Applied Mathematics in the Electricity Industry Management

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16th SEFI MWG Seminar

July 2012

Content

1. Introduction
2. Structure of the optimization courses
3. Learning material
4. Competencies
5. Model development
6. High-end models
7. Conclusions

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Introduction

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- "Spare the rod and spoil the child" is no longer valid, *good mood* and *enthusiasm* is an important tool in teaching mathematics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

Introduction   Structure   Material   Competencies   Model develop.   High-end models

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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.

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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.

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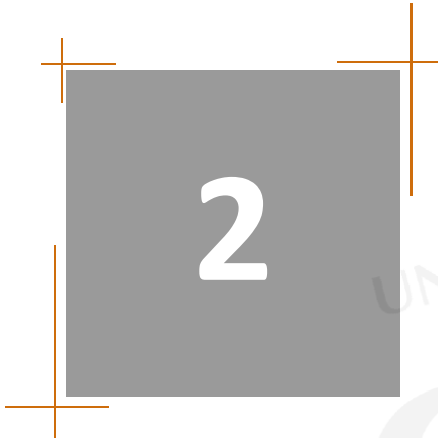July 2012

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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

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I am sorry for Germany, I was expecting to …

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Structure of the optimization courses
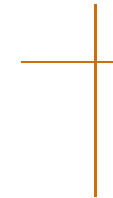
Optimization methods/models in the engineering curriculum

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┌─────────────────────────┐          ┌─────────────────────────┐
│                         │          │                         │
│   Engineering Degree    │ <──────> │  Mathematical Methods   │
│                         │          │                         │
└─────────────────────────┘          └─────────────────────────┘

┌─────────────────────────┐          ┌─────────────────────────┐
│ Erasmus Mundus          │          │ Decision support models │
│ International Master in  │ <──────> │ in the electric power   │
│ Economics and Management │          │ industry                │
│ of Network Industries   │          │                         │
└─────────────────────────┘          └─────────────────────────┘

