Two Examples of Integrated Optimization

Evolutionary Computing in Practice

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Thomas Bäck, Chief Scientist
Ulrich Hammel, Senior Scientist
NuTech Solutions, Inc.
baeck@nutechsolutions.de
www.nutechsolutions.com
Overview

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

Function

\[ \text{quality} = \sum_{i=1}^{n} \text{weight}_i \cdot \left( \frac{\text{calculated}_i - \text{desired}_i}{\text{scale}_i} \right)^2 \]

Model from Data

Subjective

Function(s)

Simulation

Experiment

Business Process Model

Evaluation

EA-Optimizer
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
Requirements II

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

- Automotive
- Aerospace
- Chemistry
- Engines, Turbines
- ...

[Logos of various companies like BMW, Volkswagen, GM, Honda, Ford, GE, Bayer, Corning, Siemens, and NUtech Solutions]
A Solution for ...

Intelligent Computing

Intelligent Computing

(Expensive) Computer Experiments

A Challenging Example: Car Body Design

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

Optimum

Unknown Landscape

Known Solution

Global Optimization

3rd Party Simulator

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
How it Works

Front-End

Project Datagram
Session Controller
controls

Project Datagram

Project Datagram

Data- & Project Management

Simulator Input File
Simulator Result File

3rd Party Simulator
3rd Party Contr.
3rd Party Contr.

3rd Party Contr.

3rd Party Contr.

Intelligent Business Engines

IBE
Features and Architecture

Unique Features:

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

ClearVu Engineering

CV/E Kernel

Modules

- CV/E Global Optimization
- CV/E Distributed Computation
- CV/E Design of Experiments
- CV/E Robust Design
- CV/E Meta Modelling
Unique Features

- Extensible XML-based Architecture
- Platform independent
- Runs 24/7 --- Hot-Plug Update
- Fast Adaptive Search
- Multi Criteria Design
- Thin Redundant Master
- ...
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
Project Templates
CV/E Global Optimizer

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

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-adaptive
- utilizes parallelism
- can deal with huge dimensions
- can deal with infeasible start designs
- can deal with mixed-integer spaces

Self-Adaptation of step sizes and directions
Multi Criteria Design

Multi Criteria Design:
Find the whole set of optimal compromises

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

Theoretical Pareto Set

Alternative Solution

Weighted Sum Solution
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
Some Examples
Application Map / FEM-2

**Finite Element Modelling**

- Car Body Design
- Air Bag Design
- Metal Stamping
- Casting

**Safety Optimization – Pilot Study**
- MDO Crash / Statics / Dynamics
- MCO B-Pillar Side Crash
- MCO Shape of Engine Mount

**MDO Car Body Concept Phase**
- MDO Crash / Statics / Dynamics

**Geometric Parameters & Forces**
- Metal Forming:
  - Preventing Crack Formation
  - Optimal Thinning

**New Experiments**
- Experimental Results

**Experimental Results**
- Inflatable Knee Bolster
- Optimal Casting Schedule for Turbine Blades

**ClearVu Engineering**

**ClearVu Solutions**
Application Map / CFD

Finite Element Modelling

Comput. Fluid Dynamics

Numerical Modelling

Discrete Event Simulation

Agent Based Modelling

System Dynamics

New Experiments

Global Optimization

Multi Criteria Design

Robust Design

Experimental Results
Application Map / CFD-2

- **Comput. Fluid Dynamics**
  - Air Foil Design
  - Siemens C Process
- **New Experiments**
- **Experimental Results**
- **Global Optimization**
  - Multipoint Airfoil Optimization: High Lift vers. Low Drag
- **Robust Design**
  - Weighted Sum Solution
  - Criterion 1
  - Criterion 2
- **Siemens C Reactor: Monocrystal Growth of Silicium Core**
Application Map / NM

- 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

Weighted Sum Solution

Criterion 2

Criterion 1
Application Map / NM-2

- New Experiments
- Experimental Results

- Reactor Fueling
- Numerical Modelling
- Optical Systems
- Optical Coatings: Optimize Reflection

