Modeling and Optimization Workshop

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modeFRONTIER

Getting to know the investigated phenomena and manage them according to its own wishes

WBTR, 12/06/2014

Ing. Vito Primavera, EnginSoft SpA
Workshop Goal

Getting to know the investigated phenomena and Manage them according to its own wishes

... but what does it mean?

- Realize the behaviour of the physical phenomena behind our applications
- Assess which are the truly important parameters affecting our phenomenon
- Plan experimental campaigns and/or build up accurate numerical models able to enwrap the driving forces embedded into the phenomenon
- Perform multi-disciplinary and multi-objective optimization at the aim to get the best performances
- Make clear our final decisions with respect ourselves and others
- Maximize efficiency and effectiveness of whole technical & decisional process
Workshop Agenda

Getting to know the investigated phenomena and Manage them according to its own wishes

Overview & Applications

- modeFRONTIER Intro
- History Cases & Theoretical Backgrounds
  1. Exploring Design Alternatives for DG5 Schemes Assisted by modeFRONTIER
  2. Using modeFRONTIER to calibrate slow soil runoff and wetting parameters for area drainage models in InfoWorks CS
  3. Multi-Objective Optimization of a Complex Water Distribution Network
- Questions & Answers
modeFRONTIER

Multi-Objective Optimization and Design Environment
modeFRONTIER is an integration platform for **multi-objective and multi-disciplinary optimization**. It provides a seamless coupling with third party engineering tools, enables the **automation** of the design simulation process, allow to perform advanced **data mining**, and facilitates **analytic decision making**
modeFRONTIER Assessing

Based on an innovative idea
1999-2002: ES.TEC.O. and modeFRONTIER v1.0 Multi-Objective Design Environment came to life

OUTCOME:
Truly Multi-Objective Optimization, together with Process Integration, goes out of the mathematics guru’s lab and - thanks to some radical innovations - is applied to any, real-world, engineering design area
The “philosophy” behind modeFRONTIER: optimization

“traditional” way:

Set-up of a design process

<table>
<thead>
<tr>
<th>Design</th>
<th>0</th>
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<th>2</th>
<th>3</th>
<th>…</th>
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<td>TRIAL</td>
<td>Error</td>
<td>TRIAL</td>
<td>Error</td>
<td>TRIAL</td>
<td>…</td>
</tr>
</tbody>
</table>

time

Improve B

Improve A
The “philosophy” behind modeFRONTIER: optimization

"traditional" way:

Set-up of a design process

Design Workflow Set-up

modeFRONTIER

automated process integration (data flow) + smart looking for better performances (logic flow)

The modeFRONTIER way:

Workflow Set-up

Decision Making Tools

Improve B

Improve A

... and with effective pictures of “what-if” scenarios analysis

= Sooner, better, more”robust” design
Process Integration: **automated data flow**

**Input Variables**
Entities that define the design space

**Output Variables**
Measures from the system

**The Black Box**
Generates the outputs accordingly to the inputs

**Multi-Disciplinary Scenario**

- **CFD**
  (CFX, StarCCM, Fluent, etc)

- **CAD**
  (CATIA, UGS, PROE, etc)

- **FEM**
  (Ansys, Nastran, Magma, FTI, Madymo, etc)

- **Others**
  (In-House codes, MATLAB, Excel, etc)
Smart Search & Evaluation of Solutions: *logic flow – “brain”*

**Input Variables**
Entities that define the design space

**Output Variables**
Measures from the system

**The Black Box**
Solvers

**Objectives & Constraints**
Compute and Check the values
Smart Search & Evaluation of Solutions: logic flow – “brain”

Input Variables
Entities that define the design space

Output Variables
Measures from the system

The Black Box
Solvers

Objectives & Constraints
Compute and Check the values

Are the results satisfactory?
Could be the solution further improved?
Smart Search & Evaluation of Solutions: logic flow – “brain”

**Input Variables**
Entities that define the design space

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---

**Input Variables**
Which set of values?

**Black Box**
Solvers

Are the results satisfactory?
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Input Variables
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Could the solution further be improved?

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The Black Box

Input Variables
Which set of values?
How modeFRONTIER is helping you

1. Process integration and clear definition of the problem ➔ workflow
How modeFRONTIER is helping you

1. Process integration and clear definition of the problem ➔ workflow

2. Numerical Optimization Algorithms (coupled with DOE) + RSM techniques (meta-modeling) help the designer to explore completely new solutions/refine in the most fast way the already good ones.
How modeFRONTIER is helping you

1. Process integration and clear definition of the problem ➔ workflow
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3. Complete automation of the loop ➔ 100% Hardware/Software resources exploiting
How modeFRONTIER is helping you

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3. Complete automation of the loop ➔ 100% Hardware/Software resources exploiting
4. Data mining (statistics, graphical data post-processing, …) + decision making, automatic report, …
How modeFRONTIER is helping you

INTEGRATION AND PROCESS AUTOMATION

OPTIMIZATION

ROBUST DESIGN AND RELIABILITY

DESIGN SPACE EXPLORATION

ANALYTICS AND VISUALIZATION

DECISION MAKING

Key partner in Design Process Innovation
How modeFRONTIER is helping you - 1 – workflow: basic bricks

Any problem to be investigated has to build-up exploiting the data and logic “bricks”:

**Free parameters** ➔ to be changed to improve the proposed solution, that is defined completely by means of them (“**input variables**”). They have some reasonable variability limits (**range**) and a list of values that they can assume (i.e.: every real number, just integer values or just few values out of a catalog **within the range**)

**Tools** ➔ programs or measures, that allow us to evaluate the behavior of our proposed solutions (“**solver**”)

**Outputs** ➔ results that are describing the behavior of the proposed solution, produced by our “solver” (“**output variables**”)

**Goals** ➔ to achieve – more than one, also not strictly concordant – that could be expressed like functions of the obtained “outputs” (“**objectives**”)

**Limits** ➔ to be strictly respected, in terms of free parameters values and/or output values (“**constraints**”)
How modeFRONTIER is helping you - 1 – workflow: graphical approach

Any problem to be investigated has to build-up exploiting the data and logic “bricks”:

Input parameters

Application Nodes (tools)

Goals

Limits

Outputs
How modeFRONTIER is helping you - 1 – workflow: graphical approach

Simple Problem – Milk Box

Consider a Milk Box with edges of length a, b, c.

2 opposing-objective problem:
- minimize S/V ratio (minimize Thermal Dispersion)
- minimize also the area of the base ‘ab’ of the solid
How modeFRONTIER is helping you - 1 – workflow: graphical approach

## Simple Problem – Milk Box

<table>
<thead>
<tr>
<th>3 INPUT VARIABLES</th>
<th><strong>Lengths of 3 edges of a box (a,b,c)</strong></th>
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<tr>
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<td><strong>Unix - bc</strong></td>
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<tr>
<td>2 OUTPUT VARIABLES</td>
<td><strong>box volume</strong></td>
</tr>
<tr>
<td></td>
<td><strong>box ext. surface</strong></td>
</tr>
<tr>
<td>2 OBJECTIVES</td>
<td><strong>min. S/V</strong></td>
</tr>
<tr>
<td></td>
<td><strong>min surf. for “ab” base</strong></td>
</tr>
<tr>
<td>1 CONSTRAINT</td>
<td><strong>minimum volume limit</strong></td>
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Consider a Milk Box with edges of length a, b, c.

**2 opposing-objective problem:**
- minimize S/V ratio (minimize Thermal Dispersion)
- minimize also the area of the base ‘ab’ of the solid

- Min S/V leads to the biggest Box possible within the assigned “a”, “b”, “c” bounds
- Min area of the “ab” base leads to small “plant-sized” shapes
How modeFRONTIER is helping you - 1 – workflow: graphical approach

Simple Problem – Milk Box

3 INPUT VARIABLES

- Lengths of 3 edges of a box (a, b, c)

SOLVER

- Unix - bc

2 OUTPUT VARIABLES

- Box volume
- Box ext. surface

2 OBJECTIVES

- Min. S/V
- Min surf. for “ab” base

1 CONSTRAINT

- Minimum volume limit
How modeFRONTIER is helping you - 1 – workflow definition

- Single-Process Integration
How modeFRONTIER is helping you - 1 – workflow definition

- Single-Process Integration
How modeFRONTIER is helping you - 1 – workflow definition

- Single-Process Integration
modeFRONTIER is basically able to **integrate and manage any kind of software** (commercial on “in-house”)
How modeFRONTIER is helping you - 2 – whole exploration of design space

- Design Of Experiments (DOE) → initial “picture”
How modeFRONTIER is helping you - 2 – whole exploration of design space

- Design Of Experiments (DOE) → initial "picture"
- Optimization Algorithms (with strategy wizard)
How modeFRONTIER is helping you - 2 – DOE methods:

- **Space Filler DOEs** serve as the starting point for a subsequent optimization process or a database for response surface training.

- **Statistical DOEs** are useful for creating samplings for the sensitivity analysis thus allowing in-depth understanding of the problem by identifying the sources of variation.

- **Robustness and reliability DOEs** help create a set of stochastic points for robustness evaluation.

- **Optimal Designs DOEs** are special purpose techniques used for reducing the dataset in a suitable way.
How modeFRONTIER is helping you - 2 – Optimization Algorithms

Complete array of optimization algorithms covering deterministic, stochastic and heuristic methods for single and multi-objective problems.