┌─────────────────────────┐          ┌─────────────────────────┐
│ Master in Research       │          │ Deterministic           │
│ in Engineering Systems   │ <──────> │ Optimization            │
│ Modelling                │          │ Stochastic Optimization │
└─────────────────────────┘          └─────────────────────────┘
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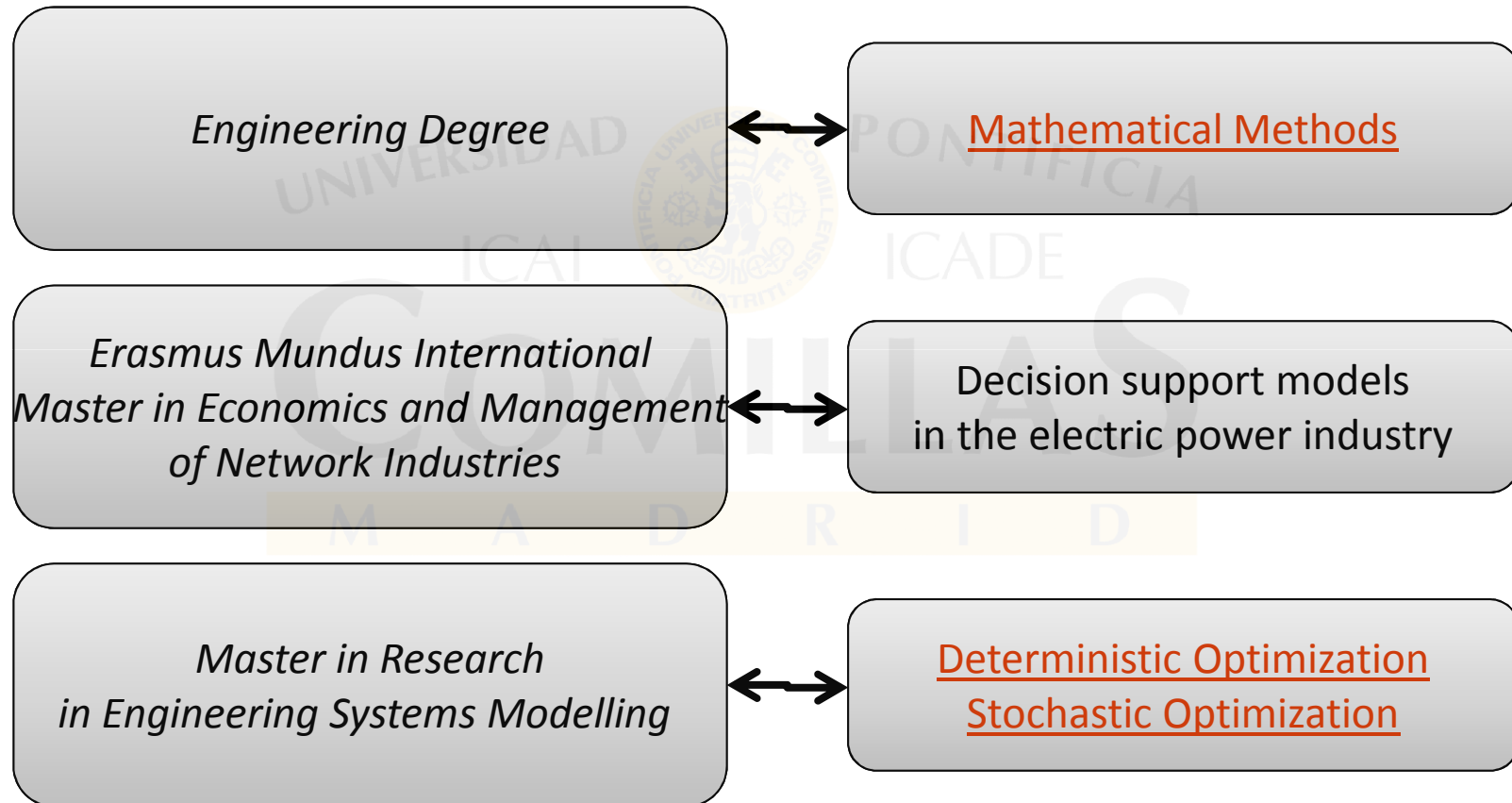
General objectives

- 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.

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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

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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*

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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

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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?)

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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

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For those that have not been able to see the frog

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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
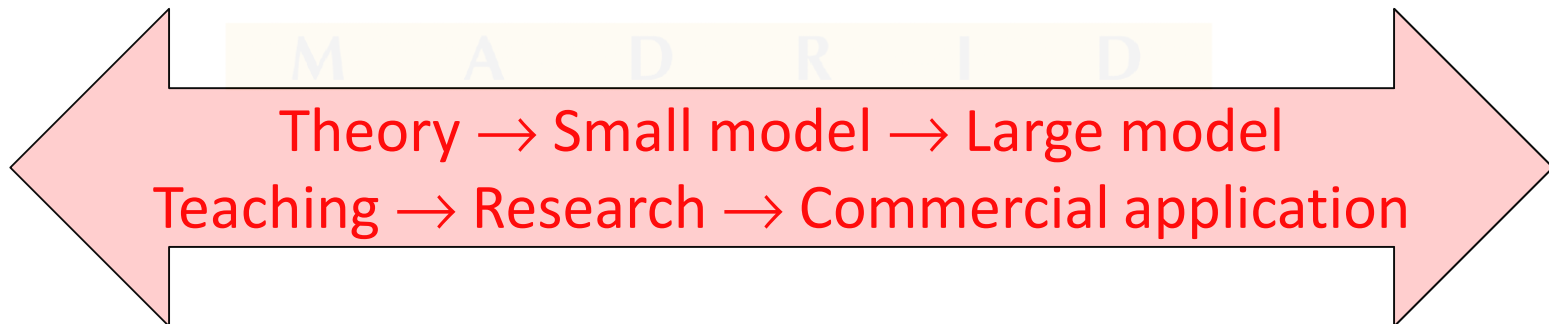
Algebraic modeling languages: characteristics

- 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*.

