Applied Mathematics in the Electricity Industry Management

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Motivation

- Mathematics are *useful*, connected to reality. It is not just a knowledge, it is an *attitude* in engineering.
- Make the mathematics *accessible*, explain mathematics for shepherds (dummies).
- Mathematical concepts explained with the help of geometrical or economical interpretation.
- “Spare the rod and spoil the child” is no longer valid, *good mood* and *enthusiasm* is an important tool in teaching mathematics.
- *Pitfall* for engineering students: formal mathematical algorithms substituted by *common sense* or *rule of thumb*. 
Approach

• **Practical experience** of teaching applied mathematical methods at undergraduate, master and doctorate levels in a School of Engineering
• **Close relationship** between what we teach and we research and develop
• We have developed some *real decision support tools* to help in taking operation and investment decisions in the electricity industry
Operations Research (OR)

• Defined as the application of advanced scientific analytical methods in improving the effectiveness in operations, decisions and management of a company.

• Management Science, Business Analytics or Decision Science.

• The science of better (motto of the Operational Research Societies (http://www.scienceofbetter.org/)) or as decision support models or advanced analytical methods.

• Science in the frontier between primarily economics and engineering.
OR Applications

- *Life itself is a matter of OR* is the slogan of the EURO (European Operational Research Societies).
- There are many fields where OR methods can be applied to improve decision making.
- The *electricity industry* and the OR have always been good companions for many years
  - Decision support tools allow managing the operation and to evaluate long-term capital-intensive decisions in the electricity industry.
Optimization

- Optimization selects the *best decisions* among the innumerable feasible options available. It is a prescriptive technique.
- Optimization appears in *last year* of undergraduate curriculum
  - More mature students which have proven they “know” mathematics
  - *Optimization is not “rejected” by the students unless it reminds calculus or algebra to them*
- Students look for usefulness, connection with applications is crucial
I am sorry for Germany, I was expecting to ...
Structure of the optimization courses

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Optimization methods/models in the engineering curriculum

- Engineering Degree
- Erasmus Mundus International Master in Economics and Management of Network Industries
- Master in Research in Engineering Systems Modelling
- Mathematical Methods
- Decision support models in the electric power industry
- Deterministic Optimization
- Stochastic Optimization
General objectives

• Two main objectives:
  1. Learn how to build models for a certain decision problem
  2. Understand the technique used to solve them.
• The student has to be able to develop optimization models using high-level languages.
Contents

- Classical *optimization methods*
  - Linear programming (LP)
  - Mixed integer programming (MIP)
  - Nonlinear programming (NLP)
  - Mixed complementarity problem (MCP)
  - Stochastic programming (SP)

- Some *specialised algorithms* used to solve large-scale optimization problems such as
  - Benders’ decomposition
  - Lagrangian relaxation
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Learning material
Learning material

- OpenCourseWare approach to provide all the material fully accessible via the web
  - Lecture notes
  - Slides from all the professors
  - Set of solved problems
  - Previous exams
- We encompass theory, numerical examples and computer examples along the course.
- Daily schedule on the web page
  - http://www.iit.upcomillas.es/aramos/MME.htm
  - http://www.iit.upcomillas.es/aramos/O.htm
  - http://www.iit.upcomillas.es/aramos/OE.htm
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Competencies
Competencies of the mathematical curriculum

1. Thinking mathematically
2. Reasoning mathematically
3. Posing and stating mathematical problems
4. Modeling mathematically
5. Representing mathematical entities
6. Handling mathematical symbols and formalism
7. Communication in, with, and about mathematics
8. Making use of aids and tools
Competencies

- Recognize the *diverse fields* where optimization techniques can be applied
- Understand and apply the *techniques* used for decision making
- *Model and solve prototype* optimization problems of diverse nature using an algebraic modeling language
- Analyze, synthesize and *interpret* the solutions obtained
- Present the model in a *written report and orally*
- Learn how to *work in a group* for doing the practice
- Understanding the *mathematical principles* that support the algorithms and their potential application
- Achieve *mathematical rigorousness*
Additional competencies at master level (i)

- **Professional-oriented** master
  - Achieve a general understanding of the mathematical models
  - Understand their input and output and their use in an industry context
  - Understand how different functions of the company are done by means of mathematical models
  - Write a technical report where describing the use of a mock-up model to a case study and analyze the results
Additional competencies at master level (ii)

