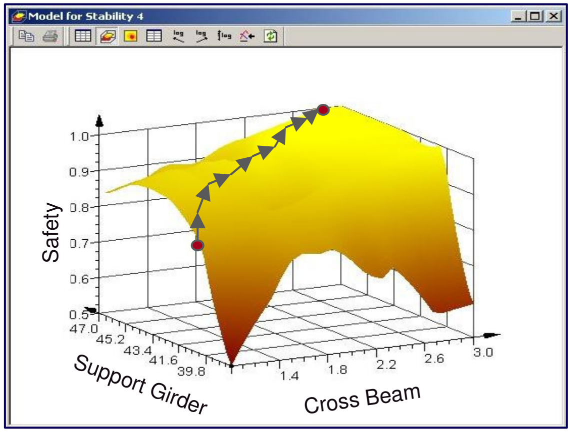
Project Templates



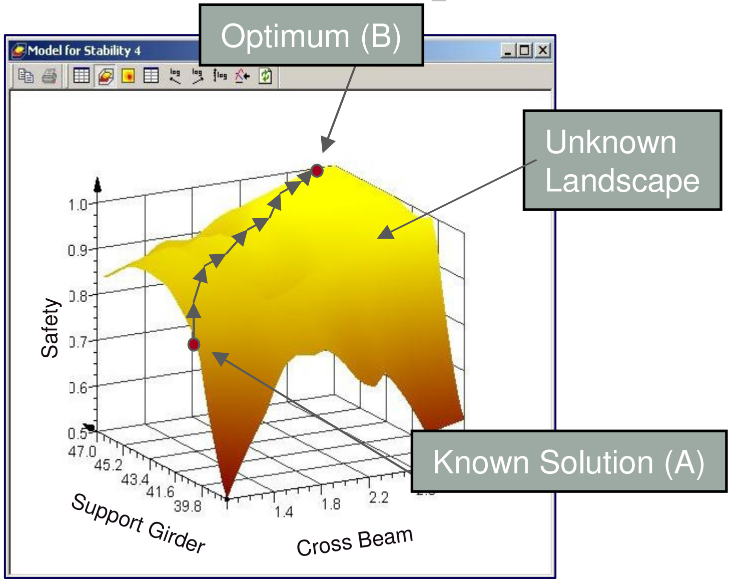
CV/E Global Optimizer

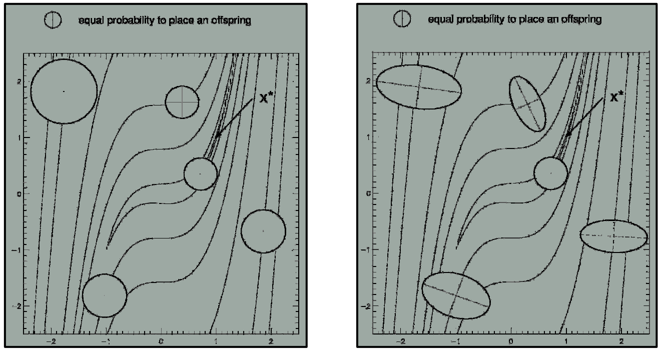


Features:

- Fast adaptive search
- Self-Adaptive Evolution Strategies
- Flexible constraint handling
- Handles infeasible initial solutions
- Variable degree of paralelism
- Multi criteria design
- Mode for the unexperienced users

Fast Adaptive Search





Self-Adaptation of step sizes and directions

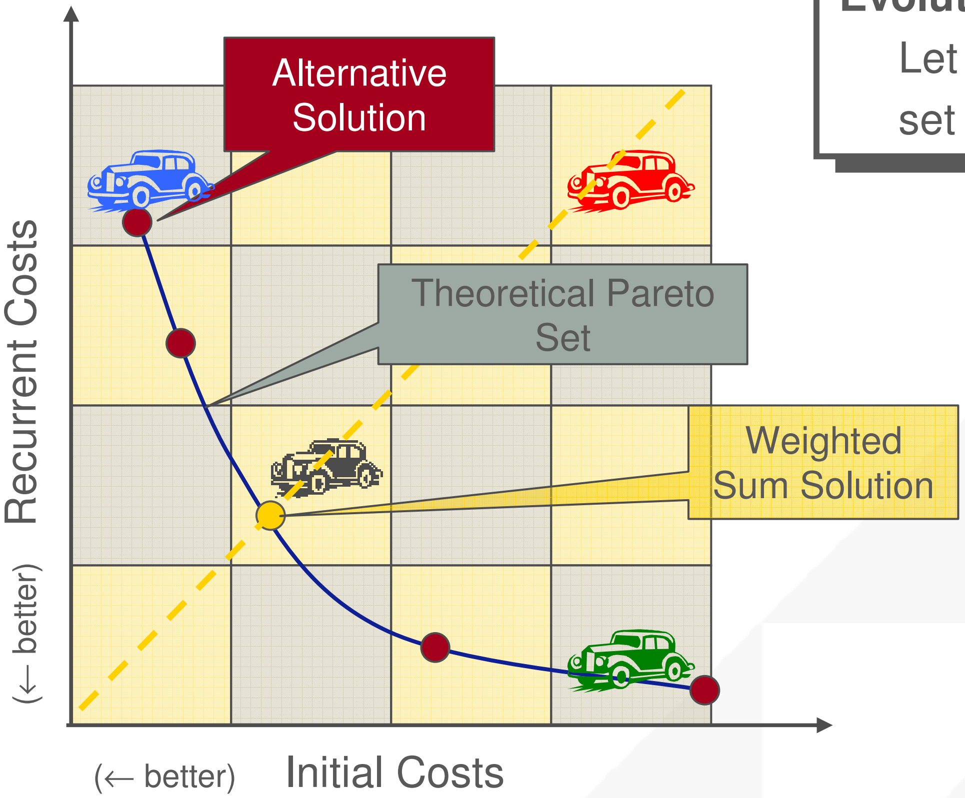
How to get
- from A to B (or equivalent solution)
- with high probability
- but minimal effort
- in an unknown landscape

Enhanced Evolution Strategies (ES)
- robust
- fast
- self-adapitve
- utilizes parallelism
- can deal with huge dimensions
- can deal with infeasible start designs
- can deal with mixed-integer spaces

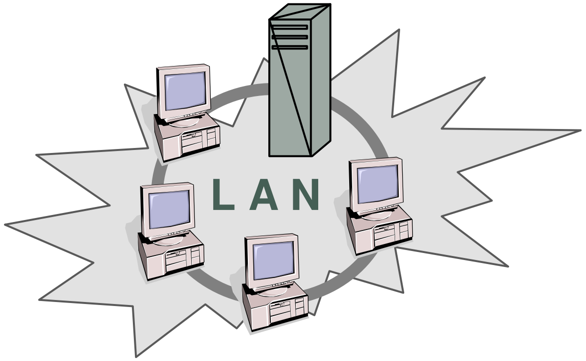
Multi Criteria Design

Multi Criteria Desgin:
Find the whole set of optimal compromises

Evolutionary Multi Criteria Desgin:
Let the population of solutions represent the set of optimal compromises



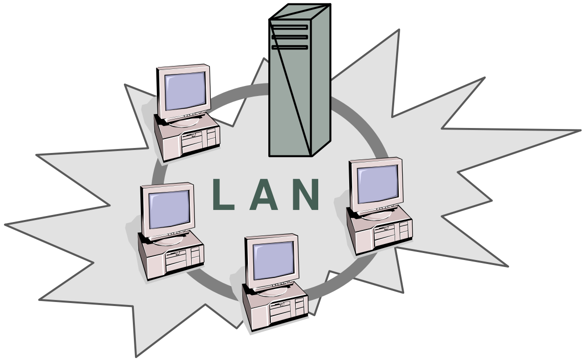
CV/E Distributed Computation



Features:

- Turns existing computer networks into robust computing cluster
- Improves access to computer farms
- Exploits inherent parallelism
- **Turns vulnerable hard/software environments into 24/7- systems**
- Eases administration of complex infrastructures
- Interfaces to 3rd-party batch-systems
- **Persistent Project Datagrams**
- Decentralized collaboration

CV/E Distributed Computation -2



...

- **Redundant Thin Master architecture**
- Master operates independent of Front-Ends
- Distinguished Failure Reactions
- Advanced Data- and Projectmanagement
- Flexible Permissions-Scheme
- Hot-Plug Updates
- Supports Heterogenous Networks
- Process Monitoring †
- Simple Native Batch System†

† available with release 2.2

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Some Examples

Application Map / FEM

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Finite Element Modelling

Comput. Fluid Dynamics

Numerical Modelling

Discrete Event Simulation

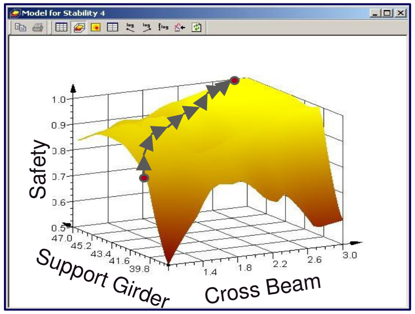
Agent Based Modelling

System Dynamics

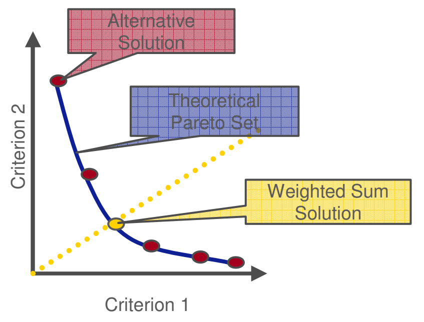
New Experiments

Experimental Results

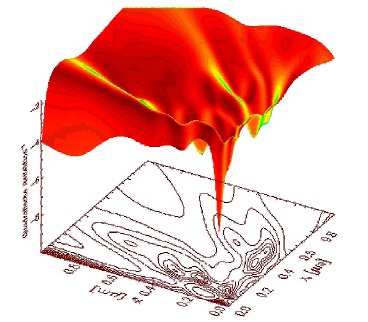
Global Optimization



Multi Criteria Design



Robust Design



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Application Map / FEM-2

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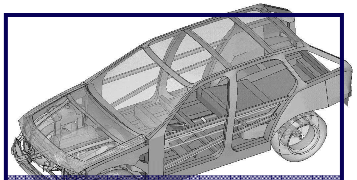
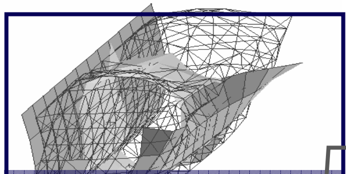
Finite Element Modelling

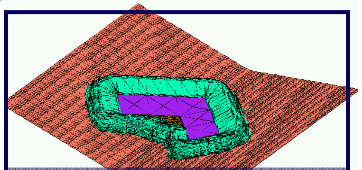


Car Body Design

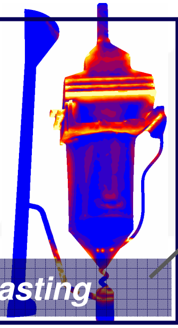


Air Bag Design

Inflatable Knee Bolster (Ford)



Metal Stamping



Casting

Optimal Casting Schedule for Turbine Blades (Access Materials + Processes)

Safety Optimization – Pilot Study (BMW)

- MDO Crash / Statics / Dynamics
- MCO B-Pillar Side Crash
- MCO Shape of Engine Mount

MDO Car Body Concept Phase (VW)

- MDO Crash / Statics / Dynamics

Geometric Parameters & Forces (AutoForm®)

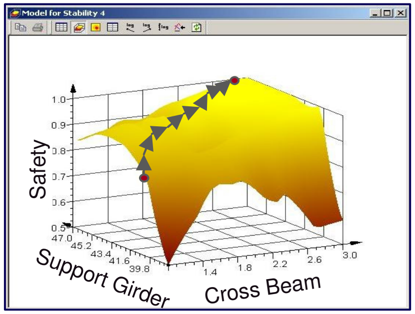
Metal Forming: (BMW)

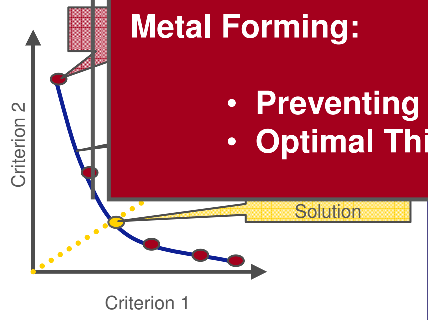
- Preventing Crack Formation
- Optimal Thinning

New ...