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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.

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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
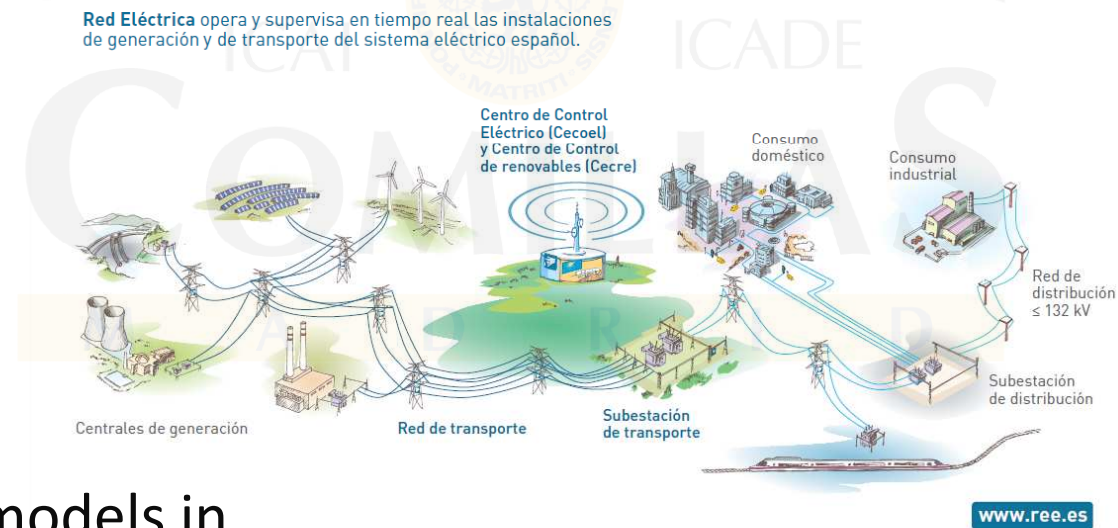
Mock-up models in

http://www.iit.upcomillas.es/aramos/Ramos_CV.htm#ModelosAyudaDecision

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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
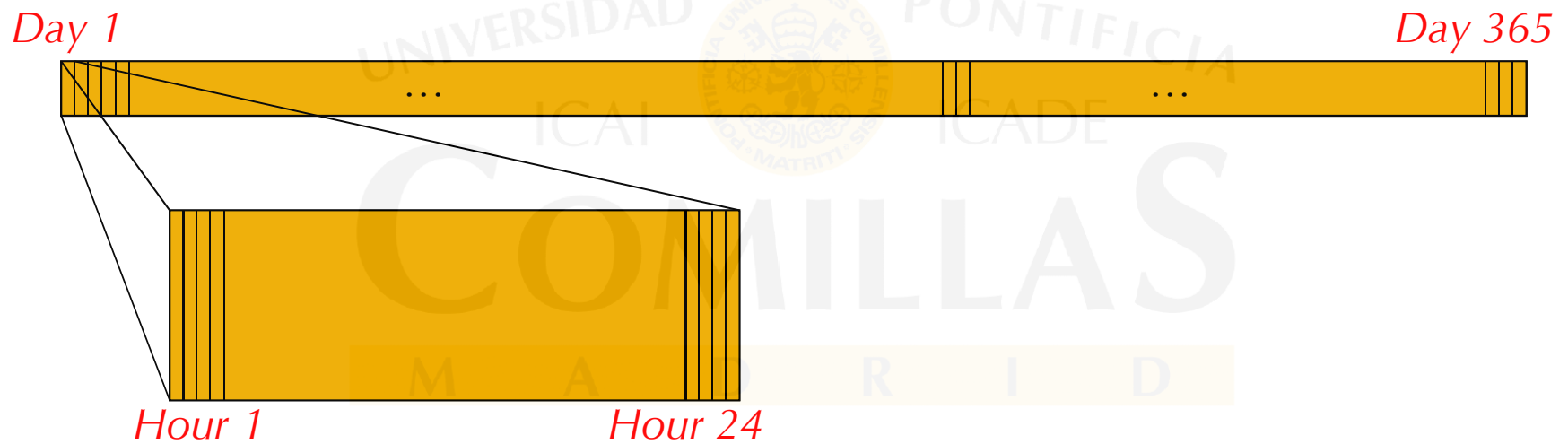
Time scope