- **Research-oriented** master
  - Develop from scratch their own mathematical optimization model
  - How to *extend the models* from an small scale to a large scale
  - Learning how to *model efficiently*
  - *Write a technical report* where describing the optimization problem, the mathematical formulation, the code solving it and analyze the results
  - *Oral communication* is important when using mathematics (engineering point of view?)
Assessment

- **Undergraduate** level
  - Individual evaluation by a written exam with open books and pocket calculators
  - Technical report with a journal paper structure written by a group of two persons
  - Oral communication by the group to the students and professor

- **Graduate** level
  - Technical report for an application case of their interest and within the content of the subject
For those that have not been able to see the frog
Model development
Know how

- To achieve these competencies the students learn by doing.
- They have to build mock-up optimization models by using an algebraic modelling language at both undergraduate and master levels.
- In particular, we use General Algebraic Modelling System GAMS (http://www.gams.de/)
- It is the communicating path between theory, small and large-scale cases, teaching, research and real use

Theory → Small model → Large model
Teaching → Research → Commercial application
Algebraic modeling languages: characteristics

• These languages are used for *rapid prototyping* given that allow flexibility for *continuous refinement* of the model and therefore generate a huge *decrease in maintenance effort*.

• Relevant characteristics:
  – High-level computer programming languages for the formulation of *complex mathematical optimization* problems
  – *Notation similar to algebraic notation*. They provide a concise and readable definition of problems in the domain of optimization
  – Do not solve problems directly, but ready-for-use links to state-of-the-art algorithms. Therefore, allow the modeller to *concentrate in the modelling process*
Algebraic modeling languages: advantages

• Main advantages:
  – *Independency* of the mathematical model and data, solution method (solver), operating system or user interface
  – At the same time, models can *benefit from* advances in hardware, solution methods or interfaces to other systems
  – These advantages are also important for *developing high-end models*.
Transition to high-end models

- Students develop *mock-up optimization models*. However, *commercial-grade models* are needed to support decisions for large-scale electric systems.

- *Scaling-up* models is a major task, from a *computational* and from a *mathematical* point of view.
  - A very *careful computer implementation* has to be followed and probably a *specific optimization algorithm* must be used.

- People from the electric companies are aware of the usefulness of mathematical models. However, in these models it is crucial to *balance the mathematics and algorithms involved and the practical solutions* provided by them.
High-end models
High-end models

1. Short-term daily unit commitment model
2. Hydrothermal scheduling model
3. Market equilibrium model
4. Transmission expansion planning model

Mock-up models in

http://www.iit.upcomillas.es/aramos/Ramos_CV.htm#ModelosAyudaDecision
Short-term daily unit commitment model (i)

- Determine the technical and economic impact of intermittent generation (IG) and other types of emerging technologies (active demand response, electric vehicles, concentrated solar power, solar photovoltaic) into the medium-term system operation including reliability assessment.

- Results consist of generation output including IG surplus, pumped storage hydro and storage hydro usage, and adequacy reliability measures. The benefits of improving IG predictions can also be determined by changing forecast error distributions and re-running the model.

- Solved as a **MIP** problem + **Monte Carlo Simulation**
Time scope
Short-term daily unit commitment model (iii)

Daily Operation Planning

WG Forecast Error Simulation

Committed units

Reservoir levels

Day 1

Day 2

Day 3

Day 365
Hydrothermal scheduling model

- Manage the integrated operation planning of both hydro and thermal power plants
- Emphasis paid in stochastic water inflows and topological relations among hydro reservoir
- Posed as a *multistage stochastic MIP* solved by *stochastic dual dynamic programming*
Scenario recombining tree example

In each node a decision is made and afterwards stochastic parameters are revealed.

Inflow: 25 m³/s
Prob: 0.55

Inflow: 30 m³/s
Prob: 0.60

Inflow: 30 m³/s
Prob: 0.35

Inflow: 15 m³/s
Prob: 0.40

Inflow: 15 m³/s
Prob: 0.65

Inflow: 20 m³/s
Prob: 0.45
Multiple basins

- Hydro subsystem is divided in a set of independent hydro basins:
Solution of a stochastic model

1. Stochastic parameters
2. Scenario tree generation
3. Stochastic optimization
4. Stability of the stochastic solution?

- YES
- NO
Market equilibrium model

- Stated as the profit maximization problem of each generation company (GENCO) subject to the constraint that determines the electricity price as a function of the demand, which is the sum of all the power produced by the companies. Each company profit maximization problem includes all the operational constraints that the generating units must satisfy.