Multi ...

Experimental Results





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Application Map / CFD

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Finite Element Modelling

Comput. Fluid Dynamics

Numerical Modelling

Discrete Event Simulation

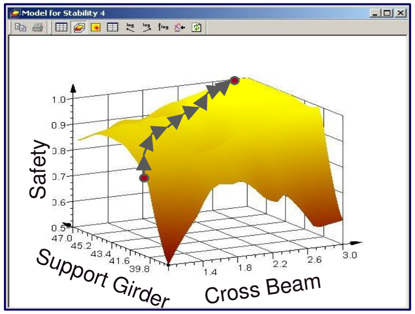
Agent Based Modelling

System Dynamics

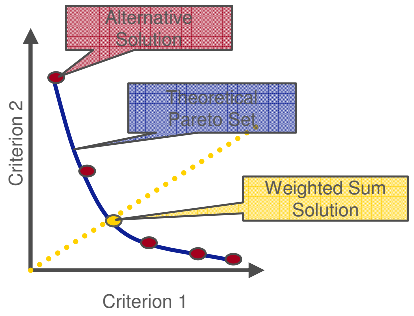
New Experiments

Experimental Results

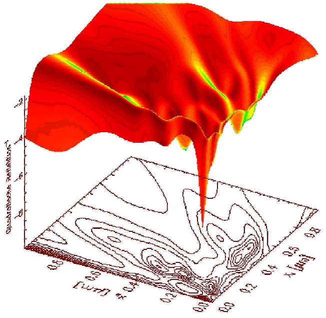
Global Optimization



Multi Criteria Design



Robust Design



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Application Map / CFD-2

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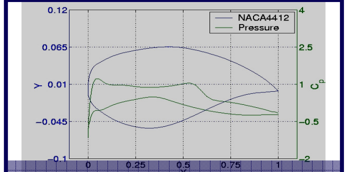
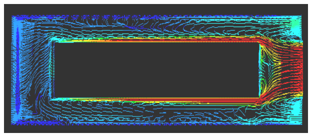
New Experiments

Comput. Fluid Dynamics



Air Foil Desing

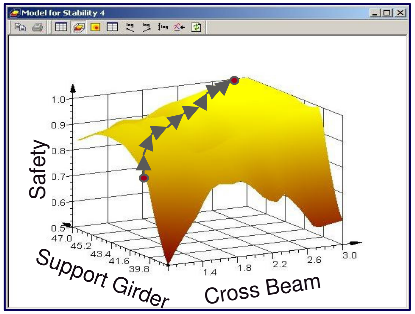


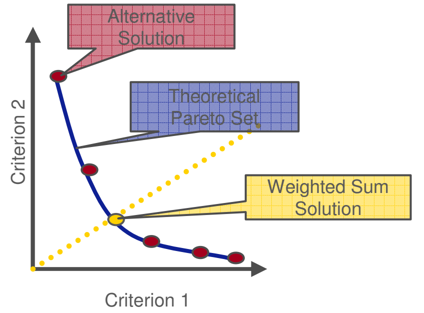
Siemens C Process

Siemens C Reactor: Monocrystal Growth of Silicium Core

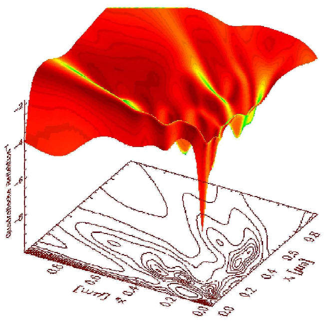
Multipoint Airfoil Optimization: High Lift vers. Low Drag

Global Op





Robust Design



Experimental Results

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Application Map / NM

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Finite Element Modelling

Comput. Fluid Dynamics

Numerical Modelling

Discrete Event Simulation

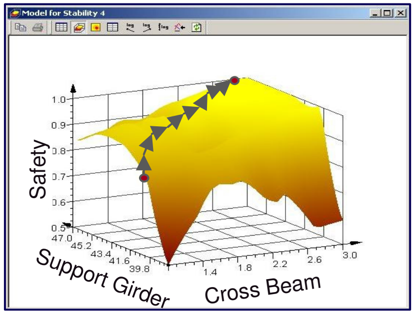
Agent Based Modelling

System Dynamics

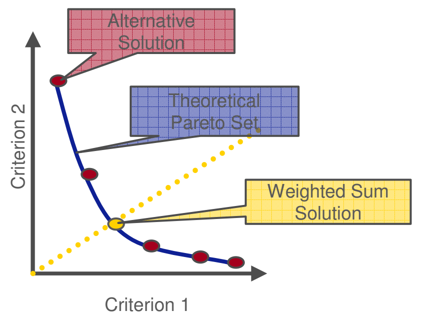
New Experiments

Experimental Results

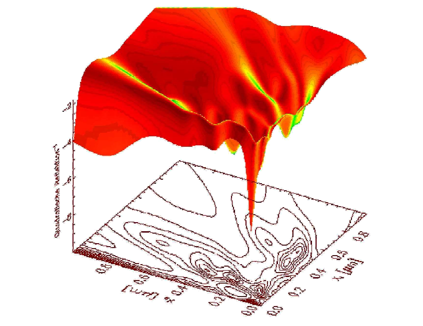
Global Optimization



Multi Criteria Design



Robust Design



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Application Map / NM-2

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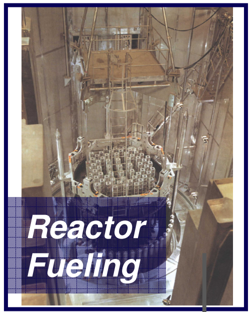
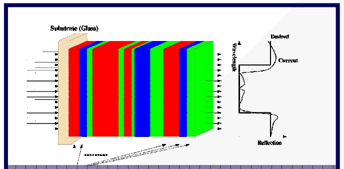
Numerical Modelling



Reactor Fueling



Optical Systems

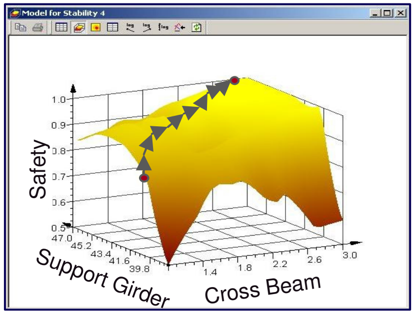
Optimize Fuel Assembly Reload Patterns — SIEMENS

Optical Coatings: Optimize Reflection — CORNING

New Experiments

Experimental Results

Global Optimization



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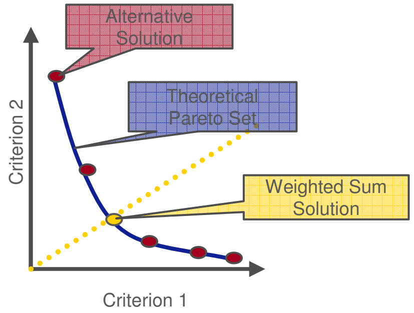

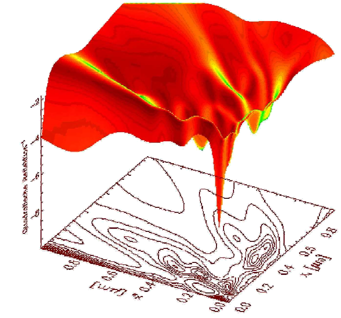

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Application Map / DES

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Finite Element Modelling

Comput. Fluid Dynamics

Numerical Modelling

Discrete Event Simulation

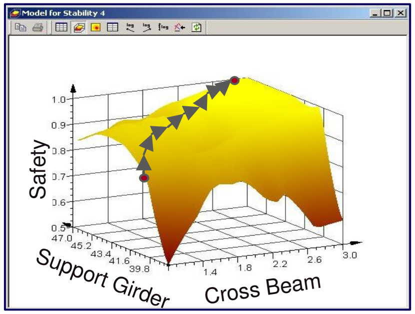
Agent Based Modelling

System Dynamics

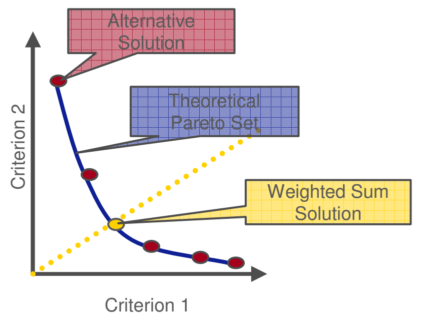
New Experiments

Experimental Results

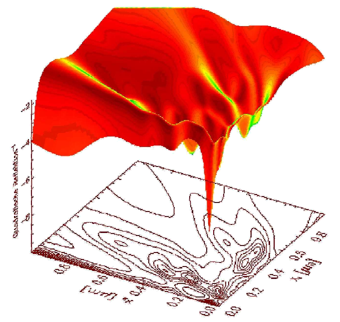
Global Optimization



Multi Criteria Design



Robust Design



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Application Map / DES-2

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Traffic Dependend Dynamic Optimization Ministerie van Verkeer en Waterstaat