Day 1 · · · · · · Day 365

Hour 1   Hour 24

Short-term daily unit commitment model (iii)
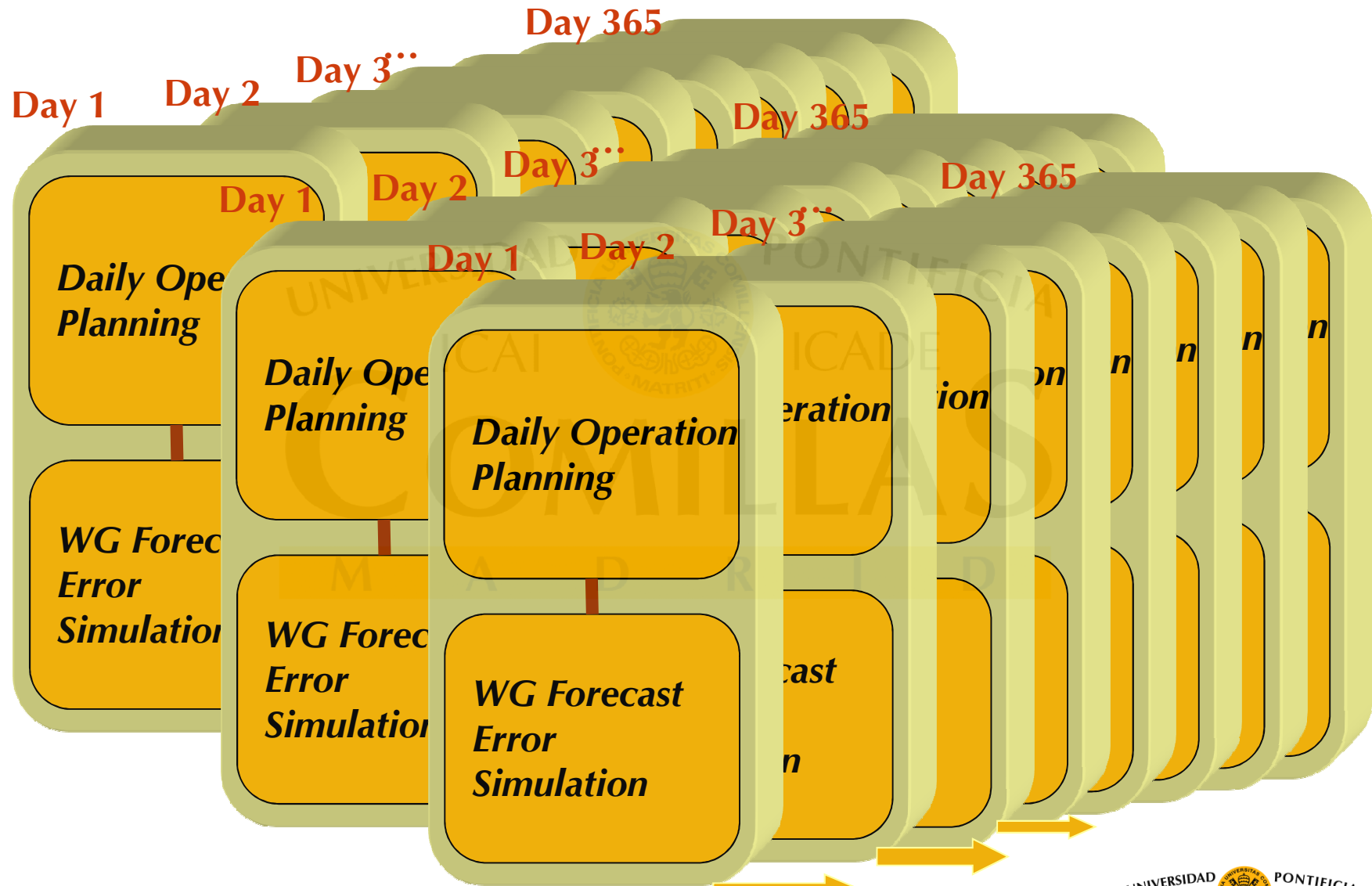
Hydrothermal scheduling model