Beside the traditional methods, modeFRONTIER provides fine-tuned hybrid algorithms combining the strengths of single approaches.
How modeFRONTIER is helping you - 2 – multi-objective problems

“false” multi objective solution

\[
\begin{align*}
\min & \quad f_i(x_k) \\
\text{s.t.} & \quad g_c(x_k) \leq 0
\end{align*}
\]

\(i = 1, n \text{ objectives}\)
\(k = 1, n \text{ variables}\)
\(c = 1, n \text{ constraints}\)

Transform a multi-objective optimization problem into an equivalent single one. The solution (one solution) depends on the choice of the parameter values.

\[
\begin{align*}
\min & \quad h(x_k) = \sum_{i=1}^{\text{nobj}} \alpha_i f_i(x) \\
\text{s.t.} & \quad g_c(x_k) \leq 0
\end{align*}
\]

Arbitrarily chosen
How modeFRONTIER is helping you - 2 – multi-objective problems

"true" multi objective solution

\[
\begin{align*}
\min f_i(x_k) & \quad i = 1, n \text{ objectives} \\
g_c(x_k) & \leq 0 \quad k = 1, n \text{ variables} \\
c = 1, n \text{ constraints}
\end{align*}
\]

set of optimal solutions usually known as Pareto Frontier

Pareto Frontier: do not exist solutions with better values for all the objectives \(\rightarrow\) not dominated solutions
How modeFRONTIER is helping you - 2 – More about Pareto Frontier

Pareto Frontier set: different trade-off between objectives

\[ f_1, \text{ to be minimized} \]
\[ f_2, \text{ to be minimized} \]
How modeFRONTIER is helping you - 2 – More about Pareto Frontier

Pareto Frontier set: different trade-off between objectives

\[ f_1, \text{to be minimized} \]

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How modeFRONTIER is helping you - 2 – More about Pareto Frontier

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A dominated by B
How modeFRONTIER is helping you - 2 – More about Pareto Frontier

Pareto Frontier set: different trade-off between objectives

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\[ f_1, \text{ to be minimized} \]

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How modeFRONTIER is helping you - 2 – More about Pareto Frontier

Pareto Frontier set: different trade-off between objectives

- A dominated by B
- B dominated by C

f1, to be minimized

f2, to be minimized
Pareto Frontier set: different trade-off between objectives

A dominated by B
B dominated by C
D and C are not dominated
How modeFRONTIER is helping you - 2 – More about Pareto Frontier

Pareto Frontier set: different trade-off between objectives

- \( f_1 \), to be minimized
- \( f_2 \), to be minimized

\( A \) dominated by \( B \)

\( B \) dominated by \( C \)

\( D \) and \( C \) are not dominated

- Pareto Frontier

- \( f_1 \) \( \rightarrow \) single point
- \( f_1, f_2 \) \( \rightarrow \) curve
- \( f_1, f_2, f_3 \) \( \rightarrow \) 3D surface

- \( n \) functions \( \rightarrow \) \( n \)-dim surface
How modeFRONTIER is helping you - 2 – exploration

Simple Problem – Milk Box

Initial Configuration

Min Objective Function 1

Min Objective Function 2
How modeFRONTIER is helping you - 2 – weight function

Simple Problem – Milk Box

Mono – Obj.: reduction of the problem to a unique function

\[ F(x) = w_1 \cdot \text{Obj}_1 + w_2 \cdot \text{Obj}_2 + w_3 \cdot \text{Obj}_3 \ldots \]

# des = 120
How modeFRONTIER is helping you - 2 – Pareto Frontier

Simple Problem – Milk Box

Multi – Obj.: Pareto Frontier
Set of optimal trade-offs

# des = 120
RSM (Response Surface Methodology), or meta-modeling, is a valid strategy which serves as a surrogate for heavy simulation processes, allowing engineers to fast-run the classic optimization process, and/or only experimental data are available (no numerical model does exist)
How modeFRONTIER is helping you - 2 – DOEs + Optimization Algorithms + RSM

RSM (Response Surface Methodology), or meta-modeling, is a valid strategy which serves as a surrogate for heavy simulation processes, allowing engineers to fast-run the classic optimization process, and/or only experimental data are available (no numerical model does exist)

**How does it work in modeFRONTIER?**

1. RSMs are **trained** from an available database of real designs and validated one against another.

2. The best model is used to **compute** the outputs of the system; this process is called **virtual optimization**.

3. The best designs obtained through virtual optimization are then **evaluated by the real solver**

**Main advantages**

- perform thousands of design evaluations in short time
- accelerate the optimization step
- use small amounts of data efficiently
- smart exploitation of available computational resources
How modeFRONTIER is helping you - 2 – Robust Design and Reliability of Optimum

The input parameters uncertainty is reflected in the outputs of the system

modeFRONTIER multi-objective robust design optimization (MORDO) algorithms generate a scatter of samples (noise factors) around the design, in order to verify how sensitive the design is to variations, i.e. whether the values of the outputs are still within the user-defined limits.
### How modeFRONTIER is helping you - 3 – automating the workflow

<table>
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<th>holidays</th>
<th>2/3</th>
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<tr>
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<td>Meal, home, sleep</td>
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<tr>
<td>designing</td>
<td>Other works</td>
<td>1/2</td>
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<tr>
<td>calculate</td>
<td>others</td>
<td>1/2</td>
</tr>
<tr>
<td>Calculate 1/12</td>
<td>Others 11/12</td>
<td></td>
</tr>
</tbody>
</table>

Without mF, calculations have to be run one by one, a lot of time is not used.

Conversely, once the workflow is set in mF, the calculations run automatically and the available time is fully used.

Calculate 12/12
How modeFRONTIER is helping you - 4 – Data Mining, Robust Design, ...

“Question”

What do numerical and/or experimental data mean?

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<td>0.00E+00</td>
<td>1.50E+00</td>
<td>5.50E+01</td>
<td>1.10E+01</td>
<td>2.65E+04</td>
<td>6.05E-01</td>
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<td>3.70E+01</td>
<td>0.00E+00</td>
<td>1.30E+00</td>
<td>5.50E+01</td>
<td>1.10E+01</td>
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<td>8.00E+00</td>
<td>1.70E+01</td>
<td>3.70E+01</td>
<td>0.00E+00</td>
<td>1.30E+00</td>
<td>9.00E+01</td>
<td>1.10E+01</td>
<td>3.01E+04</td>
<td>5.24E-01</td>
</tr>
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<td>6.50E+00</td>
<td>1.70E+01</td>
<td>3.70E+01</td>
<td>0.00E+00</td>
<td>1.30E+00</td>
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<td>9.00E+00</td>
<td>2.69E+04</td>
<td>5.38E-01</td>
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<td>8.00E+00</td>
<td>1.70E+01</td>
<td>1.90E+01</td>
<td>0.00E+00</td>
<td>1.50E+00</td>
<td>9.00E+01</td>
<td>1.10E+01</td>
<td>2.51E+04</td>
<td>5.79E-01</td>
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<tr>
<td>22</td>
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<td>3.10E+01</td>
<td>2.90E+01</td>
<td>0.00E+00</td>
<td>1.10E+00</td>
<td>9.00E+01</td>
<td>9.00E+00</td>
<td>2.75E+04</td>
<td>4.89E-01</td>
</tr>
</tbody>
</table>
How modeFRONTIER is helping you - 4 – Data Mining, Robust Design, ...

“Question”

What do numerical and/or experimental data mean?

• How can we **analyse in a efficient way** the available data?
• Which are the **relationship** between the input variables, objectives, and constraints?
• Which are the **most important design variables**?
• Can we **reduce** the variables space?
• What is the **best design space region** to address for the optimization process?
• What is a **reasonable number of objectives or constraints** to assess?
modeFRONTIER provides a complete and comprehensive environment for data analysis and visualization, enabling statistical assessment of complex datasets.

Its sophisticated post-processing tools, such as Sensitivity Analysis, Multi-Variate Analysis, and Visual Analysis, allow results from multiple simulations to be visualized in a meaningful manner and key factors to be identified.
How modeFRONTIER is helping you - 4 – Statistical Analyses (... some tools)

**Correlation Matrix** (or **Scatter Matrix**) quantifies the linear correlation between variables (both input-output, input-input and output-output)

- **Only statistical DOE designs** (no optimization)
- **First-order correlation:**
  - $1 \rightarrow$ full correlation
  - $0 \rightarrow$ no correlation

Reduce objectives number
How modeFRONTIER is helping you - 4 – Statistical Analyses (... some tools)

Correlation Matrix (or Scatter Matrix) quantifies the linear correlation between variables (both input-output, input-input and output-output)

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- First-order correlation:
  1 ➔ full correlation
  0 ➔ no correlation

Reduce objectives number
How modeFRONTIER is helping you - 4 – Statistical Analyses (... some tools)

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- Only statistical DOE designs (no optimization)
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  0 → no correlation

Reduce objectives number

Obj 8 → no correlation
How modeFRONTIER is helping you - 4 – Statistical Analyses (... some tools)

**t-Student Chart** allows to perform a sensitivity analysis with the aim to highlight the most important input variables in respect of the objective functions.

Every pie chart is an objective and the slices are the input variables.
**t-Student Chart** allows to perform a **sensitivity analysis** with the aim to highlight the most important input variables in respect of the objective functions.

- **obj1**
- **obj2**
- **obj3**
- **obj4**
- **obj5**
- **obj6**
- **obj7**
- **obj8**
- **obj9**

**threshold filter**

Reduce number of the design parameters.
Interaction btw variables ⇒ first-order interaction effects $F=F(x*y)$

**DOE Interaction Effects** chart shows if the interaction of two variables (e.g. $x*y$) has an effect on the output (while main effect is 0 for both)
SOM (Self Organizing Maps) ➔ statistical tool for multivariate analysis

If the number of variables is high (more than 4 or 5), it becomes prohibitive to plot all the information by classical 2-dimensional charts. **SOMs:**
- project high-dimensional data space into **low-dimensional space** (usually 2D)
- put “similar” data samples to nearby cells
How modeFRONTIER is helping you - 4 – Multivariate Analysis - SOM (… some tools)

SOM (Self Organizing Maps) ➔ statistical tool for multivariate analysis

If the number of variables is high (more than 4 or 5), it becomes prohibitive to plot all the information by classical 2-dimensional charts. SOMs:

- project high-dimensional data space into low-dimensional space (usually 2D)
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How modeFRONTIER is helping you - 4 – Multivariate Analysis - SOM (… some tools)

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- put “similar” data samples to nearby cells
modeFRONTIER

...some applications
Application Fields

Aerospace
CFD/Structural interaction on 3d wing
Flap Splitting and Wing Setting analysis
Shape analysis of airfoil profile
Ramjet-Powered Missile analysis
Supersonic Transport Airplane studies

Water Industry, Distribution Networks, ...
Drainage and flooding risk assessment
Efficient management of water and wastewater distribution networks
Multi-Objective Optimization of Water Distribution Network

Turbomachinery
Centrifugal Compressor 3D analysis
Axial Turbine 3D analysis
Axial Compressor 3D analysis
Turbine single stage 2D steady and unsteady analysis
Turbine 2 stages 2D unsteady analysis

Powertrain Optimization
Inlet ducts 3D analysis
Water Jacket 3D analysis
Exhaust ducts 3D analysis
Whole engine 1D analysis
(CFD and Cooling Manifolds applications)

Experimental Application
Washing Machine experimental assessment
Burners Modelling and prediction studies

Combustion
Burners Pre-mixer analysis for a Gas Turbine
Complex Chemistry reactions

Power plants and Heat Exchange cases
Heat Exchanger for Domestic Boilers analysis
Axisymmetric Fin designing for Heat Exchangers
Evaporator geometry analysis
Domestic Refrigerator thermal analysis

Multibody, Crash, Structural, Vibro-Acustics
Automotive braking system analysis
Vehicle Comfort-Handling analysis
Racing Vehicle Suspension set-up analysis
Vacuum Bell analysis
Electro-Magnetic Actuator analysis
Frontal Frame crash analysis

Manufacturing
Injection Molding analysis for automotive components
Metal Casting analysis
Metal sheet forming and thermo-forming analysis

Marine
Ship hull design
Wave wash minimisation analysis
Stabilising fin analysis
3D full ship study
Ship structure optimisation
modeFRONTIER was used to determine the exact amount of pre-stress in cables (input variables) such to achieve the final post-tensions (objective) determined through measurements.