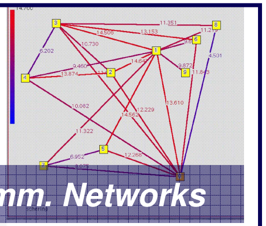
Routing Table Optimization SIEMENS

New Experiments

Experimental Results

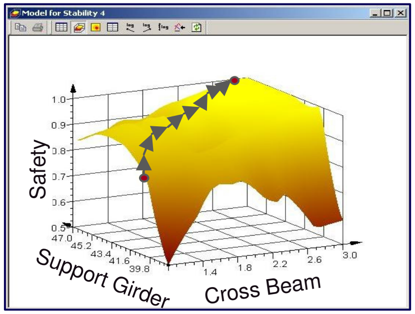
Discrete Event Simulation

Traffic Control

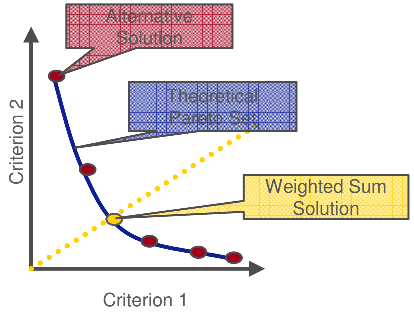


Comm. Networks

Global Optimization



Multi Criteria Design



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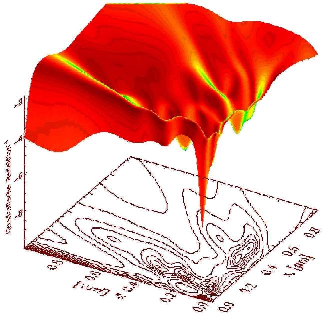

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Application Map / ABM

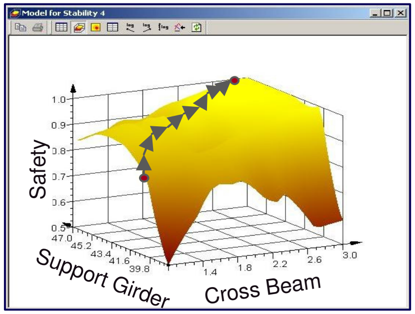
ClearVu Engineering™

- Finite Element Modelling
- Comput. Fluid Dynamics
- Numerical Modelling
- Discrete Event Simulation
- **Agent Based Modelling**
- System Dynamics

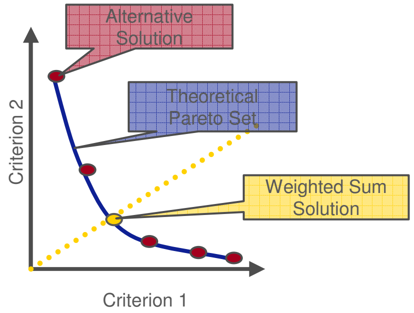
New Experiments

Experimental Results

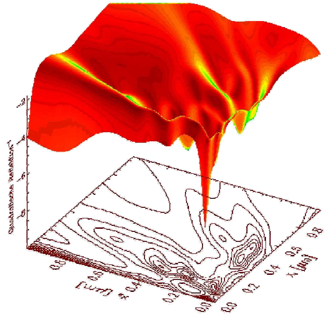
Global Optimization



Multi Criteria Design



Robust Design



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Application Map / ABM-2

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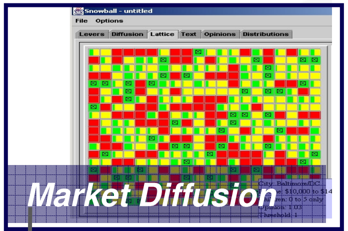
New Experiments

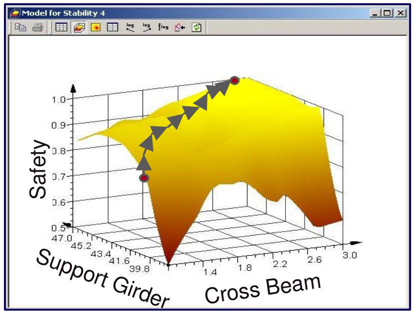
Agent Based Modelling

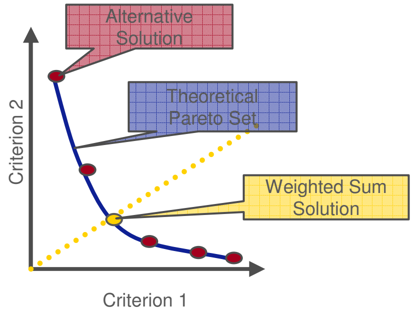
Market Diffusion



Modelling Consumer Behavior

Global Optimization





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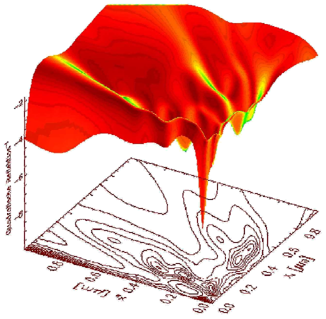

Experimental Results

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Application Map / SD

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Finite Element Modelling

Comput. Fluid Dynamics

Numerical Modelling

Discrete Event Simulation

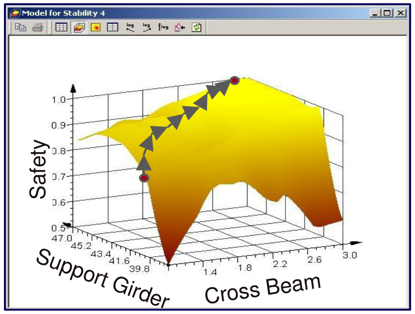
Agent Based Modelling

System Dynamics

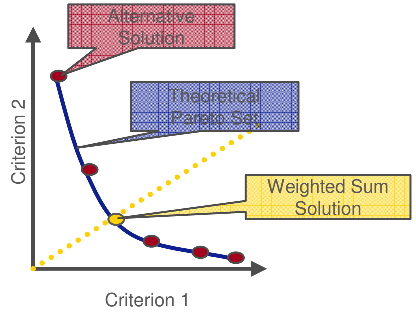
New Experiments

Experimental Results

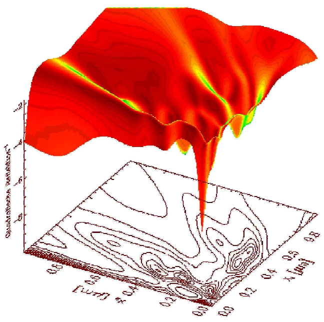
Global Optimization



Multi Criteria Design



Robust Design



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Application Map / SD-2

Corporate Planning:

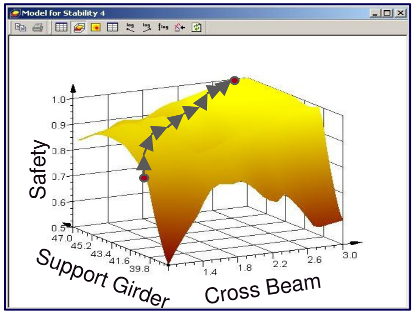
- **Capacity Planning; Very Large Time Scales**
- **Price Dynamics**
- **CO_2 - Trading**

System Dynamics

New E

Experimental Results

Global Optimization



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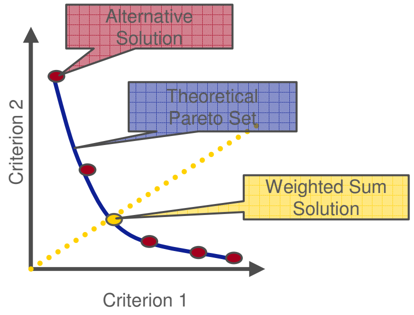

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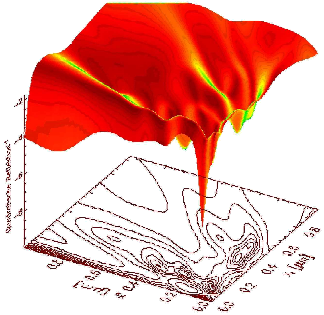

Application Map / End

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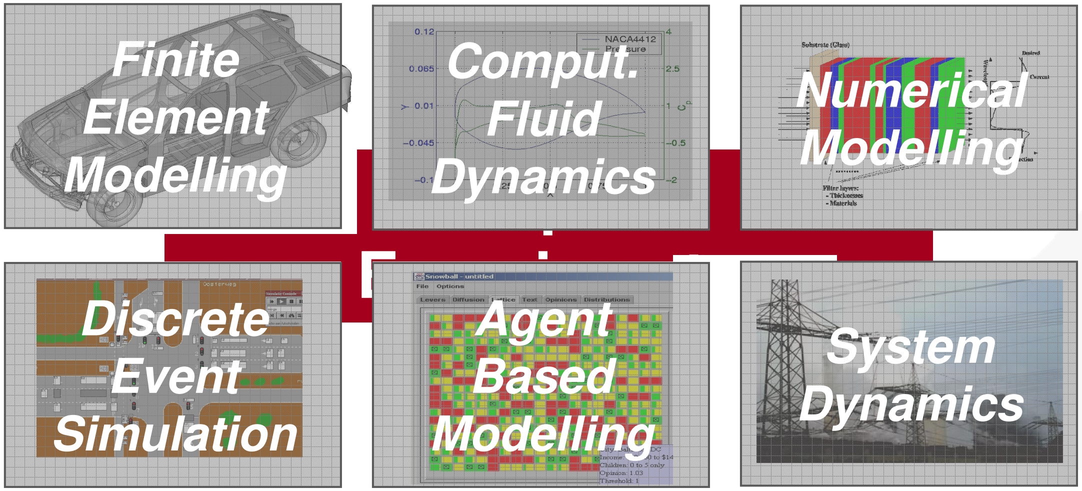
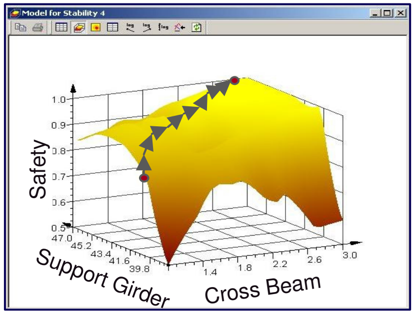
transformational solutions



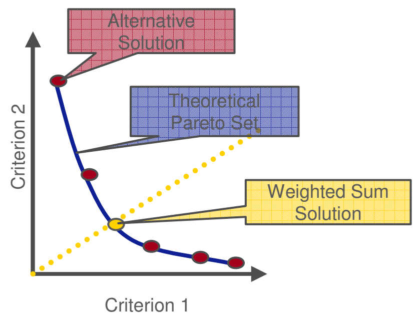
New Experiments

Experimental Results

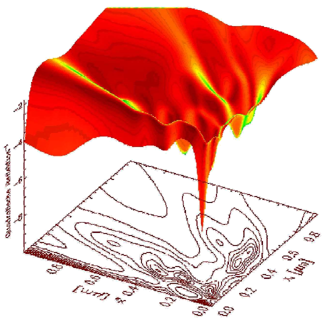
Global Optimization



Multi Criteria Design



Robust Design



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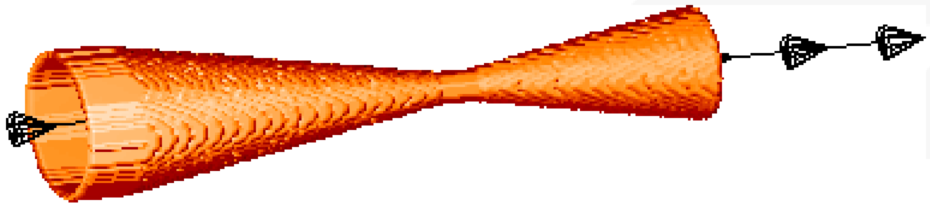
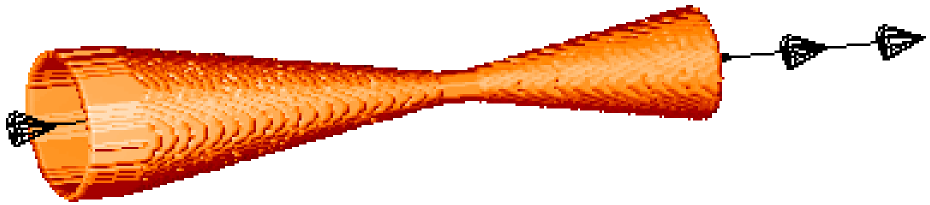
Engineering Optimization