- Formulated as a *mixed complementarity problem*
Stating the problem: Each company’s problem

Maximize:

Company 1’s optimization problem

Objective function

Subject to:

Technical constraints

Company 1’s optimization problem

Company e’s optimization problem

Company E’s optimization problem

Company net revenues for the entire scope considered

- Inter-period
  - Fuel stock management
  - Hydro scheduling

- Intra-period
  - Weekly hydro pumping
  - Variable bounds

- Other sources of revenue
  - CTCs
  - Long-term contracts...

- Inverse demand function

- Market constraints
Stating the problem: Using the model

SYSTEM DATA
- Companies
- Demand
- Generation (costs, limits...)

MARKET RESULTS
- Market share
- Electricity prices
- Revenue and output per unit

Electric power market
Mixed complementarity problem (MCP)

- Combining a **system of equations** with a **complementarity problem**
- Generalization of the complementarity problem

**System of equations**

\[
\begin{align*}
\nabla_x L^e (x, \lambda, \mu) &= \frac{\partial L^e}{\partial x^e} = 0 \\
\nabla_\mu L^e (x, \lambda, \mu) &= \frac{\partial L^e}{\partial \mu_j^e} = h_j^e = 0 \\
\lambda_k^e \cdot g_k^e &= 0 \\
g_k^e &\leq 0 \\
\lambda_k^e &\leq 0
\end{align*}
\]

\[x \text{ free} \quad \mu_j^e \text{ free}\]
Equivalent mixed complementarity problem for all the companies

Company 1’s optimality conditions
\[ \nabla_x L^1(x, \lambda, \mu) = \frac{\partial L^1}{\partial x^i} = 0 \]
\[ \nabla_x L^1(x, \lambda, \mu) = \frac{\partial L^1}{\partial \mu_j} = h^1_j = 0 \]
\[ \lambda^1_k \cdot g^1_k = 0 \quad g^1_k \leq 0 \quad \lambda^1_k \leq 0 \]

Company e’s optimality conditions
\[ \nabla_x L^e(x, \lambda, \mu) = \frac{\partial L^e}{\partial x^i} = 0 \]
\[ \nabla_x L^e(x, \lambda, \mu) = \frac{\partial L^e}{\partial \mu_j} = h^e_j = 0 \]
\[ \lambda^e_k \cdot g^e_k = 0 \quad g^e_k \leq 0 \quad \lambda^e_k \leq 0 \]

Company E’s optimality conditions
\[ \nabla_x L^E(x, \lambda, \mu) = \frac{\partial L^E}{\partial x^i} = 0 \]
\[ \nabla_x L^E(x, \lambda, \mu) = \frac{\partial L^E}{\partial \mu_j} = h^E_j = 0 \]
\[ \lambda^E_k \cdot g^E_k = 0 \quad g^E_k \leq 0 \quad \lambda^E_k \leq 0 \]

Price-m(y)=0

Electric power market

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Transmission expansion planning model

- Determines the investment plans of new facilities (lines and other network equipment) for supplying the forecasted demand at minimum cost. Tactical planning is concerned with time horizons of 15-30 years. Its objective is to evaluate the future network needs. The main results are the guidelines for future structure of the transmission network.

- Stated as a MIP solved by Benders’ decomposition
Transmission expansion planning model

- Load
- Existing and future generation
- Existing network
- Candidate network

Automatic transmission plan generation

Transmission plan evaluation

Best transmission expansion plans

- Reliability criteria
- Financial criteria
- Environmental criteria
- Investment and operation cost. System operation

Introduction

Structure

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Competencies

Model develop.

High-end models
Transmission expansion planning model

- Dynamic tactical transmission planning

Automatic generation of transmission expansion plans

Economic evaluation of transmission plans:
- Operation module
- Reliability module

Introduction | Structure | Material | Competencies | Model develop. | High-end models
The famous Spanish strategy for playing football

and the winner is ...
Conclusions
Conclusions

• Mathematical *model development* and the *use of models* for taking decisions is a part of the curriculum of the School of Engineering at undergraduate and graduate level.

• Mathematical formulation of models allows the students to advance in their *logical thinking, formulating* them in an algebraic modelling language, familiarize them with reality and how the models can be employed for *decision support*.

• *Competencies fit very well* in the general mathematical competencies

• Algebraic modeling language is the *communicating trail* between theory, small and large-scale cases, teaching, research and real use

• Natural continuation between *mock-up models* explained to the students and *high-end models* developed as part of funded research.
THANK YOU VERY MUCH FOR YOUR ATTENTION

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