- 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*

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Scenario recombining tree example

Inflow: 30 m³/s
Prob: 0.60

Inflow: 25 m³/s
Prob: 0.55

wet

dry

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

wet

Inflow: 30 m³/s
Prob: 0.35

dry

wet

Inflow: 15 m³/s
Prob: 0.40

Inflow: 20 m³/s
Prob: 0.45

dry

Inflow: 15 m³/s
Prob: 0.65

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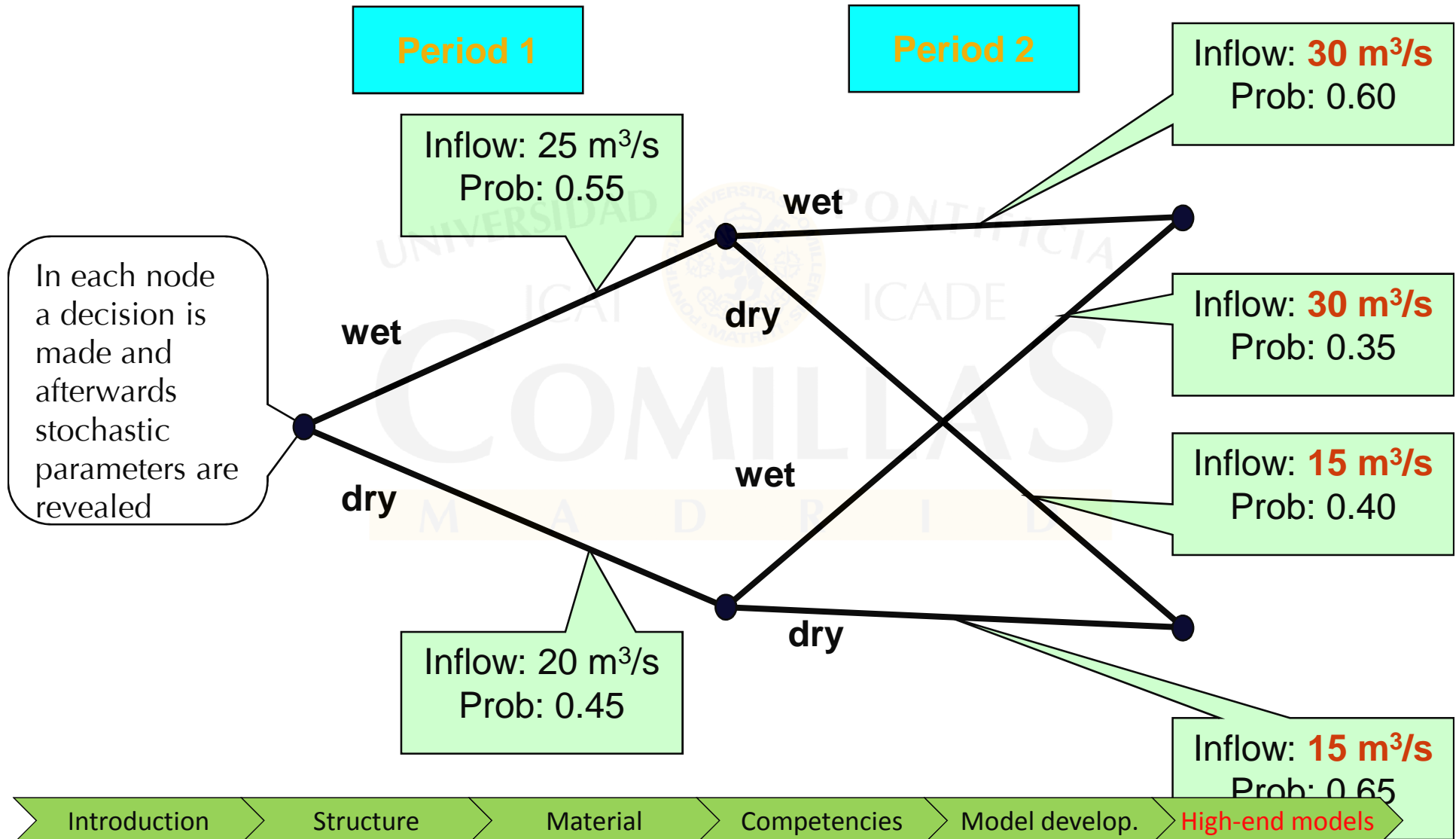
Multiple basins