Optimization Creating Innovation

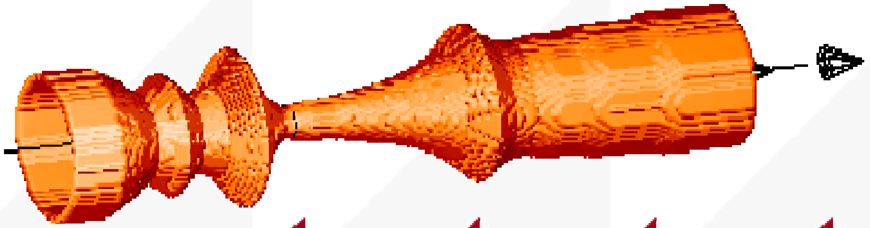
- Illustrative Example: Optimize Efficiency
  - Initial:



  - Evolution:



- 32% Improvement in Efficiency !



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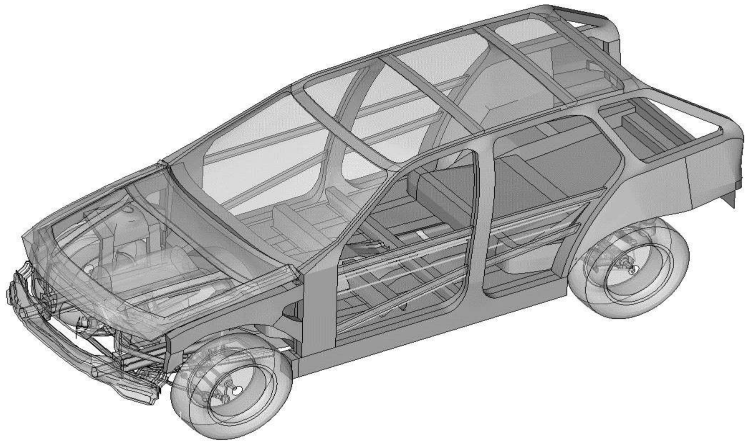
Safety Optimization – Pilot Study

- 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

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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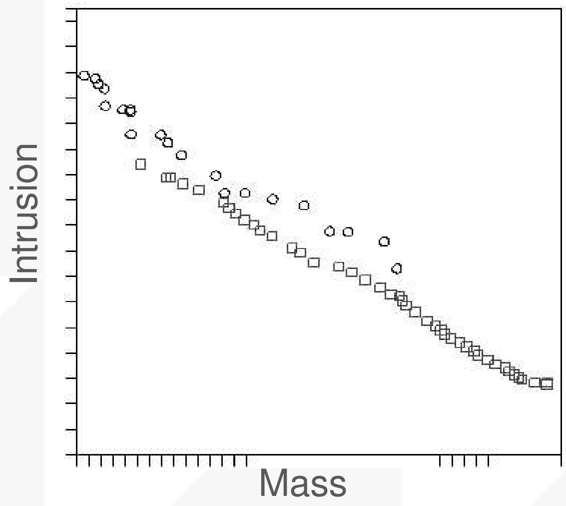
MCO B-Pillar – Side Crash

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

- ES successfully developed Pareto front



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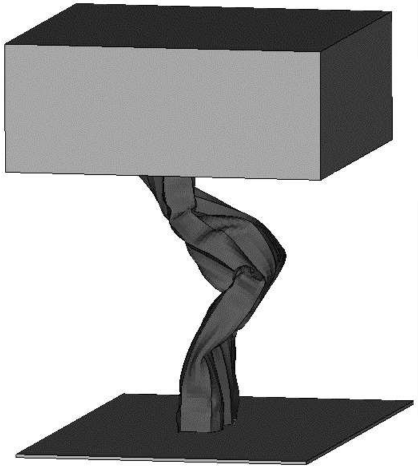
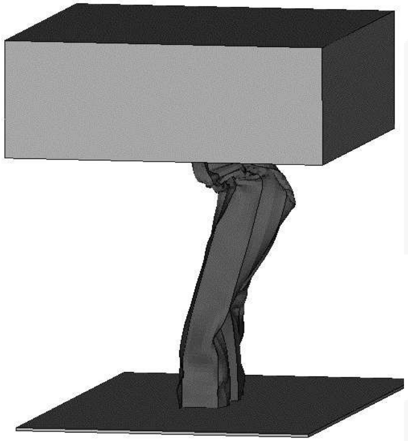
MCO Shape of Engine Mount

- 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





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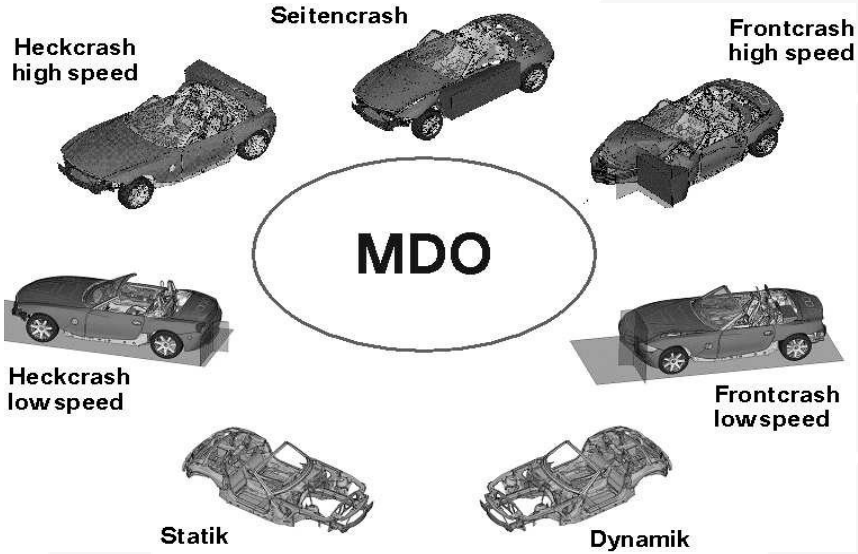
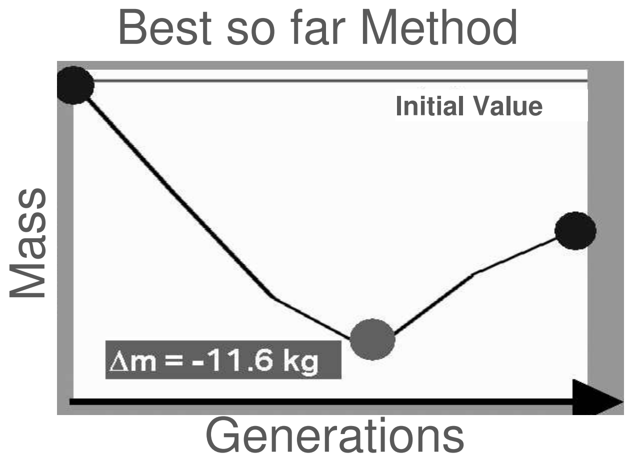
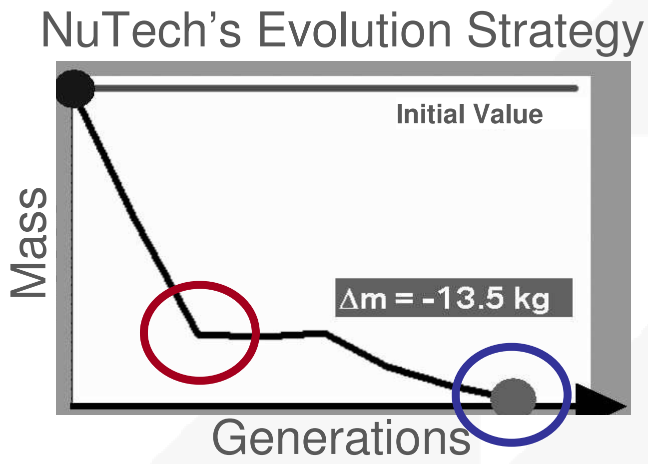
Safety Optimization – Example of use

- 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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Mixed-Integer Evolution Strategies

Mixed-Integer Evolution Strategy

- Optimization Task Definition:

$$f(r_1, \ldots, r_{n_r}, z_1, \ldots, z_{n_z}, d_1, \ldots, d_{n_d}) \rightarrow min$$

subject to:

$$r_i \in [r_i^{min}, r_i^{max}] \subset \mathbb{R}, \;\; i = 1, \ldots, n_r$$

$$z_i \in [z_i^{min}, z_i^{max}] \subset \mathbb{Z}, \;\; i = 1, \ldots, n_z$$

$$d_i \in D_i = \{d_{i,1}, \ldots, d_{i,|D_i|}\}, i = 1, \ldots, n_d$$

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Mixed-Integer Evolution Strategy

- Mutation operator:

for $i = 1, \ldots, n_r$ **do**
  $s_i' \leftarrow s_i \exp(\tau_g \mathrm{N}_g + \tau_l \mathrm{N}(0,1))$
  $r_i' = r_i + N(0, s_i')$
end for
for $i = 1, \ldots, n_z$ **do**
  $q_i' \leftarrow q_i \exp(\tau_g \mathrm{N}_g + \tau_l \mathrm{N}(0,1))$
  $z_i' \leftarrow z_i + \mathrm{G}(0, q_i')$
end for
$p_i' := 1/[1 + \frac{1-p_i}{p_i} * \exp(-\tau_l * \mathrm{N}(0,1))]$
for $i \in \{1, \ldots, n_d\}$ **do**
  if $\mathrm{U}(0,1) < p_i'$ **then**
    $d_i' \leftarrow$ uniformly randomly value from D_i
  end if
end for

Learning rates (local)

Learning rates (global)