- the FE model integrated with modeFRONTIER to compute each configuration tensions is Straus7
MultiDisciplinary Example: Engineering and Cost Multi-disciplinary Optimization

From Wing Sizing to Business Plans: The Tremendous Potential of an Optimization Tool

International modeFRONTIER Users’ Meeting 2010

Savoia Excelsior Palace
Trieste, Italy
27 - 28 May 2010

Full presentation available within modeFRONTIER International Users’ Meeting proceedings, 2010
A GT-Power model is used for a calibration.

Experimental data (volume efficiency vs. rpm chart) is available and GT-Power model parameters (HT coefficients, valves timing, etc..) have to be set to match the curve.

The optimisation objective is the minimisation of mean squared distance between experimental and numerical curves.
Automotive: numerical model calibration

- A GT-Power model is used for a calibration.
- Experimental data (volume efficiency vs rpm chart) is available and GT-Power model parameters (HT coefficients, valves timing, etc) have to be set to match the curve.
- The optimization objective is the minimization of mean squared distance between experimental and numerical curves.
A GT-Power model is used for calibration.

Experimental data (volume efficiency vs. rpm chart) is available, and GT-Power model parameters (HT coefficients, valves timing, etc.) have to be set to match the curve.

The optimization objective is the minimization of mean squared distance between experimental and numerical curves.
An initial ellipsoid is modified with Bezier curves (CATIA v5), and scaled to the target volume. Mesh by ICEM and CFD by CFX5

Optimization goals:
• minimum drag
• lowest center of gravity
Thanks for your time!

Vito Primavera
v.primavera@enginsoft.it
Exploring Design Alternatives for DG5 Schemes Assisted by modeFRONTIER

modeFRONTIER coupled to InfoWorks CS

David Moseley, John Barnes (ES UK), Vito Primavera (ES Italy)
Abstract

- This activity will demonstrate the following:

  ✓ How modeFRONTIER can be applied to DG5 (register for flooding problems) flood alleviation
  ✓ How automated techniques and smart optioneering can propose a range of optimal scheme alternatives
  ✓ How alternative designs are created, flooding quantified, and costs calculated
  ✓ How designs are tested against multiple Design Storms and Time Series Rainfall (TSR) evaluation
  ✓ The incorporation of cost models to permit direct financial comparison of alternatives, and the systematic assessment of every monitored performance attribute under every storm condition, providing robust auditing of all possible design requirements
Background

- EnginSoft UK set up a Steering Group (SG) to allow the Water Industry to drive the development of a software platform (based on InfoWorks CS and modeFRONTIER) addressed to meet the expectation and requirements of the experts in the field.
- Several meetings have been held and the outcome of those meetings has directly influenced the functionality of the Interface.
- Furthermore, the SG members have requested certain case studies be conducted and reported in order to jointly test the software and verify its capability.
- This paper was carried out on one of the models provided by one of the members or the SG.
- The following Companies have active members in the Steering Group:
  - Anglian Water, Southern Water, Yorkshire Water, Wessex Water
  - Atkins Global, Clear, Pick Everard, Mott MacDonald, MWH Global, Remwater, Innovyze
Outline

- **Automated techniques:**
  - The new design process
  - Application to a real-world problem

- **Smart optioneering:**
  - The control of input parameters
  - The collection of data
  - Data mining
  - Solution delivery
Automated Techniques
Generic design process

Design Decisions
Generic design process

Design Decisions

Product / Process

InfoWorks™ CS
Generic design process

Design Decisions

Product / Process

Performance

InfoWorks™ CS
Generic design process

Design Decisions

Product / Process

Performance

How do I best fulfil the design requirements?

heuristic
Generic design process

Design Decisions → Product / Process → Performance

Smart Algorithms

systematic
modeFRONTIER design process
modeFRONTIER design process
modeFRONTIER design process

Design Decisions

Product / Process
modeFRONTIER design process

Design Decisions
Product / Process
Performance
modeFRONTIER design process

- Smart Algorithms
- Product / Process
- Performance
- Design Decisions

- InfoWorks™ CS
- NewPipeWidth
- Group1Diameters
- Group4Diameters
- Group6Diameters
- Group8Diameters
- Group11Diameters
- W30 API 1901
- W60 API 1802
- W60 API 1807
- Cost Obj
- TotDG5Floods_Cat
- Flooding Obj
- Weirs Obj
- Pumps Obj
modeFRONTIER design process

- **Design Decisions**
- **Product / Process**
- **Performance**

Excel Interface Inputs

InfoWorks™ CS

Excel Interface Outputs
Interface for InfoWorks CS

- The Interface is a layer (in the form of a spreadsheet) between modeFRONTIER and InfoWorks CS that enables InfoWorks CS to be run automatically.

- modeFRONTIER carries out sequential InfoWorks simulations adjusting input variables and evaluating improvements to verification fits from each run.
Application: Sewerage at Thorpe-le-Soken (UK)

Thorpe-le-Soken (UK): small village with a number DG5 flood locations
Application: Sewerage at Thorpe-le-Soken (UK)

Thorpe-le-Soken (UK): small village with a number DG5 flood locations
Application: Sewerage at Thorpe-le-Soken (UK)

Thorpe-le-Soken (UK): small village with a number DG5 flood locations
Application: Sewerage at Thorpe-le-Soken (UK)

Thorpe-le-Soken (UK): small village with a number DG5 flood locations
Application: InfoWorks CS Model @ Thorpe-le-Soken (UK)
Overflow at the pumping station could not exceed 4 spills per year
Overflow at the pumping station could not exceed 4 spills per year

New and upgraded pipes

A manually engineered solution was looked at that had a combination of new pipes and pipe upgrades (colour intensity ➔ major upgrading)
Overflow at the pumping station could not exceed 4 spills per year

New and upgraded pipes

A manually engineered solution was looked at that had a combination of new pipes and pipe upgrades (colour intensity ➔ major upgrading)

Q1: how reduce the cost?
Q2: what other solutions with storages?
Application: Interface with Optioneering Extension
Application: Interface with Optioneering Extension

Infoworks / modeFRONTIER Interface
Optioneering Mock-Up

Inputs Panel

Selected Base Run (Event 1): CG\GoshillIMF\RUNG\Run Group Nadia Solution\RUN\Opt-5.mP;Winter x1; 30min
Selected Base Run (Event 2): only one event selected
Selected Base Run (Event 3): only one or two events selected
Implied Network: CG\GoshillIMF\NET\Option 5 - Collector sewer Culvert storage option_2

The created Run will be named by the time of its creation, extended by the contents of the cells below:

User String to Add: _OptionStudy_ID_ User ID to Add: 132
Example Run Name: opt_2019_02_08-22:55:25_OptionStudy_ID_132

During Verification, the user string is specified on the mFlinks pages instead!

Choose Parameters to Modify

<table>
<thead>
<tr>
<th>Object Type</th>
<th>Object Name</th>
<th>Parameter Name</th>
<th>Parameter Value</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>conduct</td>
<td>Joint.2</td>
<td>conduit_width</td>
<td>300.0</td>
<td>Everything OK</td>
</tr>
</tbody>
</table>

Add the parameter selected above to the list below

Delete any parameters marked "x" from the list below

List of Selected Parameters

<table>
<thead>
<tr>
<th>Mark</th>
<th>Object Type</th>
<th>Object Name</th>
<th>If Link, Which Suffix?</th>
<th>Parameter Name</th>
<th>Original Value</th>
<th>Modified Value</th>
</tr>
</thead>
</table>
Application: Interface with Optioneering Extension

Select inputs from drop down menus
Click button to add an input variable
Application: Interface with Optioneering Extension

The input is added to the list
Application: Interface with Optioneering Extension

Infoworks / modelFRONTIER Interface
Optioneering Mock-Up

Inputs Panel

Selected Base Run (Event 1): \texttt{CG*GexhillIMF\RLNG\Run Group Nadia Solution\RUN*Opt 5 mf\Winter a 3}; 30min
Selected Base Run (Event 2): only one event selected
Selected Base Run (Event 3): only one or two events selected
Implied Network: \texttt{CG*GexhillIMF\NET*Opt 5 - Collector sewer Culvert storage option 2}

The created Run will be named by the time of its creation, extended by the contents of the cells below:

- User String to Add: \\
- User ID to Add: 132
- Example Run Name: opt 2010 02 08 22:55:25 OptStudy_ID_132

During Verification, the user string is specified on the mfLinks pages instead!

Choose Parameters to Modify

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<th>Object Type</th>
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</thead>
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<td>Joint.2</td>
<td>conduit_width</td>
<td>300.</td>
<td>Everything OK</td>
</tr>
</tbody>
</table>

Add the parameter selected above to the list below

<table>
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<tr>
<th>Mark</th>
<th>Object Type</th>
<th>Object Name</th>
<th>If Link, Which Suffix?</th>
<th>Parameter Name</th>
<th>Original Value</th>
<th>Modified Value</th>
</tr>
</thead>
<tbody>
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<td>conduit</td>
<td>Joint</td>
<td></td>
<td>conduit_width</td>
<td>300.</td>
<td>400</td>
</tr>
</tbody>
</table>

The current value in the model is shown
Application: Interface with Optioneering Extension

The automated modeFRONTIER process will change the value in the InfoWorks model by updating this cell.
Application: Cost Model

Excel Interface Inputs

InfoWorks™ CS

Excel Interface Outputs

Product / Process
# Application: Cost Model

## Inputs

A table showing inputs for the cost model, including flood types, conduit references, US nodes, suffixes, DS nodes, US/DS ratios, and target flooding values.