- Global Optimization
  - Optimize Fuel Assembly Reload Patterns
  - Support Girder, Cross Beam, Safety

- Multi Criteria Design
  - Weighted Sum Solution
  - Criterion 1
  - Criterion 2

- Global Optimization
- Multi Criteria Design
- Reactor Fueling
- Numerical Modelling
- Optical Systems
- Optical Coatings: Optimize Reflection

- Global Optimization
  - Optimize Fuel Assembly Reload Patterns
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- Multi Criteria Design
  - Weighted Sum Solution
  - Criterion 1
  - Criterion 2
Application Map / DES

- Finite Element Modelling
- Comput. Fluid Dynamics
- Numerical Modelling
- Discrete Event Simulation
- Agent Based Modelling
- System Dynamics
- Global Optimization
- Multi Criteria Design
- Robust Design

New Experiments
- Computer Experiments
- Numerical Modelling
- Com.Fluid Dynamics
- Agent Based Simulation
- System Dynamics

Experimental Results
- Finite Element Modelling
- Comput. Fluid Dynamics
- Numerical Modelling
- Discrete Event Simulation
- Agent Based Modelling
- System Dynamics
- Global Optimization
- Multi Criteria Design
- Robust Design
Application Map / DES-2

Traffic Dependend Dynamic Optimization

New Experiments

Discrete Event Simulation

Global Optimization

Support Girder

Cross Beam

Safety

Multi Criteria Design

Weighted Sum Solution

Criterion 1

Criterion 2

Robust Design

Routing Table Optimization

Experimental Results

Comm. Networks

Traffic Control
Application Map / ABM

New Experiments

Experimental Results

Global Optimization

Multi Criteria Design

Robust Design

Finite Element Modelling

Comput. Fluid Dynamics

Numerical Modelling

Discrete Event Simulation

Agent Based Modelling

System Dynamics

Global Optimization

Multi Criteria Design

Robust Design

Safety

Support Girder

Cross Beam

Criterion 1

Criterion 2

Weighted Sum Solution
Application Map / ABM-2

New Experiments

Experimental Results

Agent Based Modelling

Market Diffusion

Modelling Consumer Behavior

Global Optimization

Robust Design

Safety
Support Girder
Cross Beam

Weighted Sum Solution

Criterion 1
Criterion 2

Criterion 1
Criterion 2
Corporate Planning:

- Capacity Planning; Very Large Time Scales
- Price Dynamics
- CO₂ - Trading

System Dynamics

Global Optimization

Multi Criteria Design

Robust Design
Application Map / End

- Finite Element Modelling
- Computational Fluid Dynamics
- Numerical Modelling
- Discrete Event Simulation
- Agent Based Modelling
- System Dynamics
- Global Optimization
- Multi Criteria Design
- Robust Design

New Experiments
Experimental Results

- Computer Experiments
- Discrete Event Simulation
- Numerical Modelling
- Comput. Fluid Dynamics
- System Dynamics
- Finite Element Modelling
- Agent Based Modelling
- Robust Design
- Multi Criteria Design
- Global Optimization
Engineering Optimization
Optimization Creating Innovation

Illustrative Example: Optimize Efficiency

Initial:

Evolution:

32% Improvement in Efficiency!
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

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Avg. reduction (kg)</th>
<th>Max. reduction (kg)</th>
<th>Min. reduction (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best so far</td>
<td>-6.6</td>
<td>-8.3</td>
<td>-3.3</td>
</tr>
<tr>
<td>NuTech ES</td>
<td>-9.0</td>
<td>-13.4</td>
<td>-6.3</td>
</tr>
</tbody>
</table>
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
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:

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

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

\[
d_i \in D_i = \{d_{i,1}, \ldots, d_{i,|D_i|}\}, \quad i = 1, \ldots, n_d
\]
Mixed-Integer Evolution Strategy