Geometrical distribution

Mutation probabilities

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Application Examples

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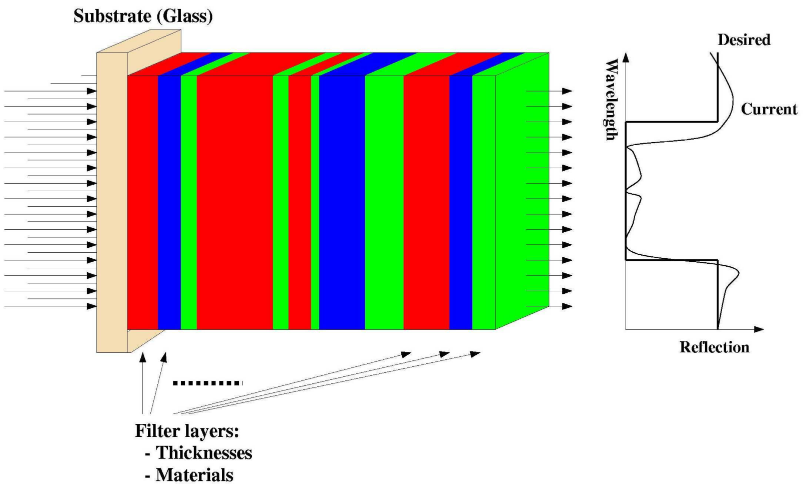
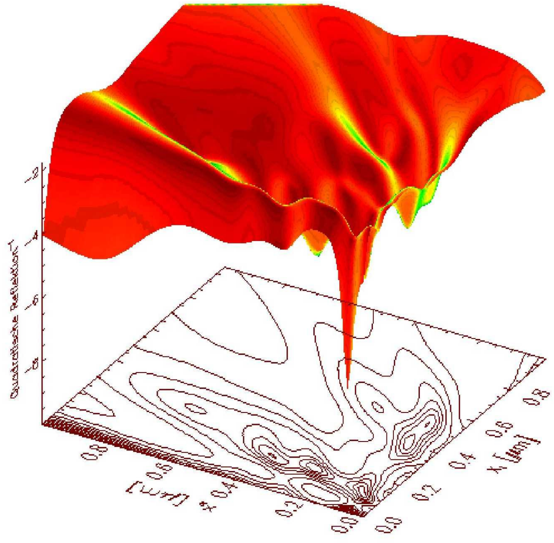
Example: Optical Coating Design





- Nonlinear, mixed-integer
- Variable dimensionality
- Minimize deviation from desired performance
- Excellent synthesis method

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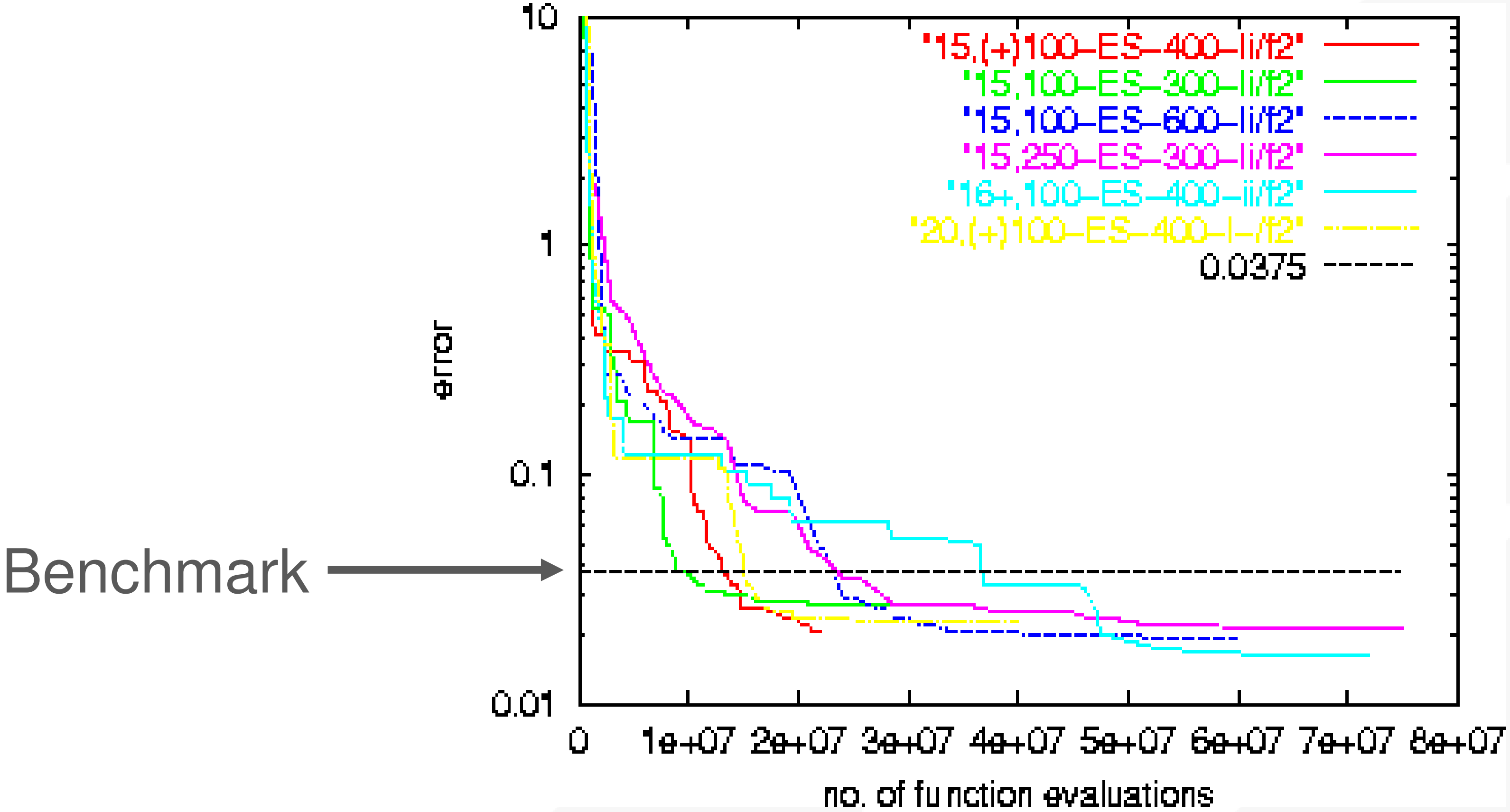
Example: Optical Coating Design

$$quality = \sum_{i=1}^{15} weight_i \cdot \left(\frac{calculated_i - desired_i}{scale_i} \right)^2 \rightarrow \min$$

- Dielectric filter design
- $n=40$ layers
- Layer thicknesses x_i in [0.01, 10.0]
- Quality: Sum of quadratic penalty terms

Example: Results



- Factor 2 in quality, 10 in effort !
- Reliable, repeatable results

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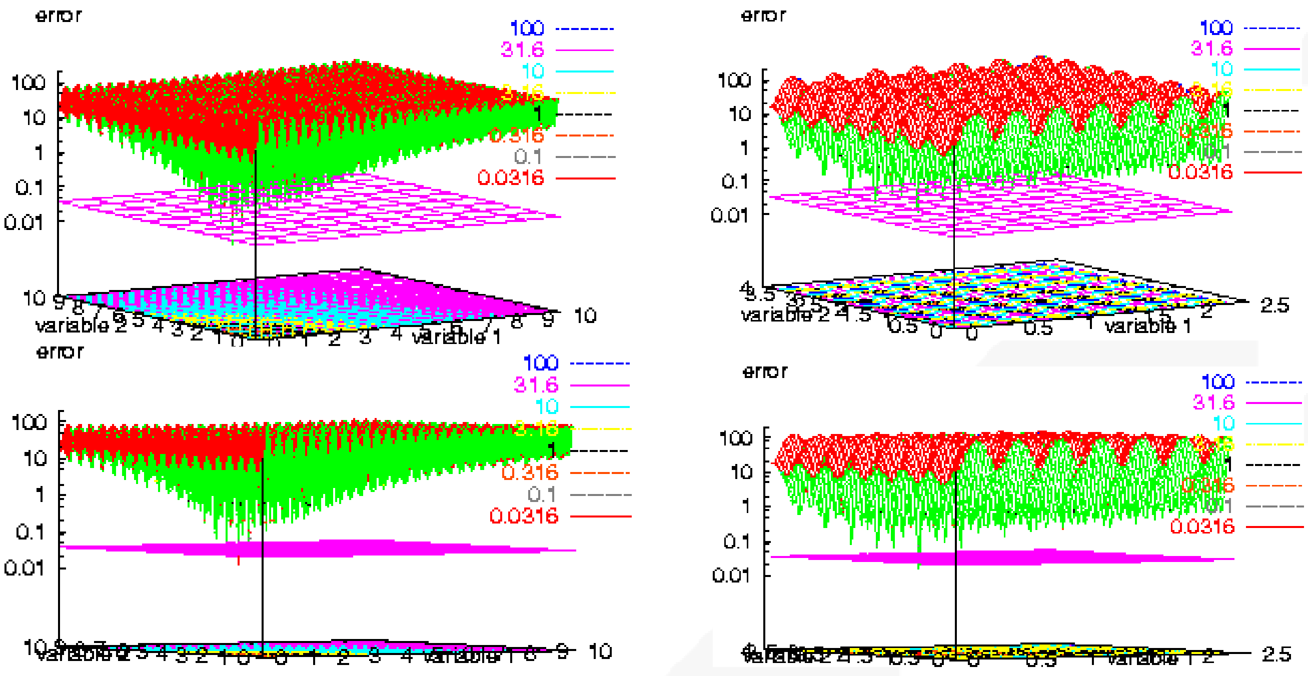
Example: Problem Topology