<table>
<thead>
<tr>
<th>Flood Type</th>
<th>Conduit Ref</th>
<th>US Node</th>
<th>Suffix</th>
<th>DS Node</th>
<th>US/DS</th>
<th>Target (m)</th>
<th>Flooding Value (m)</th>
<th>Ground Type</th>
<th>Unit Cost (£)</th>
<th>Total Cost (£)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USFlood</td>
<td>Conn_Bartonville.1</td>
<td>Conn_Bartonville</td>
<td></td>
<td>Conn_Velindre</td>
<td>US</td>
<td>0.063</td>
<td>0</td>
<td>Highway</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USNoFlood</td>
<td>Conn_Bentpenny.1</td>
<td>Conn_Bentpenny</td>
<td></td>
<td>TA09217002</td>
<td>US</td>
<td>0</td>
<td>0</td>
<td>Highway</td>
<td></td>
<td></td>
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<tr>
<td>USNoFlood</td>
<td>Conn_Elms.1</td>
<td>TA0207701</td>
<td></td>
<td>US</td>
<td>US</td>
<td>0</td>
<td>0</td>
<td>Highway</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USNoFlood</td>
<td>Conn_Galatia.1</td>
<td>Conn_Galatia</td>
<td></td>
<td>US</td>
<td>US</td>
<td>0</td>
<td>0</td>
<td>Highway</td>
<td></td>
<td></td>
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<tr>
<td>USNoFlood</td>
<td>Conn_Goathouse.1</td>
<td>Conn_Goathouse</td>
<td></td>
<td>Conn_Elms</td>
<td>US</td>
<td>0</td>
<td>0</td>
<td>Highway</td>
<td></td>
<td></td>
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<td>USNoFlood</td>
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<td>US</td>
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<td>0</td>
<td>0</td>
<td>Highway</td>
<td></td>
<td></td>
</tr>
<tr>
<td>USNoFlood</td>
<td>Conn_Haddonfarm.1</td>
<td>Conn_Haddonfarm</td>
<td></td>
<td>Conn_Goathouse</td>
<td>US</td>
<td>0.08895</td>
<td>0</td>
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<td></td>
</tr>
<tr>
<td>DGS</td>
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<td>Conn_lighthouse</td>
<td></td>
<td>NEWMH09</td>
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<td>Highway</td>
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<td>DGS</td>
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<td></td>
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<td>1624.20</td>
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<tr>
<td>DGS</td>
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<td>3112.14</td>
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<td>Conn_Sunnybank</td>
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<td>0</td>
<td>Highway</td>
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<td>1824.74</td>
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<tr>
<td>DGS</td>
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<td>Conn_Rausdalehouse</td>
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<td>Highway</td>
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<tr>
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<td>US</td>
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<td>Highway</td>
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<tr>
<td>Flood</td>
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<td>Conn_Thebungalow</td>
<td></td>
<td>TA021303</td>
<td>US</td>
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<td>0</td>
<td>Highway</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DGS</td>
<td>Conn_Thebungalow.1</td>
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<td></td>
<td>TA0224601</td>
<td>US</td>
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<td>Highway</td>
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<td>5300.56</td>
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<tr>
<td>USFlood</td>
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<td>Conn_Bentpenny</td>
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<td></td>
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<td>DS</td>
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<td>Highway</td>
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## Outputs

A table showing collated outputs for modeFRONTIER, including description, value, and other relevant data.

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**Application: Cost Model**

**Inputs**

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**Outputs**

- No. DGS Floods: 2
- No. Worse Floods: 1
- No. New Floods: 0
- No. Floods At New Pipes: 0
- No. US Worse Floods: 4
- No. Worse Weirs: 0
- Total Flooding Depth: 0.15622
- Ave. Flooding Depth: 0.02231743
- Worst Flooding Depth: 0.11272
- No. Failed Constraints: 7

**User Defined Outputs (Flood Depth)**

Set whether a manhole is a DG5 location.
## Application: Cost Model

### Inputs

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**Set the flooding target**
Application: Cost Model

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Has the manhole flooded?

- Yes
- No
## Application: Cost Model

### Inputs

- **Set whether the pipe is under a road?**

### Outputs

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Application: Cost Model

What is the cost of upgrading this pipe upgrade?
# Application: Cost Model

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## Outputs

### Summary of Costs

- **Total Cost**: $947034.08

### Collated Outputs for modeFRONTIER

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<thead>
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<th>Description</th>
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<tr>
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*Summary of cost: Total Cost = $947034.08*
### Application: Cost Model

#### Inputs

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#### Outputs

**Collated Outputs for modeFRONTIER**

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<th>Value</th>
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<tr>
<td>No. New Floods</td>
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<tr>
<td>No. Floods At New Pipes</td>
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<td>Pump Volume</td>
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#### Summary of floods

- Tot. DGS Flood: 0.14900
- Tot. Worse Floods: 0.0030
- Tot. New Flood: 0.0000
- Tot. Floods At New Pipes: 0.0000
- Tot. US Worse Floods: 0.0042
- Pump Volume: 0.0000
Application: modeFRONTIER Workflow

- Excel Interface Inputs
- Excel Interface Outputs
- modeFRONTIER
- Design Decisions
- Product / Process
- Performance
Application: modeFRONTIER Workflow
Application: modeFRONTIER Workflow

Inputs to be changed are setup in modeFRONTIER
Outputs to be monitored are setup in modeFRONTIER
Variables are linked to InfoWorks CS via the Excel interface
Application: modeFRONTIER Workflow

Designs are scheduled according to a smart algorithm.
Cost and flooding are minimised while DG5 manholes, weir levels and pumps must be below a target value.
If the critical storm passes cost and flooding criteria then the other design storms will be assessed.
The design storms are run
Application: Smart Algorithms
Application: Smart Algorithms

Generation 1

Generation 2
Smart Optioneering [1]:
only pipe upgrades
Global Results

Main area of interest

Flooding vs. Cost

Manual Solution

Cost

Flooding
Global Results

Main area of interest: Flooding

Manual Solution

Cost

Flooding

ID
2736
2462
2189
1915
1642
1368
1094
821
547
274
0
DG5 Compliant Results

Main area of interest

Potential area of interest

Flooding

Cost

Manual Solution

ID
2736
2462
2189
1915
1642
1368
1094
821
547
274
0
Filtering Results: Axis Parallel Chart

Results:
Filtering Results: Axis Parallel Chart

Results:

- Cost Object: 934680
- Flooding Object: 11.2
- Total DG5 Floods Cost: 0.133
- Total DG5 Floods: 0.000
- Pumps Object: 1781.7
- Weirs Object: 772.8
- NoDG5 Floods: 0.000

Total cost of solution: 58
Filtering Results: Axis Parallel Chart

Results:

Total cost of solution

DG5 + Non DG5 floods
Filtering Results: Axis Parallel Chart

Results:

Total cost of solution

DG5 + Non DG5 floods

DG5 flood
Filtering Results: Axis Parallel Chart

Results:

- **Tot Cost of Solution**
- **DG5 + Non DG5 Floods**
- **DG5 Flood**
- **Volume of Water Pumped for Treatment**

- **Cost Obj**
- **Flooding Obj**
- **Total DG5 Floods Cost**
- **Pumps Obj**
- **Weirs Obj**
- **No DG5 Floods**
Filtering Results: Axis Parallel Chart

Results:

- DG5 + Non DG5 floods
- DG5 flood
- Volume of water pumped for treatment
- Volume of water spilt to the water course

Cost Obj: 934680

TotDG5Floods_Cst: 1581.7

NoDG5Floods: 5
Filtering Results: Axis Parallel Chart

Results:

- DG5 + Non DG5 floods
- DG5 flood
- Volume of water pumped for treatment
- Volume of water spit to the water course
- # DG5 floods

Cost Obj: 934680
Flooding Obj: 1.12
TokDG5Floods_Cst: 0.133
Pumps Obj: 1751750.0
Weirs Obj: 704700.0
NoDG5Floods: 13

Total cost of solution
DG5 + Non DG5 floods
DG5 flood
Volume of water pumped for treatment
Volume of water spit to the water course
# DG5 floods
Filtering Results: Axis Parallel Chart

Results:

- Manual
- Solution 1
- Solution 2

- Total cost of solution
- DG5 + Non DG5 floods
- DG5 flood
- Volume of water pumped for treatment
- Volume of water spilt to the water course
- # DG5 floods

- DG5 + Non DG5 floods
- DG5 flood
- Volume of water pumped for treatment
- Volume of water spilt to the water course
- # DG5 floods

Cost Obj
Flooding Obj
TotDG5Floods_Cst
Pumps Obj
Weirs Obj
NoDG5Floods
Detailed Results

Results:

Two solutions have been chosen from the Pareto Front to assess Time Series Rainfall (TSR): Manual Solution, Solution 1, Solution 2.
Design Solution 1

Manual Solution:

Width = 2000mm
Height = 1000mm

1000-2000mm
525mm
450mm
375mm
300mm
225mm
150mm
Design Solution 1

Manual Solution:
Width = 2000mm
Height = 1000mm

mF Solution 1:
Width = 1925mm
Height = 1000mm
Design Solution 1

Manual Solution:
Width = 2000mm
Height = 1000mm

mF Solution 1:
Width = 1925mm
Height = 1000mm
Design Solution 1

Manual Solution:

Width = 2000mm
Height = 1000mm

mF Solution 1:

Width = 1925mm
Height = 1000mm

Description | Cost
--- | ---
Total Cost | £910,983
Saving | £23,000 (2.5%)
Design Solution 1: Flooding

Critical Flooding (2 locations) vs. TSR

TSR example:
M30-60 = expected depth of rainfall in millimetres (mm) from a storm lasting 60 minutes with a return period of 30 years

TSR RUN = 3.5 spills per year at overflow
Design Solution 1: Flooding

Critical Flooding (2 locations) vs. TSR

TSR example:
M30-60 = expected depth of rainfall in millimetres (mm) from a storm lasting 60 minutes with a return period of 30 years