Mutation operator:

\[
\begin{align*}
&\text{for } i = 1, \ldots, n_r \text{ do } \\
&s_i' \leftarrow s_i \exp(\tau_g N_g + \tau_l N(0, 1)) \\
&r_i' = r_i + N(0, s_i') \\
&\text{end for} \\
&\text{for } i = 1, \ldots, n_z \text{ do } \\
&q_i' \leftarrow q_i \exp(\tau_g N_g + \tau_l N(0, 1)) \\
&z_i' = z_i + G(0, q_i') \\
&\text{end for} \\
&p_i' := \frac{1}{1 + \frac{1-p_i}{p_i} \exp(-\tau_l \cdot N(0, 1))} \\
&\text{for } i \in \{1, \ldots, n_d\} \text{ do } \\
&\quad \text{if } U(0, 1) < p_i' \text{ then } \\
&\qquad d_i' \leftarrow \text{uniformly randomly value from } D_i \\
&\quad \text{end if} \\
&\text{end for}
\end{align*}
\]
Application Examples
Example: Optical Coating Design

- Nonlinear, mixed-integer
- Variable dimensionality
- Minimize deviation from desired performance
- Excellent synthesis method
Example: Optical Coating Design

\[
\text{quality} = \sum_{i=1}^{15} \text{weight}_i \cdot \left( \frac{\text{calculated}_i - \text{desired}_i}{\text{scale}_i} \right)^2 \rightarrow \text{min}
\]

- 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
Example: Problem Topology

Vicinity of global optimum
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:

- Vessel Border
- Sidebranch
- Lumen
- Shadow
- Plaque
# Experimental Results on IVUS images

## Parameters for the lumen feature detector

<table>
<thead>
<tr>
<th>name</th>
<th>type</th>
<th>range</th>
<th>dependencies</th>
<th>default</th>
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<tbody>
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<td>integer</td>
<td>[2, 150]</td>
<td>&gt; mingray</td>
<td>35</td>
</tr>
<tr>
<td>mingray</td>
<td>integer</td>
<td>[1, 149]</td>
<td>&lt; maxgray</td>
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<td>ordinal</td>
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<td></td>
</tr>
<tr>
<td>relativeopenings</td>
<td>boolean</td>
<td>{false, true}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nrofcloses</td>
<td>integer</td>
<td>[0, 100]</td>
<td>used if not relativeopenings</td>
<td>5</td>
</tr>
<tr>
<td>nrofopenings</td>
<td>integer</td>
<td>[0, 100]</td>
<td>used if not relativeopenings</td>
<td>45</td>
</tr>
<tr>
<td>scanlindedir</td>
<td>ordinal</td>
<td>{0, 1, 2}</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>scanindexleft</td>
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<td>[-100, 100]</td>
<td>&lt; scanindexright</td>
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<td>&gt; scanindexleft</td>
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<td>{0, 1}</td>
<td></td>
<td>1</td>
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<tr>
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<td>{ellipse, circle}</td>
<td></td>
<td>ellipse</td>
</tr>
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<td>sigma</td>
<td>continuous</td>
<td>[0.5, 10.0]</td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>scantype</td>
<td>ordinal</td>
<td>{0, 1, 2}</td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>sidestep</td>
<td>integer</td>
<td>[0, 20]</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>sidecost</td>
<td>continuous</td>
<td>[0.0, 100]</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>nrofflines</td>
<td>integer</td>
<td>[32, 256]</td>
<td></td>
<td>128</td>
</tr>
</tbody>
</table>
Intravascular Ultrasound Image Analysis: Results

On each of 5 data sets algorithm ran for 2804 evaluations – 19.5h of total computing time