- Vicinity of global optimum

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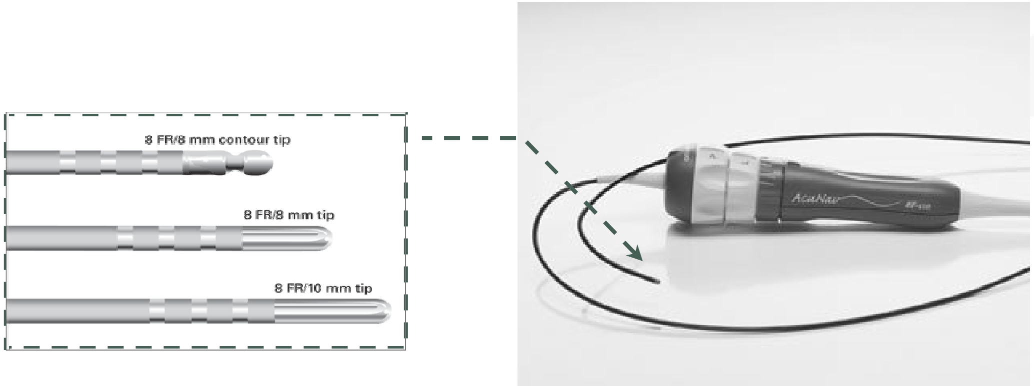
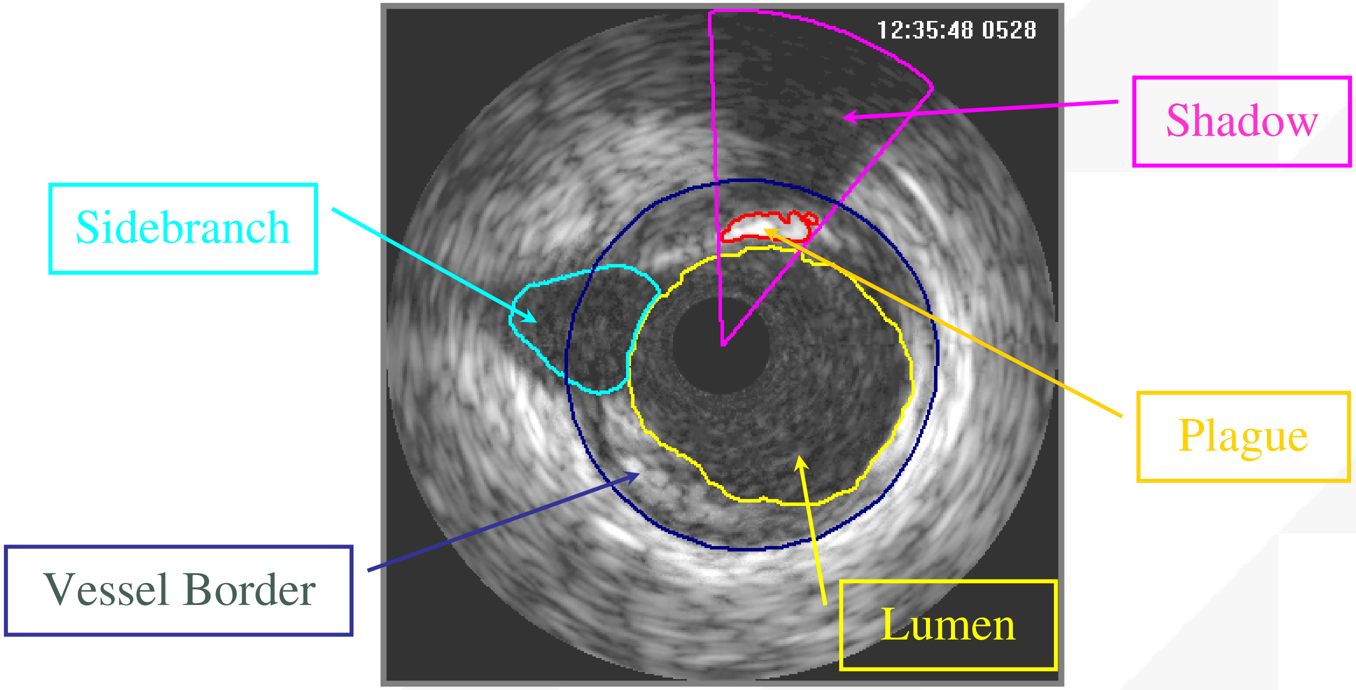
Example: Intravascular Ultrasound Image Analysis

- Real-time high-resolution tomographic images from the inside of coronary vessels:



Intravascular Ultrasound Image Analysis

- Detected Features in an IVUS Image:



Experimental Results on IVUS images

- Parameters for the lumen feature detector

name	type	range	dependencies	default
	—			
maxgray	integer	[2, 150]	$>$ mingray	35
mingray	integer	[1, 149]	$<$ maxgray	1
connectivity	ordinal	4,6,8		6
relativeopenings	boolean	{false,true}		true
nrofcloses	integer	[0, 100]	used if not relativeopenings	5
nrofopenings	integer	[0, 100]	used if not relativeopenings	45
scanlinedir	ordinal	{0,1,2}		1
scanindexleft	integer	[-100, 100]	$<$ scanindexright	-55
scanindexright	integer	[-100, 100]	$>$ scanindexleft	7
centermethod	ordinal	{0,1}		1
fitmodel	ordinal	{ellipse, circel}		ellipse
sigma	continuous	[0.5 10.0]		0.8
scantype	ordinal	{0,1,2}		0
sidestep	integer	[0, 20]		3
sidecost	continuous	[0.0, 100]		5
nroflines	integer	[32, 256]		128

Intravascular Ultrasound Image Analysis: Results

- On each of 5 data sets algorithm ran for 2804 evaluations – 19,5h of total computing time

dataset	default parameters		parameter solution 1		parameter solution 2		parameter solution 3		parameter solution 4		parameter solution 5	
	fitness	s.d.	fitness	s.d.	fitness	s.d.	fitness	s.d.	fitness	s.d.	fitness	s.d.
1	395.2	86.2	148.4	39.5	159.8	43.5	185.4	43.0	144.8	42.0	271.0	74.8
2	400.2	109.2	183.3	59.2	180.7	58.4	207.2	69.2	232.7	71.0	352.0	73.1
3	344.8	65.6	205.9	69.8	203.9	70.1	164.4	49.7	183.9	80.3	327.1	55.9
4	483.1	110.6	284.4	92.7	269.0	73.2	250.4	80.4	173.2	64.7	330.1	82.2
5	444.2	90.6	368.4	100.9	370.9	102.5	462.2	377.3	168.7	64.0	171.8	54.5

Performance of the best found MI-ES parameter solutions

- A paired two-tailed t-test was performed on the difference measurements for each image dataset using a 95% confidence interval (p=0.05)
- The null-hypothesis is that the mean difference results of the best MI-ES individual and the default parameters are equal.

- Significant improvement over expert tuning

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Other Examples

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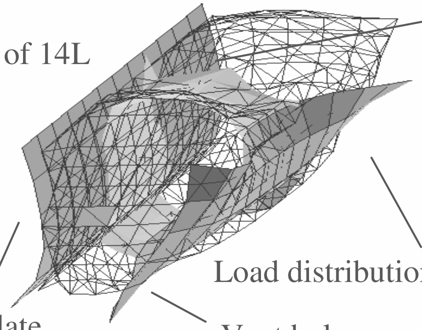
Inflatable Knee Bolster

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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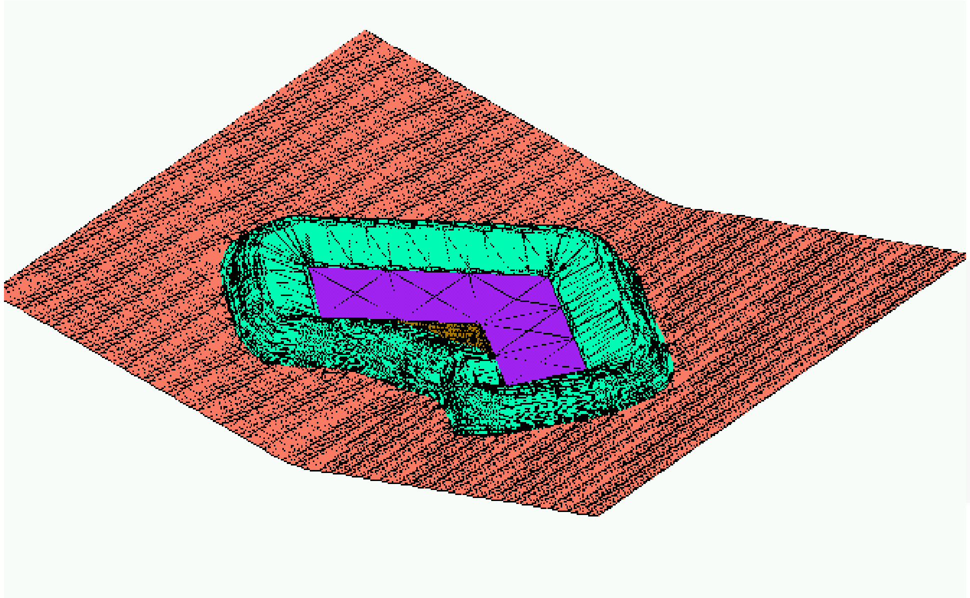
Optimization of metal stamping process

AutoForm® FEM-Simulation Software for Sheet Metal Forming



- **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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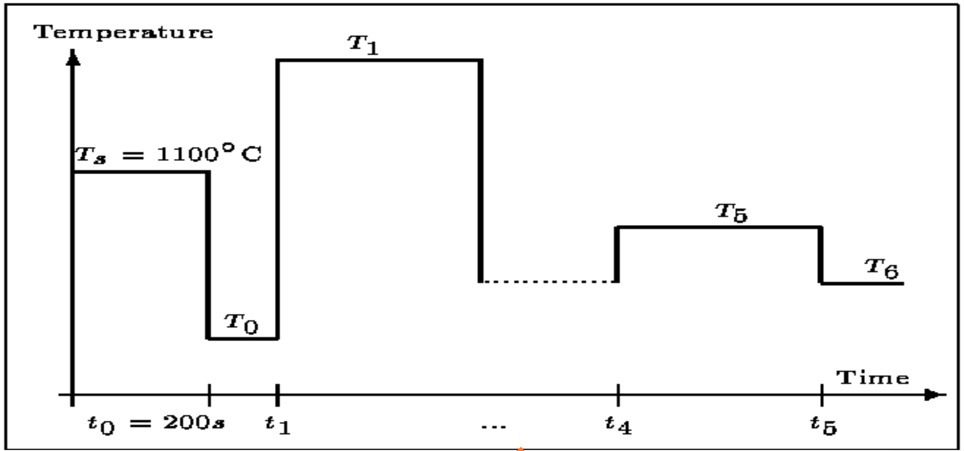
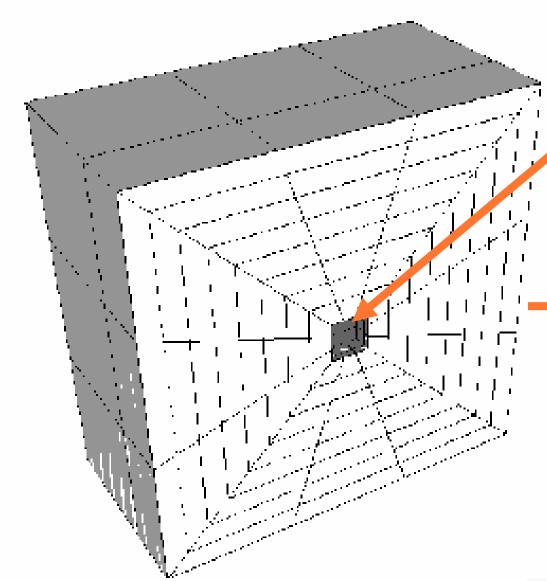
Steel Cube Temperature Control

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



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



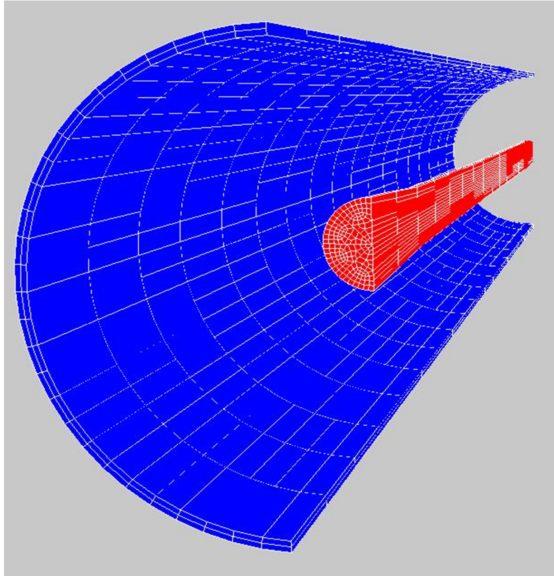
$$\Delta T_{max}$$

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

NuTech Solutions science for business — Access Materials + Processes — RWTH AACHEN RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Siemens C Reactor