<table>
<thead>
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Design Solution 1: Flooding

Critical Flooding (2 locations) vs. TSR

TSR example:
M30-60 = expected depth of rainfall in millimetres (mm) from a storm lasting 60 minutes with a return period of 30 years

<table>
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<td>0.0m³</td>
<td>0.0m³</td>
<td>-</td>
</tr>
<tr>
<td>M30-480</td>
<td>0.0m³</td>
<td>0.0m³</td>
<td>-</td>
</tr>
<tr>
<td>M30-720</td>
<td>0.0m³</td>
<td>0.0m³</td>
<td>-</td>
</tr>
</tbody>
</table>

TSR RUN = 3.5 spills per year at overflow
Design Solution 2

Manual Solution:
Width = 2000mm
Height = 1000mm

mF Solution 2:
Width = 1850mm
Height = 1000mm

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cost</td>
<td>£904,790</td>
</tr>
<tr>
<td>Saving</td>
<td>£30,000 (3.2%)</td>
</tr>
</tbody>
</table>
**Design Solution 2: Flooding**

**Critical Flooding (2 locations) vs. TSR**

<table>
<thead>
<tr>
<th>Storm</th>
<th>Manual</th>
<th>mF</th>
<th>Comp</th>
</tr>
</thead>
<tbody>
<tr>
<td>M30-30</td>
<td>0.6m³</td>
<td>0.1m³</td>
<td>-0.5m³</td>
</tr>
<tr>
<td>M30-60</td>
<td>6.0m³</td>
<td>3.6m³</td>
<td>-2.4m³</td>
</tr>
<tr>
<td>M30-120</td>
<td>6.5m³</td>
<td>3.3m³</td>
<td>-3.2m³</td>
</tr>
<tr>
<td>M30-240</td>
<td>0.0m³</td>
<td>0.0m³</td>
<td>-</td>
</tr>
<tr>
<td>M30-480</td>
<td>0.0m³</td>
<td>0.0m³</td>
<td>-</td>
</tr>
<tr>
<td>M30-720</td>
<td>0.0m³</td>
<td>0.0m³</td>
<td>-</td>
</tr>
</tbody>
</table>

TSR RUN = 3.9 spills per year at overflow
Smart Optioneering [2]:
with Storage Options
Urban Flood Prevention

**Input variables**
- 50 Pipe diameters
- 6 Storage volumes
- 8 New manhole options

**Output variable**
- 100 flood volumes
- 1 total project cost

**Objective**
- Minimise Cost and Flooding

**Optimisation Strategy**
- Multi-Objective
- MOGA-II / NSGA-II with MFGA
Urban Flood Prevention

Area of potential solutions

Pareto Frontier

Cost of the manually engineered solution

Total Flooding

Cost

ID

0

156

1565

1408

1252

1096

939

782

626

470

313

156
Urban Flood Prevention

Solution 1
Solution 2
Solution 3
Solution 4

Cost

Total Flooding

Pareto Frontier

Unacceptable flooding

ID
1565
1408
1252
1096
939
782
626
470
313
156
0
Urban Flood Prevention
Urban Flood Prevention

Most Important Floods → Least Important Floods
Urban Flood Prevention

Most Important Floods ——— Least Important Floods
Urban Flood Prevention

Most Important Floods → Least Important Floods
Urban Flood Prevention

Most Important Floods ➔ Least Important Floods

Cost_Obj  Flooding_Obj  NoDG5Floods  NoWorseFloods  USFloodings
1.34708  1.25756  36    18    25
1.16803  1.07850  34  31  17  23
0.98897  0.89897  31  29  16  22
0.89431  0.80900  26  14  13  20
0.80900  0.80900  24  12  18
0.72037  0.72037  22  11
0.63084
0.54131
0.45177
0.36224
0.27271
0.18318
0.09365
0.04111
0.00000
Urban Flood Prevention

Most Important Floods → Least Important Floods

Cost_Obj
Flooding_Obj
NoDG5Floods
NoWorseFloods
USFlooding
Urban Flood Prevention

Most Important Floods  Least Important Floods

![Graph showing urban flood prevention data.](image-url)
Urban Flood Prevention

Most Important Floods ➔ Least Important Floods

Solution 1
Solution 2
Solution 3
Solution 4
Urban Flood Prevention

Manually Engineered Solution

Solution 1:  
(Cost Saving 8.5%)

600mm
525mm
450mm
375mm
300mm
225mm
New Manholes
Storage

S2+S9 (372m³)
S8 (96m³)
S7 (245m³)
Recap From the last SGM (Steering Group Meeting)

We have shown that...

- We can advance the Pareto Frontier **beyond a manually engineered solution**

- A **theme of solutions** can be explored (for example: pumped storage vs. upgraded pipes)

- Designs can be explored **upfront** at the design stage and give clear objective direction to the project

- A **cost-model** can be implemented to assess cost-effectiveness

- The problem can be reduced to a **single objective optimisation of cost**
Executive Summary

- Advanced automated design optimisation has been carried out using modeFRONTIER coupled to InfoWorks CS

- Optimisation has been limited to downgrading pipe diameters to a manually engineered solution – This gives “a like for like comparison”

- modeFRONTIER has identified two key solutions:
  - Solution 1 shows a cost reduction of 2.5% (£23,000)
  - Solution 2 shows a cost reduction of 3.2% (£30,000)

- A greater cost reduction (8.5%) has also been identified using modeFRONTIER by exploring new design themes. However, this saving is based on a cost model that requires further refinement

- This is approximately one weeks work to obtain these solutions
Conclusion

Solution 1

- 2.5% cost saving of £23,000
- Comparable DG5 flooding performance to manual solution
- TSR compliant (3.5 spills a year)

Solution 2

- 3.2% cost saving of £30,000
- Comparable DG5 flooding performance to manual solution
- TSR compliant (3.9 spills a year)
Using modeFRONTIER to calibrate slow soil runoff and wetting parameters for area drainage models in InfoWorks CS

David Searby (Wessex Water)
David Moseley (EnginSoft UK)
Vito Primavera (EnginSoft Italy)
• Total flow in **sewer collection systems** is the sum of:

1. **“dry-weather” flow** ➞ 2 standard components
   - **base flow** (wastewater from residential, commercial, and industrial areas released to the sanitary sewer system)
   - **ground water flow** (groundwater infiltration - GWI - that enters sewer system through defective pipes, pipe joints, breaks, ... irrespective of rainfall availability)
Total flow in sewer collection systems is the sum of:

1. “dry-weather” flow ➔ 2 standard components
   - base flow (wastewater from residential, commercial, and industrial areas released to the sanitary sewer system)
   - ground water flow (groundwater infiltration - GWI - that enters sewer system through defective pipes, pipe joints, breaks, … irrespective of rainfall availability)

2. rainfall-derived inflow and infiltration (RDII) ➔ rainfall-driven flow that makes its way to the collection system

RDII is the main cause of sewer overflows ➔ every water authority needs to control & predict RDII ➔ reliable mathematical drainage models are “welcome” ➔ drainage models calibration vs. monitored data
• **Need** for tools for Calibration
• **The tools**: [modeFRONTIER](#) and the [InfoWorks Interface](#)
• **Method** for Slow Runoff Calibration
• Examples
• **Conclusions and next steps**
• Programme of modelling for AMP5 (Asset Management Plans, where “5” means runs from April 2010 to March 2015)
• Looking (as ever…) to minimise capital spend ➞ tendency to use storage solutions
• Understanding more important post rainfall inflows (“slow runoff”)
Need for tools

- Tools: New UK, GIM (soil and ground store) - All essentially empirical
- Calibration parameters unmeasurableViewable
- Essentially a “force fitting” exercise
- Time consuming – in one case one monitor fit using GIM ground store took two weeks due to seasonal variation in ground water table
modeFRONTIER
modeFRONTIER
modeFRONTIER
modeFRONTIER

Simulate the design process & outcome...

- Feasible
- Faster
- Cheaper
- More Robust

Adjust variables → Run simulations → Read results → Smart Algorithms → Simulation Tool
modeFRONTIER

Adjust variables → Smart Algorithms → Run simulations → Read results → design process & outcome ...

Feasible
Faster
Cheaper
More Robust
The Interface for InfoWorks CS

The Interface is a layer (in the form of a spreadsheet) between modeFRONTIER and InfoWorks CS that enables InfoWorks CS to be run automatically.

modeFRONTIER carries out sequential InfoWorks simulations adjusting input variables and evaluating improvements to verification fits from each run.
**Interface Functionality**

**Verification Variables**
- Diurnal Flow
- Baseflow
- Area 1
- Area 2
- Area 3
- Pipe Roughness
- Sediment Depth

**Scaling / Distribution to each pipe or subcatchment**

**Network Model**

**Runs**

**Standard Outputs (at Flow Monitor locations only)**
- Average Flow
- Peak Flow
- Volume
- Depth

**Grouped sub-catchment mode:**
- it permits changes to be made to specific features of the network model
- the contents of the model are automatically grouped by flow monitor and changes are made to these groups
Subcatchment Collections

- Interface automatically builds subcatchment collections based on the topology of the network and the location of the Flow Monitors.
Subcatchment Collections

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Subcatchment Collections

- Interface automatically builds **subcatchment collections** based on the topology of the network and the location of the Flow Monitors
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- Interface automatically builds **subcatchment collections** based on the topology of the network and the location of the Flow Monitors.
Bifurcations

- The Interface deals with bifurcations by creating artificial flow monitor locations at their root.
- Of course, no flow monitor data exists for these locations.
Bifurcations

- The Interface deals with bifurcations by creating artificial flow monitor locations at their root.
- Of course, no flow monitor data exists for these locations.
Verification Interface Parameters

Parameters available for adjustment (input) and monitoring (output):

<table>
<thead>
<tr>
<th>Phase</th>
<th>Controls</th>
<th>Targets (WaPUG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Day</td>
<td>• Baseflow</td>
<td>• Night flow period mean</td>
</tr>
<tr>
<td></td>
<td>• (pro-rata by area within each subcatchment collection)</td>
<td>• Peak flow</td>
</tr>
<tr>
<td></td>
<td>• Population</td>
<td>• Volume</td>
</tr>
<tr>
<td></td>
<td>• (in proportion to original population within each subcatchment collection)</td>
<td></td>
</tr>
<tr>
<td>Storm</td>
<td>• Scaled</td>
<td>• Peak Flow</td>
</tr>
<tr>
<td></td>
<td>• Area 1</td>
<td>• Time of Peak Flow</td>
</tr>
<tr>
<td></td>
<td>• Area 2</td>
<td>• Peak Depth</td>
</tr>
<tr>
<td></td>
<td>• Area 3</td>
<td>• Volume</td>
</tr>
<tr>
<td></td>
<td>• Sediment Depth</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Pipe Roughness</td>
<td></td>
</tr>
</tbody>
</table>

(note: the user specifies the limits within which any parameter may be adjusted)
The primary purpose for this extension is to permit the arbitrary modification of InfoWorks models to allow entirely user-defined objectives and studies.