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

Inflow

Storage hydro plant

Run of the river plant

Basin 1

Basin 2

Basin 3

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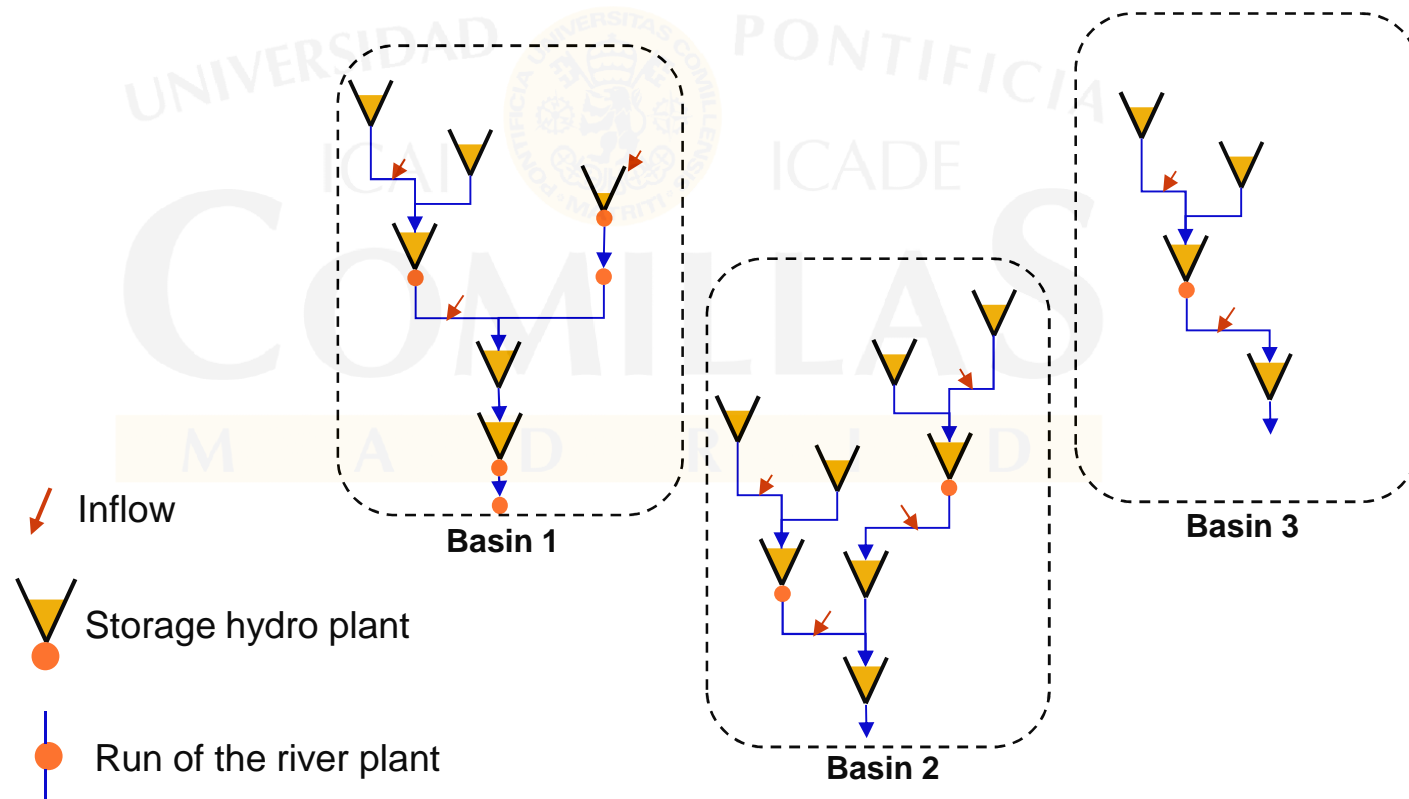
Solution of a stochastic model


```
        ┌─────────────────────────┐
        │  Stochastic parameters  │
        └─────────────────────────┘
                    │
                    ▼
        ┌─────────────────────────┐
        │ Scenario tree generation│──────────┐
        └─────────────────────────┘          │ NO
                    │                         │
                    ▼                         │
        ┌─────────────────────────┐          │
        │  Stochastic optimization│          │
        └─────────────────────────┘          │
                    │                         │
                    ▼                         │
        ┌─────────────────────────┐          │
        │     Stability of the    │          │
        │   stochastic solution?  │──────────┘
        └─────────────────────────┘
                    │
                   YES
```