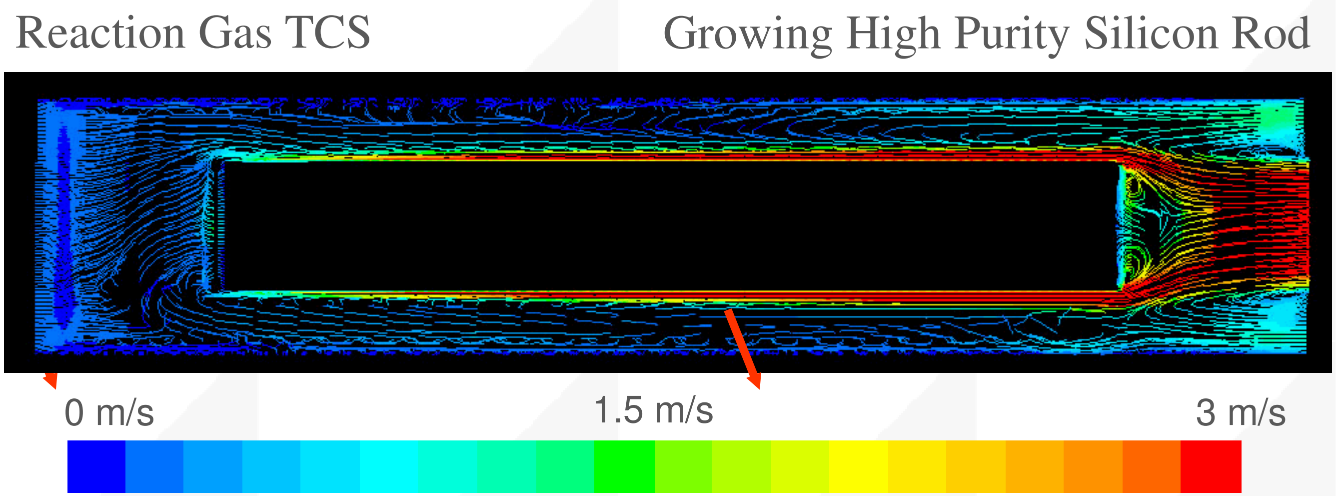
- Maximisation of growth speed
- Minimisation of diameter differences



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

Optimsation of 15 process parameters:

Production time 35 hours → 30 hours



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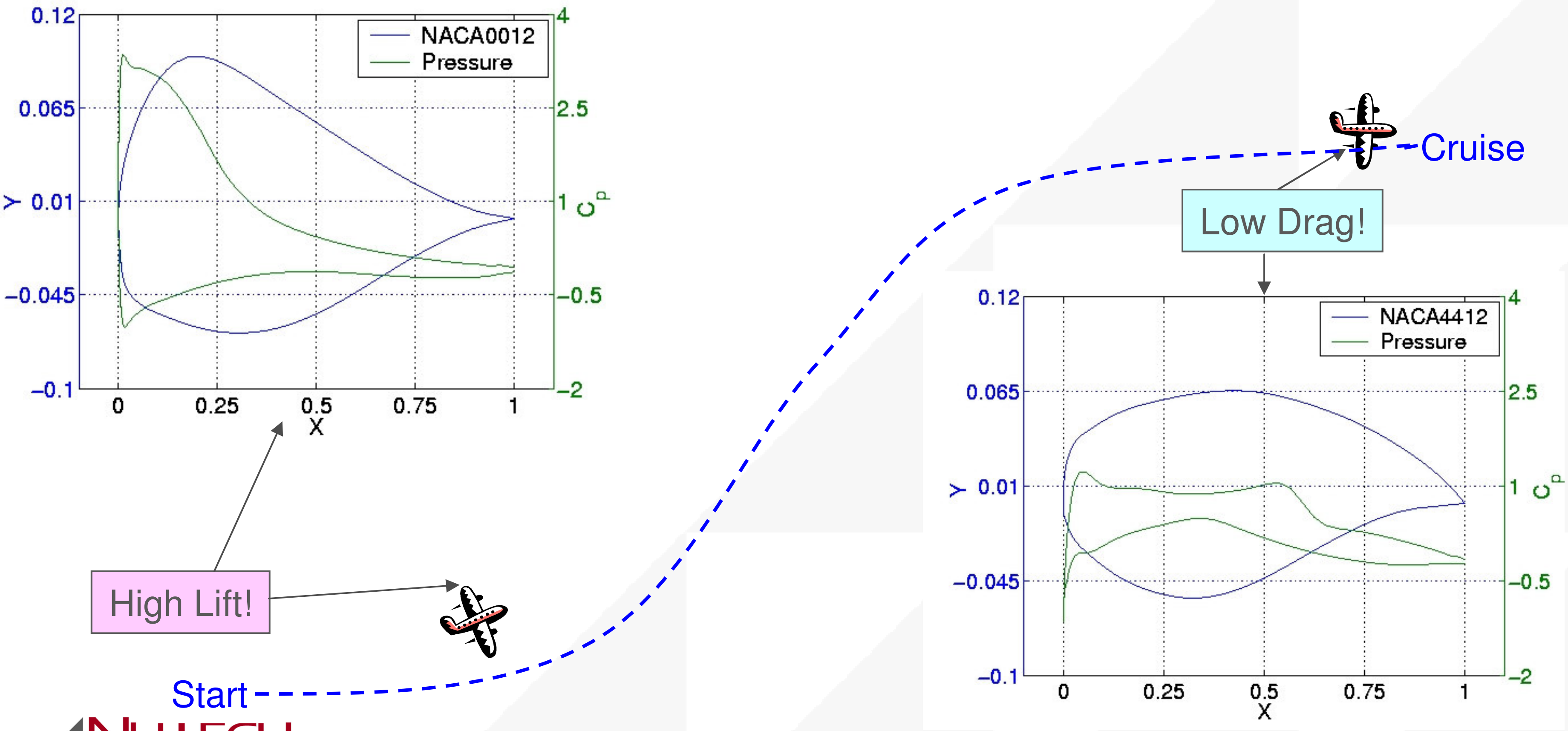
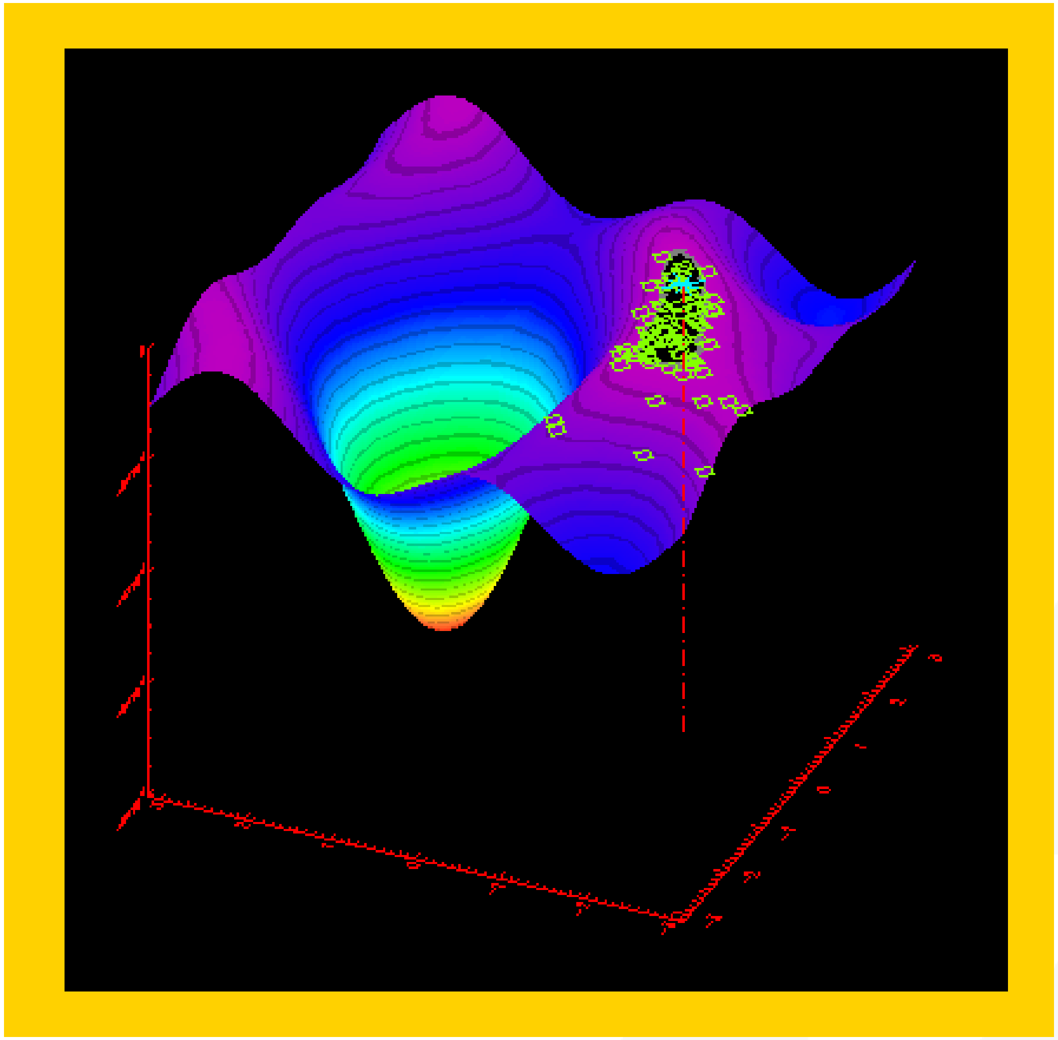
Multipoint Airfoil Optimiziation