In this Optioneering mode exactly the same process is used without reference to the grouping of subcatchment collections to provide this control.
Interface coupled with modeFRONTIER

- Simulated results are compared to real flow monitor data
- modeFRONTIER adjusts the available variables with the target of minimising differences between observed and predicted flows

<table>
<thead>
<tr>
<th>Verification Variables</th>
<th>Network Model</th>
<th>Runs</th>
<th>Standard Outputs (at Flow Monitor locations only)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diurnal Flow</td>
<td></td>
<td></td>
<td>Average Flow</td>
</tr>
<tr>
<td>Baseflow</td>
<td></td>
<td></td>
<td>Peak Flow</td>
</tr>
<tr>
<td>Area 1</td>
<td></td>
<td></td>
<td>Volume</td>
</tr>
<tr>
<td>Area 2</td>
<td></td>
<td></td>
<td>Depth</td>
</tr>
<tr>
<td>Area 3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pipe Roughness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sediment Depth</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Scaling / Distribution to each pipe or subcatchment
Interface coupled with modeFRONTIER

- Simulated results are compared to real flow monitor data
- modeFRONTIER adjusts the available variables with the target of minimising differences between observed and predicted flows
Interface coupled with modeFRONTIER

• Simulated results are compared to real flow monitor data

• modeFRONTIER adjusts the available variables with the target of minimising differences between observed and predicted flows

Veriﬁcation Variables

- Diurnal Flow
- Baseflow
- Area 1
- Area 2
- Area 3
- Pipe Roughness
- Sediment Depth

Scaling / Distribution to each pipe or subcatchment

Network Model

Runs

Standard Outputs (at Flow Monitor locations only)

- Average Flow
- Peak Flow
- Volume
- Depth

Real Flow Data

Compare to Sim

Sim Errors

How do I reduce the Sim errors to zero?
How can the Slow Runoff Parameters be Adjusted? Methods

• **Two methods** were considered
  1. Define a unique “Land Use” for groups of subcatchments associated with each flow monitor
     • For each Land Use, define its own unique Runoff for sub-area 3
     • Tune the parameters of the Runoff definition
  2. Define a common “Land Use” for all subcatchments affected by slow runoff
     • For this Land Use, define a series of increasingly-slow Runoff definitions for sub-areas 3 to 8
     • Redistribute the subcatchment land in sub-area 3 among the sub-areas 3 to 8
     • The redistribution pattern should be common to groups of subcatchments associated with each flow monitor
How can the Slow Runoff Parameters be Adjusted? 2nd Method selected

- For each subcatchment, the land was redistributed by multiplying the original sub-area with a **redistribution function**, which uses a single parameter “beta” which ranges from 100 (no change) to 0 (all the area moved to the “slowest” response)

![Graph showing the value of Beta for different types of land](image)
How can the Slow Runoff Parameters be Adjusted? 2nd Method selected

- For a particular subcatchment, the method may be represented visually as shown below:

- Roof and road (areas 1 and 2) assessed using OS data and evaluation of disposal route
- Permeable/slow runoff represented by up to 6 runoff surfaces (3-8) with increasing RRVs
- modeFRONTIER adjusts total amount and “mix” of areas 3-8
How can the Slow Runoff Parameters be Adjusted? 2nd Method selected

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- Permeable/slow runoff represented by up to 6 runoff surfaces (3-8) with increasing RRVs
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The modeFRONTIER Process Flow

Scales factors and Redistribution factors

Extract a base network from InfoWorks CS

Redistribute Area 3 according to each flow monitor’s beta value

Rescale permeable and impermeable areas

Build new network and re-run simulation

Extract results and compare with targets

Flow Data

Smart Algorithms
Selecting targets for modeFRONTIER

Rainfall

06:00 25/5/2008
16:00 26/5/2008
06:00 27/5/2008
16:00
Selecting targets for modeFRONTIER

Flow Monitor 06
Selecting targets for modeFRONTIER

DS end of conduit AB123456
Selecting targets for modeFRONTIER

DS end of conduit AB123456
Selecting targets for modeFRONTIER

DS end of conduit AB123456

<table>
<thead>
<tr>
<th>Network Location</th>
<th>Result Type</th>
<th>Window Start</th>
<th>Window End</th>
<th>Result Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link AB123456 (DS)</td>
<td>Peak Depth</td>
<td>t1</td>
<td>t2</td>
<td>Depth “a”</td>
</tr>
</tbody>
</table>
Selecting targets for modeFRONTIER

DS end of conduit AB123456

<table>
<thead>
<tr>
<th>Network Location</th>
<th>Result Type</th>
<th>Window Start</th>
<th>Window End</th>
<th>Result Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link AB123456 (DS)</td>
<td>Peak Depth</td>
<td>t1</td>
<td>t2</td>
<td>= Depth “a”</td>
</tr>
<tr>
<td>Link AB123456 (DS)</td>
<td>Volume</td>
<td>t3</td>
<td>t4</td>
<td>= Volume “b”</td>
</tr>
</tbody>
</table>
Selecting targets for modeFRONTIER

DS end of conduit AB123456

<table>
<thead>
<tr>
<th>Network Location</th>
<th>Result Type</th>
<th>Window Start</th>
<th>Window End</th>
<th>Result Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link AB123456 (DS)</td>
<td>Peak Depth</td>
<td>t1</td>
<td>t2</td>
<td>Depth “a”</td>
</tr>
<tr>
<td>Link AB123456 (DS)</td>
<td>Volume</td>
<td>t3</td>
<td>t4</td>
<td>Volume “b”</td>
</tr>
<tr>
<td>Link AB123456 (DS)</td>
<td>Peak Flow</td>
<td>t5</td>
<td>t6</td>
<td>Flow “c”</td>
</tr>
</tbody>
</table>

![Graph showing Depth and Flow with selected window times](image)
Selecting targets for modeFRONTIER

DS end of conduit AB123456

- The user selects a results location, type and a time window
- The interface extracts the result value from the simulation
- Multiple targets must be set along a simulation history to characterise slow runoff
- Different confidence levels can be applied to different monitors
Example: Chosen Network

- 350 subcatchments, 346 nodes, 3 flow monitors (FM5, FM6, FM16)
- Total simulation time 3.5 days
- 3 identified event periods
Example: Progress to Convergence

- The error between the simulation and the chosen targets quickly reduces
  - The steps show modeFRONTIER moving from exploration phases (flat regions) to adjustment phases (sudden improvements given by a gradient algorithm)
Example: Progress to Convergence

- The error between the simulation and the chosen targets quickly reduces
  - The steps show modeFRONTIER moving from exploration phases (flat regions) to adjustment phases (sudden improvements given by a gradient algorithm)

- modeFRONTIER adjust the beta parameter and scale factors for each group of subcatchments
  - this graph shows the progressive tuning of the permeable area (an example)
Animation of Flow Monitor 5 Progress – omit first fit – too high
Animation of Flow Monitor 5 Progress – omit first fit – too high
Animation of Flow Monitor 5 Progress – omit first fit – too high
Animation of Flow Monitor 5 Progress – omit first fit – too high
Animation of Flow Monitor 5 Progress – omit first fit – too high
Animation of Flow Monitor 5 Progress – omit first fit – too high
Animation of Flow Monitor 6 Progress
Animation of Flow Monitor 6 Progress
Animation of Flow Monitor 6 Progress

Flow Monitor 06
Animation of Flow Monitor 6 Progress

Flow Monitor 06
Animation of Flow Monitor 6 Progress

Way Point 0
Converged (cycle 326)
Target

Flow Monitor 06
Animation of Flow Monitor 16 Progress

Flow Monitor 16
Animation of Flow Monitor 16 Progress

Flow Monitor 16
Animation of Flow Monitor 16 Progress

Flow Monitor 16
Animation of Flow Monitor 16 Progress

Flow Monitor 16
Animation of Flow Monitor 16 Progress

Flow Monitor 16
Animation of Flow Monitor 16 Progress

Way Point 0
Converged (cycle 326)
Target

Flow Monitor 16
Summary of Features

- Integration of InfoWorks CS in modeFRONTIER (mfi4IWCS) is able to:
  
  - **Automate** InfoWorks CS runs
  - **Support** verification (calibration)
  - **Assist** with optimisation solutions (‘smart’ optioneering)
Summary of Benefits

• The benefits of using InfoWorks CS + modeFRONTIER:

  – Greater software/hardware utilisation since you can run InfoWorks 24/7 in unattended mode
  – Substantial reduction in time to verify model (up to 50%)
  – Valuable diagnostic information available to help engineer understand why certain FM’s are not calibrating (at an early stage of the project)
  – Ability to calibrate slow run-off and ground water infiltration
  – Ability to optimise the solution phase and therefore realise significant capital savings
  – Advanced reporting tools offer a greater in-sight into the solutions therefore enhancing learning
Multi-Objective Optimization of a Complex Water Distribution Network

Vito Primavera, EnginSoft Italy
Activity Description & Goals

A water distribution network, with known topology, is given

- **Management** of network needs to take into account several parameters ➔ not deterministic parameters (demands on different time periods, pipes roughness, emergencies, …)

- **Crucial problem** ➔ management of losses
Activity Description & Goals

Losses

Physical
- Concentrated
- Distributed

To be removed

Q_{lost} = Kp^{1.18} 

⇒ to be reduced by pressure control methods

Administrative

⇒ Static or dynamic controls
⇒ Pressure Control Valves (PCV)
Activity Description & Goals

The current activity is aimed to:

1. Pressure minimization
2. Costs minimization (i.e. number of PCVs)

At same time, minimum demands have to be guaranteed at each network node
Activity Description & Goals

The activity has been divided into the following phases:

- **Phase_01** ➔ selection of positions and minimum number of valves, in respect of all the time periods (scenarios);
- **Phase_02** ➔ determination of the optimum opening degree of the positioned valves, for every scenario
- **Phase_03** ➔ determination of the found solution robustness in respect of pipes roughness and node demands.