<table>
<thead>
<tr>
<th>dataset</th>
<th>default parameters</th>
<th>parameter solution 1</th>
<th>parameter solution 2</th>
<th>parameter solution 3</th>
<th>parameter solution 4</th>
<th>parameter solution 5</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>fitness</td>
<td>s.d.</td>
<td>fitness</td>
<td>s.d.</td>
<td>fitness</td>
<td>s.d.</td>
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<td>1</td>
<td>395.2</td>
<td>86.2</td>
<td>148.4</td>
<td>39.5</td>
<td>159.8</td>
<td>43.5</td>
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<td>2</td>
<td>400.2</td>
<td>109.2</td>
<td>183.3</td>
<td>59.2</td>
<td>180.7</td>
<td>58.4</td>
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<tr>
<td>3</td>
<td>344.8</td>
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<td>69.8</td>
<td>203.9</td>
<td>70.1</td>
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<td>4</td>
<td>483.1</td>
<td>110.6</td>
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<td>92.7</td>
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<td>5</td>
<td>444.2</td>
<td>90.6</td>
<td>368.4</td>
<td>100.9</td>
<td>370.9</td>
<td>102.5</td>
</tr>
</tbody>
</table>

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
Other Examples
Inflatable Knee Bolster

Objective: Minimize $P_{combined}$

Subject to: \[ \text{Left Femur load } \leq 7000 \]
\[ \text{Right Femur load } \leq 7000 \]

<table>
<thead>
<tr>
<th><strong>Design Variable</strong></th>
<th></th>
</tr>
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<tbody>
<tr>
<td>IKB center offset x</td>
<td></td>
</tr>
<tr>
<td>IKB center offset y</td>
<td></td>
</tr>
<tr>
<td>KB venting area ratio</td>
<td></td>
</tr>
<tr>
<td>KB mass inflow ratio</td>
<td></td>
</tr>
<tr>
<td>DB venting area ratio</td>
<td></td>
</tr>
<tr>
<td>DB high output mass inflow ratio</td>
<td></td>
</tr>
<tr>
<td>DB low output mass inflow ratio</td>
<td></td>
</tr>
<tr>
<td>DB firing time</td>
<td></td>
</tr>
<tr>
<td>DB strap length ratio</td>
<td></td>
</tr>
<tr>
<td>Load of load limiter (N)</td>
<td></td>
</tr>
</tbody>
</table>

Performance Response

<table>
<thead>
<tr>
<th><strong>Performance Response</strong></th>
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<tbody>
<tr>
<td>HIC</td>
<td></td>
</tr>
<tr>
<td>CG</td>
<td></td>
</tr>
<tr>
<td>Left foot load</td>
<td></td>
</tr>
<tr>
<td>Right foot load</td>
<td></td>
</tr>
<tr>
<td>$P_{combined}$ (Quality)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Design</strong></th>
<th>$P_{combined}$</th>
<th># Simulations</th>
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<tbody>
<tr>
<td>Base</td>
<td>13.69</td>
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<tr>
<td>Hooke Jeeves</td>
<td>8.89</td>
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<tr>
<td>GA (Ford)</td>
<td>7.29</td>
<td>155</td>
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<tr>
<td>ES</td>
<td>6.77</td>
<td>122</td>
</tr>
</tbody>
</table>
Objective: Minimization of defects in the produced parts.

Variables: Geometric parameters and forces.

ES finds very good results in short time

Computationally expensive simulation
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

Turbine Blade after Casting
Steel Cube Temperature Control

Minimize the deviation of temperature at the cube's Surface to 1000°C!

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

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>100 OFE</th>
<th>200 OFE</th>
<th>1000 OFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQP</td>
<td>148</td>
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<td>Complex strategy</td>
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<td>(1,7)-DES</td>
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<td>(1,10)-DES</td>
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<tr>
<td>MAES</td>
<td>122</td>
<td>65</td>
<td>12</td>
</tr>
</tbody>
</table>

\[ \Delta T_{\text{max}} \]
Siemens C Reactor

- Maximisation of growth speed
- Minimisation of diameter differences

**FLUENT:** Simulation of fluid flow

**CASTS:** Calculation of Temperature and concentration field

Optimisation of 15 process parameters:

Production time 35 hours → 30 hours

Reaction Gas TCS  
Growing High Purity Silicon Rod

0 m/s  
1.5 m/s  
3 m/s
Multipoint Airfoil Optimization

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
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
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

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

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

- Evolution Strategy Module for Optimus available.
- Distribution D, A, CH by FE Design.
- Effective as of April 2005.
Thank you for your Attention!
Questions?