- **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



Optimum tracking of an ES



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

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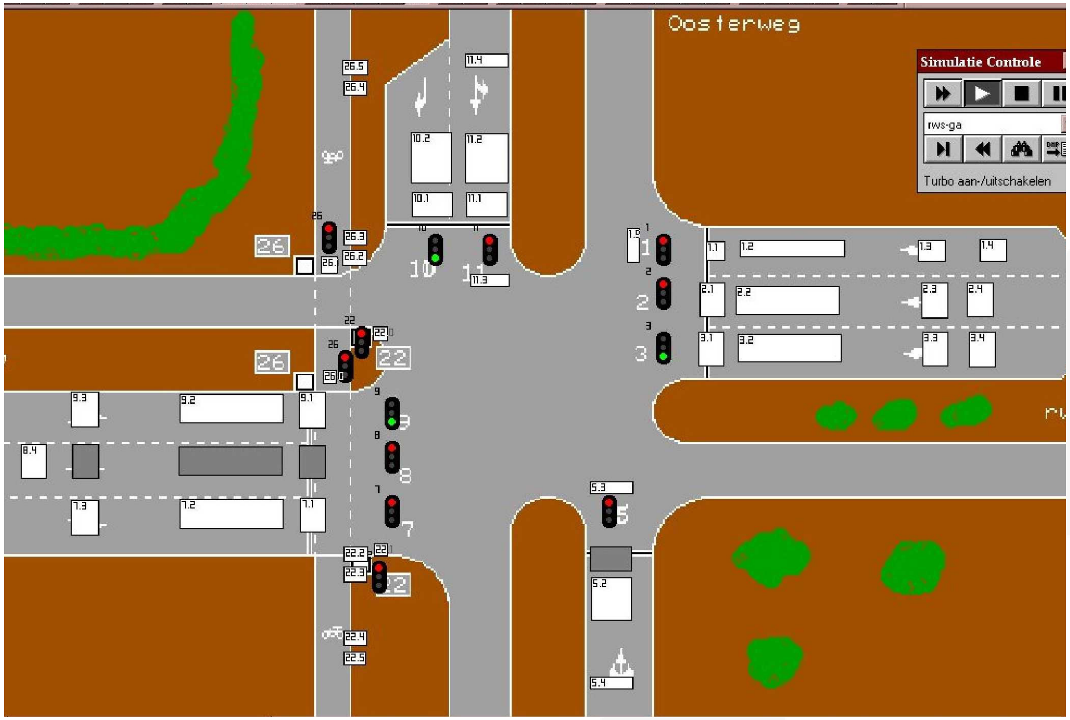
Traffic Light Control Optimization



- **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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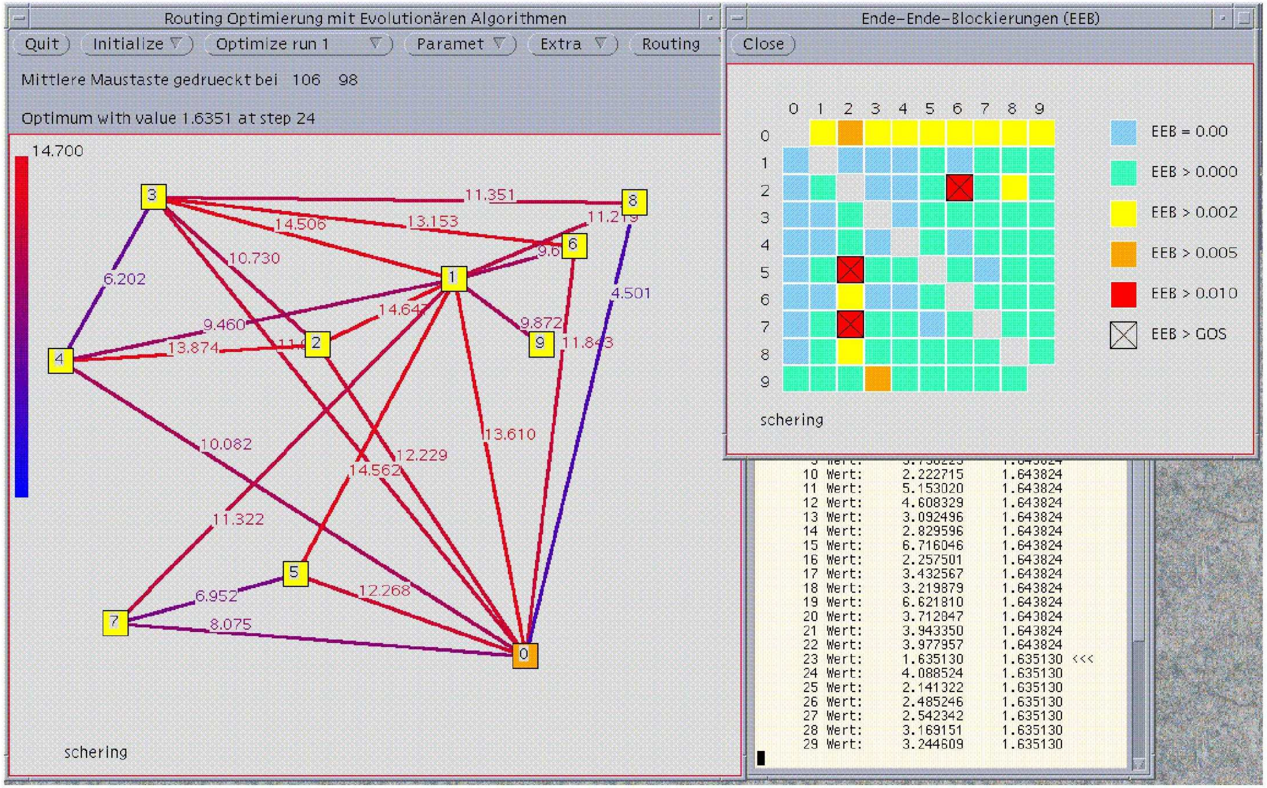
Ministerie van Verkeer en Waterstaat

Optimization of elevator control

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

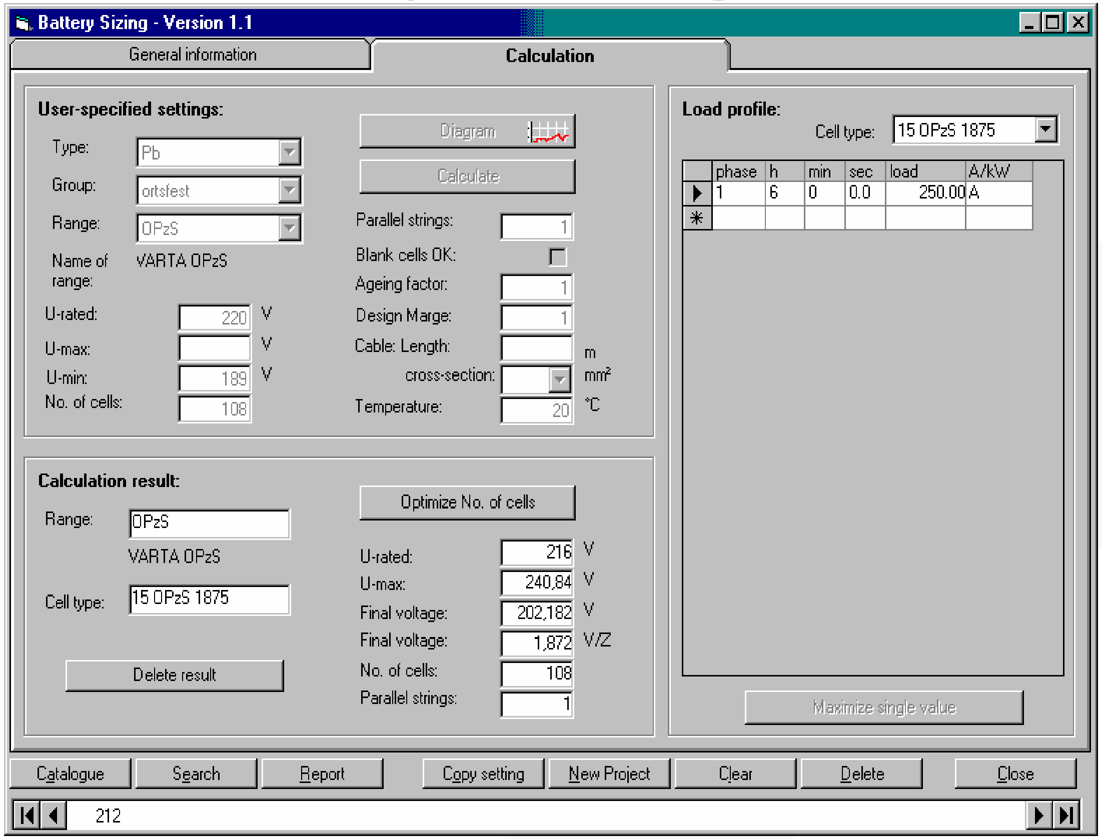
Optimization of network routing



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

Automatic battery configuration

HAWKER BATTERIEN
Standby Batteries Germany



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

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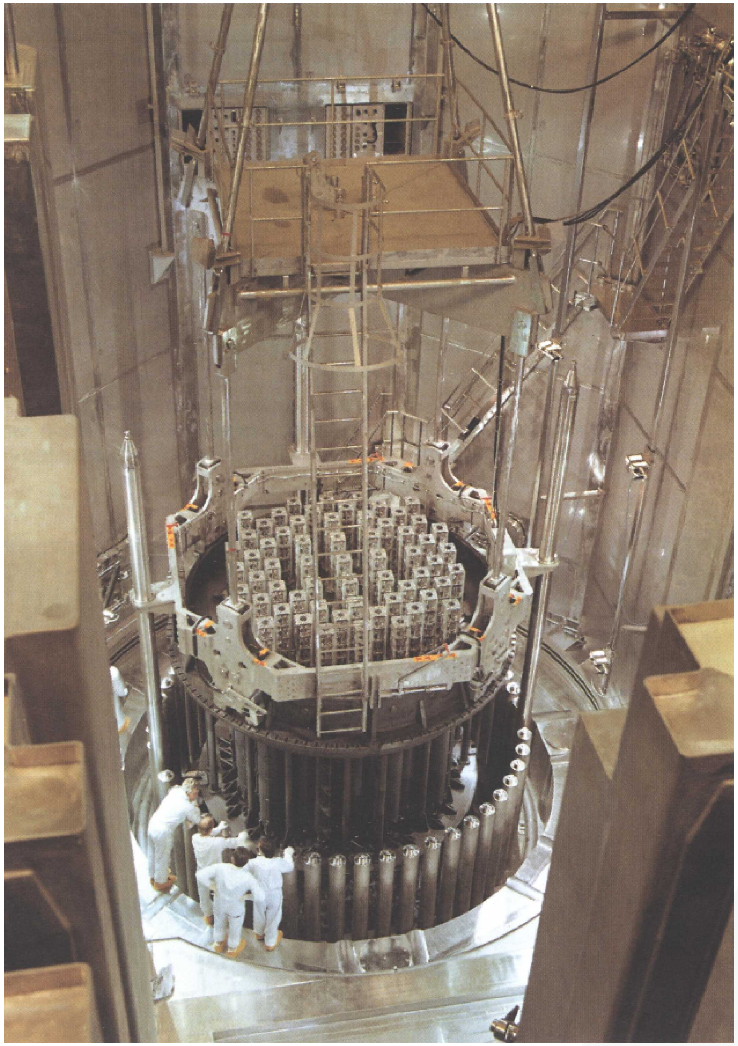
Optimization of reactor fueling.

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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Final Remarks

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Is it Worth Doing It ?

- Many competitors – indicates importance
- Having the best algorithm helps
- Having an easy to use algorithm is more important
- Self-adaptation is a wonderful feature
- You need to be fast & good
- Workflow integration is highest priority
- It‘s tough to make them pay what it is really worth !

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

Partnership

ANALYSIS

SOFTWARE

ENGINEERING

....

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

Thank you for your Attention !

Questions ?