The software tools used for the numerical analyses are:

- the water distribution network solver **EPAnet2**, freeware tool to calculate the parameters characterizing an hydraulic network
- **in-house utilities** written in C++, used to dynamically update various characteristics of the network analyzed by EPANet2
- the multi-objective design and optimization environment **modeFRONTIER**. This tool has been used for both network optimization and data post-processing.
Hydraulic Network: Piedimonte San Germano’s

The activity took into account a real water distribution network in Piedimonte San Germano, characterized by a high percentage of distributed losses due to loads usually larger in respect of the service.
Hydraulic Network: Piedimonte San Germano’s

- Networks characteristics:
  - 30 nodes
  - 42 pipes
  - 12 chains
  - 1 tank node

- Starting network configuration:
  - Valves n° = 0
  - \( \sum_{i=1}^{30} p_i = \)

<table>
<thead>
<tr>
<th>Time</th>
<th>03:00</th>
<th>06:00</th>
<th>07:00</th>
<th>09:00</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1658 m</td>
<td>1543 m</td>
<td>1222 m</td>
<td>1065 m</td>
</tr>
</tbody>
</table>

- Tank node ➔ prevalence = 180 m
Hydraulic Network: Piedimonte San Germano’s

- Networks characteristics: the presence of high water losses is demonstrated by the high demands during the night-time ➔ their values can’t be justified by number and typology of the consumers.

<table>
<thead>
<tr>
<th>Node</th>
<th>03:00</th>
<th>06:00</th>
<th>07:00</th>
<th>09:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0.612</td>
<td>0.468</td>
<td>0.612</td>
<td>0.72</td>
</tr>
<tr>
<td>3</td>
<td>0.671</td>
<td>0.664</td>
<td>0.575</td>
<td>1.08</td>
</tr>
<tr>
<td>4</td>
<td>0.199</td>
<td>0.072</td>
<td>0.106</td>
<td>0.144</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0.792</td>
<td>0.612</td>
<td>0.792</td>
<td>0.9</td>
</tr>
<tr>
<td>7</td>
<td>0.036</td>
<td>0</td>
<td>0.036</td>
<td>0.036</td>
</tr>
<tr>
<td>8</td>
<td>0.158</td>
<td>0.376</td>
<td>0.166</td>
<td>3.456</td>
</tr>
<tr>
<td>9</td>
<td>2.24</td>
<td>3.24</td>
<td>3.24</td>
<td>3.24</td>
</tr>
<tr>
<td>10</td>
<td>0.396</td>
<td>0.268</td>
<td>0.396</td>
<td>0.396</td>
</tr>
<tr>
<td>11</td>
<td>0.036</td>
<td>0.016</td>
<td>0.036</td>
<td>0.036</td>
</tr>
<tr>
<td>12</td>
<td>0.36</td>
<td>0.268</td>
<td>0.36</td>
<td>0.356</td>
</tr>
<tr>
<td>13</td>
<td>1.296</td>
<td>0.864</td>
<td>1.396</td>
<td>1.476</td>
</tr>
<tr>
<td>14</td>
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<td>0.18</td>
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</tr>
<tr>
<td>16</td>
<td>0.432</td>
<td>0.36</td>
<td>0.432</td>
<td>0.468</td>
</tr>
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<td>17</td>
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<td>18</td>
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<td>0.972</td>
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<tr>
<td>20</td>
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<td>0.468</td>
<td>0.612</td>
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</tr>
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<td>0.432</td>
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<tr>
<td>23</td>
<td>0.246</td>
<td>0.143</td>
<td>0.246</td>
<td>0.216</td>
</tr>
<tr>
<td>24</td>
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<tr>
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<td>0.252</td>
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<td>27</td>
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<td>0.236</td>
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<td>28</td>
<td>2.088</td>
<td>1.613</td>
<td>2.088</td>
<td>2.283</td>
</tr>
<tr>
<td>29</td>
<td>1.152</td>
<td>0.864</td>
<td>1.152</td>
<td>1.332</td>
</tr>
<tr>
<td>30</td>
<td>0.576</td>
<td>0.396</td>
<td>0.576</td>
<td>0.664</td>
</tr>
</tbody>
</table>

8th network node

Demands (l/s) @ 4 scenarios: 03:00, 06:00, 07:00, 09:00

Night peek demands values over 5 days measurements
Phase 01
Phase 01 – Description

Phase_01 ➔ positioning of the optimal minimum number of valves with respect to all 4 frame time scenarios. modeFRONTIER workflow relies on:

- **Input Variables**: valves number, position and opening degree
  - `on_off_valves` = 42 binary variables, where 0/1 means valve not inserted/inserted
  - `openV` = 42 variables related to opening degree of the corresponding valve (0, 5, 10, 20, 30, 50, 95 %)
  - `set_demands` = variable setting randomly which one of the 4 possible scenarios has to be considered for the current simulation

- **Output Variables**: nodes pressure
  - `nodes pressure` = pressure at 30 nodes
  - `flag` = variable checking if the given solution is balanced
Phase 01 – Description

Phase_01 ➔ positioning of the optimal minimum number of valves with respect to all 4 frame time scenarios. modeFRONTIER workflow relies on:

- **Objectives:**
  - minimize_total_pressure = objective node minimizing network total pressure
  - minimize_valves_number = objective node minimizing the total valves number

- **Constraints:**
  - pressure_constraints = 30 constraints verifying the correspondent node pressure belongs to a specified range (10 m < p < 70 m)
Phase 01 – modeFRONTIER workflow

**Dynamic generation of EPANet 2 models (new IVs)**

**Design parameters**
- **Input variables**: 88

**Design goals**
- **Objectives**: 2
- **Constraints**: 30

**Optimization’s set-up data**
- **Sampling phase**: DOE: 1500 SOBOL
- **Exploration phase**
  - Algorithm: MOGA II

**Objective Functions**
- **minimize_valves_number**
- **minimize_total_pressure**

**CPU time**
- **Number of analyses**: 21000
- **CPU time required**: ca. 20 h
Phase 01 – Results: Solutions Convergence (e.g. 9:00 am)

History Chart:
Total Pressure vs. design (9:00 a.m.)

History Chart:
Valves Number vs. design (9:00 a.m.)
Phase 01 – Results: Pareto Designs @ 03:00 am scenario

Selected designs ➔ best trade-off vs. 2 objective functions @ 03:00 am

minimize_total_pressure vs. minimize_valves_number

ID
21491
19342
17193
15045
12896
10747
8598
6449
4301
2152
3

24/06/2014
Phase 01 – Results: Pareto Designs @ 06:00 am scenario

Selected designs ➔ best trade-off vs. 2 objective functions @ 06:00 am
Phase 01 – Results: Pareto Designs @ 07:00 am scenario

Selected designs → best trade-off vs. 2 objective functions @ 07:00 am
Phase 01 – Results: Pareto Designs @ 09:00 am scenario

Selected designs ➔ best trade-off vs. 2 objective functions @ 09:00 am
Phase 01 – Results: Getting to to Know the Best

- Parallel Coordinate Charts ➔ filtering out the OFs, best designs survive

Every vertical axis represents the dominion of a different variable (both input and output), and the line connecting the values of each variable on each corresponding axis sketches every design.

The Parallel Coordinate Chart can be used to filter the most interesting solutions in the database.
Phase 01 – Results: Getting to to Know the Best

- Parallel Coordinate Charts ➔ filtering out the OFs, best designs survive

Filtering out the unfeasible designs (i.e. at least one constraint is broken), the most suitable input variables values arise ➔ getting to know the phenomena
Phase 01 – Results: Getting to to Know the Best

- Parallel Coordinate Charts ➔ filtering out the OFs, best designs survive

Filtering out the unfeasible designs (i.e. at least one constraint is broken), the most suitable input variables values arise ➔ getting to know the phenomena

Pursuing the objectives minimization, the inputs arrangement providing Pareto Designs is pointed out
Phase 01 – Results: Selection of Best

- The Post Processing Analysis highlight how the minimum of nodes prevalence sum is almost reached for 3-4 valves number configurations providing the lowest hydraulic losses.

- At management purpose, it is necessary to balance between the losses costs and the costs of actions taken to minimize losses themselves during the analysis phase, configurations for 1, 2, 3 and 4 valves have been examined.

![Graph showing loss reduction with valves number]
Phase 01 – n° Valves = 1

- Network configuration:
  - Valves n° = 1

- \[ \sum_{i=1}^{30} p_i = \]

<table>
<thead>
<tr>
<th>ORE 03:00</th>
<th>ORE 06:00</th>
<th>ORE 07:00</th>
<th>ORE 09:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>1287.80 mt</td>
<td>1070.10 mt</td>
<td>796.16 mt</td>
<td>864.67 mt</td>
</tr>
</tbody>
</table>

Average percentage of loads reduction: 26 %
Phase 01 – n° Valves = 2

- **Network configuration:**
  - Valves n° = 2

\[ \sum_{i=1}^{30} p_i = \]

<table>
<thead>
<tr>
<th>Time</th>
<th>Flow (mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORE 03:00</td>
<td>1177.00</td>
</tr>
<tr>
<td>ORE 06:00</td>
<td>926.71</td>
</tr>
<tr>
<td>ORE 07:00</td>
<td>565.12</td>
</tr>
<tr>
<td>ORE 09:00</td>
<td>490.43</td>
</tr>
</tbody>
</table>

Average percentage of loads reduction: 44 %
Phase 01 – n° Valves = 3

- Network configuration:
  - Valves n° = 3
  - $\sum_{i=1}^{30} p_i =$

<table>
<thead>
<tr>
<th>Time</th>
<th>Flow Rate (mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ORE 03:00</td>
<td>905.13</td>
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<tr>
<td>ORE 06:00</td>
<td>569.31</td>
</tr>
<tr>
<td>ORE 07:00</td>
<td>583.68</td>
</tr>
<tr>
<td>ORE 09:00</td>
<td>460.23</td>
</tr>
</tbody>
</table>

Average percentage of loads reduction: 54 %
Phase 01 – n° Valves = 4

- Network configuration:
  - Valves n° = 4
  
  \[ \sum_{i=1}^{30} p_i = \]

<table>
<thead>
<tr>
<th>ORE 03:00</th>
<th>ORE 06:00</th>
<th>ORE 07:00</th>
<th>ORE 09:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>835.63 mt</td>
<td>659.66 mt</td>
<td>475.09 mt</td>
<td>465.04 mt</td>
</tr>
</tbody>
</table>

Average percentage of loads reduction: 56 %
Phase 01 – Summary

The following table highlights the network total pressures at 4 different time shifts taken into account:

- The percentage trend of the losses reduction decreases with the increasing of the valves number, showing plateau trend
- The optimum valves number to be introduced is equal to 4, positioned on pipes 1, 2, 20 and 42

<table>
<thead>
<tr>
<th></th>
<th>03:00</th>
<th>06:00</th>
<th>07:00</th>
<th>09:00</th>
<th>Average Pressure</th>
<th>Average Reduction</th>
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</thead>
<tbody>
<tr>
<td>0 Valves</td>
<td>Pression (mt)</td>
<td>1658.60</td>
<td>1543.10</td>
<td>1222.20</td>
<td>1065.40</td>
<td>1372.33</td>
</tr>
<tr>
<td></td>
<td>% Reduction</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>1 Valve</td>
<td>Pression (mt)</td>
<td>1287.80</td>
<td>1070.10</td>
<td>796.16</td>
<td>864.67</td>
<td>1004.68</td>
</tr>
<tr>
<td></td>
<td>% Reduction</td>
<td>22 %</td>
<td>30 %</td>
<td>35 %</td>
<td>18 %</td>
<td>26 %</td>
</tr>
<tr>
<td>2 Valve</td>
<td>Pression (mt)</td>
<td>1177.00</td>
<td>926.71</td>
<td>565.12</td>
<td>490.43</td>
<td>789.82</td>
</tr>
<tr>
<td></td>
<td>% Reduction</td>
<td>29 %</td>
<td>40 %</td>
<td>53 %</td>
<td>54 %</td>
<td>44 %</td>
</tr>
<tr>
<td>3 Valve</td>
<td>Pression (mt)</td>
<td>905.13</td>
<td>569.31</td>
<td>583.68</td>
<td>460.23</td>
<td>629.59</td>
</tr>
<tr>
<td></td>
<td>% Reduction</td>
<td>45 %</td>
<td>63 %</td>
<td>52 %</td>
<td>57 %</td>
<td>54 %</td>
</tr>
<tr>
<td>4 Valves</td>
<td>Pression (mt)</td>
<td>835.63</td>
<td>659.66</td>
<td>475.09</td>
<td>465.04</td>
<td>608.86</td>
</tr>
<tr>
<td></td>
<td>% Reduction</td>
<td>49 %</td>
<td>57 %</td>
<td>61 %</td>
<td>56 %</td>
<td>56 %</td>
</tr>
</tbody>
</table>
Phase 02 – Description

Phase_02 ➔ looking for the best opening degrees for the optimum configuration coming from Phase_01 for every scenario

- Input Variables: valves opening degree (0, 5, 10, 15, 20, 30, 50, 95 %)

- Output Variables: nodes pressure

- Objective Functions: minimize network loads sum for every given scenario

- Constraints: prevalence on nodes encompassed in the range of 10 – 70 m (service conditions)

NOTE: modeFRONTIER workflow remains the same one (IV switched to constants)
Phase 02 – Summary Results

- **Optimization process**
  - DOE: from 20 to 50 SOBOL designs, depending on valves number
  - Optimization Algorithm: MOGA II (Multi-Objective Genetic Algorithm)

- Depending on the valves number, the optimization process convergence has taken from circa 1200 designs (2 hrs analysis time, 4 valves) to a number of 8 designs (1 valve)

- Optimization is mono-objective, being the valves opening degree definition the only requirement (but multiple pressure constraints management)

- Results ➔ the performance are almost the same vs. Phase_01’s, so the 1st optimization has been performed efficiently
## Phase 02 – Summary Results

### Optimization process

<table>
<thead>
<tr>
<th></th>
<th>03:00</th>
<th>06:00</th>
<th>07:00</th>
<th>09:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 Valves</td>
<td>1658.60</td>
<td>1543.10</td>
<td>1222.20</td>
<td>1065.40</td>
</tr>
<tr>
<td>% Reduction</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>1 Valve</td>
<td>1287.80</td>
<td>1070.10</td>
<td>796.16</td>
<td>864.67</td>
</tr>
<tr>
<td>% Reduction</td>
<td>22%</td>
<td>30%</td>
<td>35%</td>
<td>18%</td>
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<tr>
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<td>565.12</td>
<td>490.43</td>
</tr>
<tr>
<td>% Reduction</td>
<td>29%</td>
<td>40%</td>
<td>53%</td>
<td>54%</td>
</tr>
<tr>
<td>3 Valves</td>
<td>811.28</td>
<td>569.31</td>
<td>537.51</td>
<td>460.23</td>
</tr>
<tr>
<td>% Reduction</td>
<td>37%</td>
<td>63%</td>
<td>56%</td>
<td>57%</td>
</tr>
<tr>
<td>4 Valves</td>
<td>644.99</td>
<td>659.66</td>
<td>472.24</td>
<td>459.94</td>
</tr>
<tr>
<td>% Reduction</td>
<td>61%</td>
<td>57%</td>
<td>61%</td>
<td>57%</td>
</tr>
</tbody>
</table>

### Results

The performance are almost the same vs. Phase_01’s, so the 1st optimization has been performed efficiently.
Phase 03
Phase 03 – Description

- Phase_03 ➔ looking for the more robust solutions in respect of the non-deterministic parameters ➔ variables subject to a probabilistic distribution represent an important problem for the system performances

- A stochastic distribution has been assigned to those variables with oscillating values in time or with an unknown value at all

- This phase has been carried out through the MORDO (Multi Objective Robust Design Optimization) module available into modeFRONTIER ➔ it allows to carry out optimization analyses, searching for the solutions which are least sensible to some given stochastic parameters
Phase 03 – Description

- The 4 valves – 9:00 a.m. scenario has been investigated, since that is the time frame with the highest demands ➔ highest probability of demands variations. Following are the project parameters:
  - **stochastic input variables**: nodes demand and pipes roughness, with a definition domain comprehended in a range of 10% of the associated nominal value. A Gauss Distribution sampling of 15 values has been given to every nominal value.
  - **deterministic input variables**: valves opening degree (0, 5, 10, 15, 20, 30, 50, 95%)
  - **output variables**: nodes pressure
  - **objectives**: minimizing the mean value of the network prevalence sum, calculated on the 15 designs associated to the normal distribution
  - **constraints**: prevalence on nodes encompassed in the range of 10 – 70 m (service conditions) and pressures standard deviation < 20 m

- Optimization Process ➔ 50 SOBOL + MOGA II

Convergence has taken circa 4000 designs (7 hrs CPU time)
Phase 03 – Looking for Best Results

- Scatter Chart ➔ **Standard Deviation of Tot Pressure vs. Mean Tot Pressure**

![Scatter Chart - total_pressure_MEAN vs. total_pressure_STDEV on Robust Designs Table](image)

- Mean Tot Pressure
- STDEV Tot Pressure

< 20 m
Phase 03 – Looking for Best Results

- Phase_03 ➔ Optimum Configurations: id 2934, id 4157

These tables show the configurations of the 2 optimal solutions highlighted in the previous chart.

<table>
<thead>
<tr>
<th>Valve n.</th>
<th>Position</th>
<th>Open Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pipe 01</td>
<td>10%</td>
</tr>
<tr>
<td>2</td>
<td>Pipe 02</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>Pipe 20</td>
<td>10%</td>
</tr>
<tr>
<td>4</td>
<td>Pipe 42</td>
<td>Closed</td>
</tr>
</tbody>
</table>

4 VALVES - 09:00 Scenary (Des. 2934)

<table>
<thead>
<tr>
<th>Valve n.</th>
<th>Position</th>
<th>Open Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pipe 01</td>
<td>10%</td>
</tr>
<tr>
<td>2</td>
<td>Pipe 02</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>Pipe 20</td>
<td>5%</td>
</tr>
<tr>
<td>4</td>
<td>Pipe 42</td>
<td>Closed</td>
</tr>
</tbody>
</table>

4 VALVES - 09:00 Scenary (Des. 4157)

The 2 solutions reached both a pressure mean value very similar to Phase_02 values, and a standard deviation good “enough” to assure them to be robust solutions.
Phase 03 – Results Comparison vs. Phase 02

- Phase_03 ➔ checking robustness of Phase_02 best solution ➔ by comparing Phase_02 and Phase_03 results, it has been easy to point out similarities ➔ Phase_02 optimal solution, id 4120, becomes more robust by simply modifying the opening degree of one of its 4 valves (positioned on pipe 20) ➔ id 4157

<table>
<thead>
<tr>
<th>Valve n.</th>
<th>Position</th>
<th>Open Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pipe 01</td>
<td>10%</td>
</tr>
<tr>
<td>2</td>
<td>Pipe 02</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>Pipe 20</td>
<td>Closed</td>
</tr>
<tr>
<td>4</td>
<td>Pipe 42</td>
<td>Closed</td>
</tr>
</tbody>
</table>

Total Mean Pressure (mt): 473.48
Standard Deviation (mt): 37

<table>
<thead>
<tr>
<th>Valve n.</th>
<th>Position</th>
<th>Open Degree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pipe 01</td>
<td>10%</td>
</tr>
<tr>
<td>2</td>
<td>Pipe 02</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>Pipe 20</td>
<td>Closed</td>
</tr>
<tr>
<td>4</td>
<td>Pipe 42</td>
<td>Closed</td>
</tr>
</tbody>
</table>

Total Mean Pressure (mt): 475.88
Standard Deviation (mt): 16

Phase_02 optimum configuration
Phase_03 optimum configuration
Summary

- A fully automatized procedure has been implemented by integrating freeware EPANet 2 hydraulic software tool into modeFRONTIER

- A Multi-Objective optimization has been performed taking into account multiple and several free parameters. The results coming from provide the best trade-off solutions (Pareto Solutions), so the more suitable configurations can be selected according its own requirements

- Robustness of the solutions has been evaluated in respect of typical stochastic parameters of water hydraulic networks