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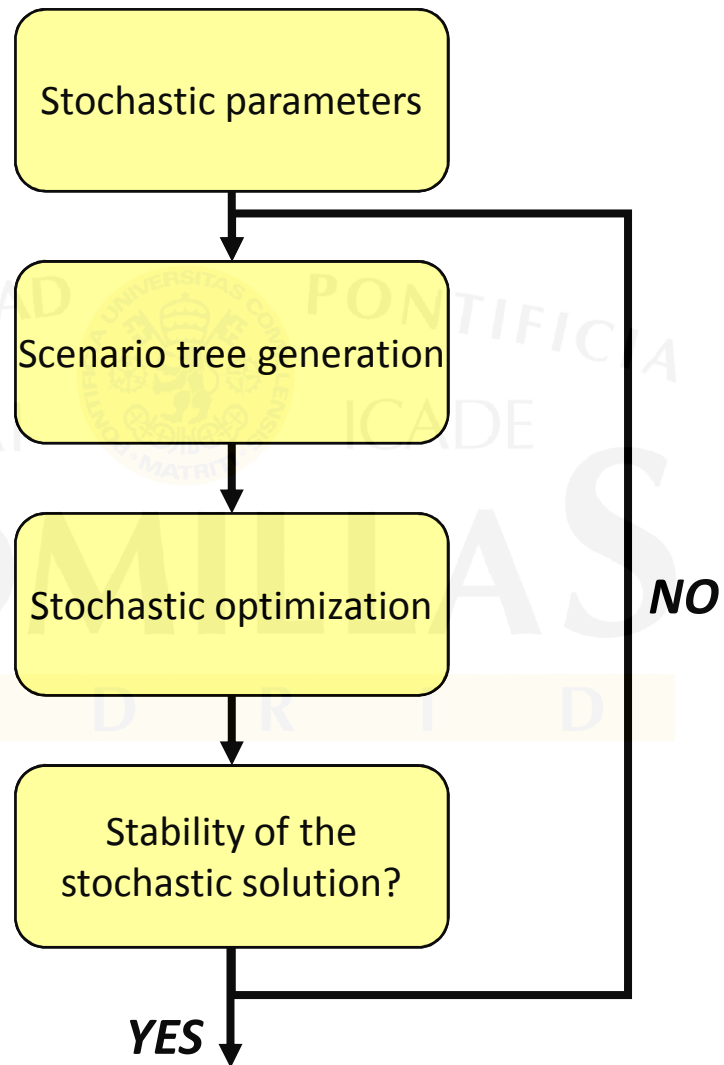
Market equilibrium model

- 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

Company 1's optimization problem

Company e's optimization problem

Company E's optimization problem

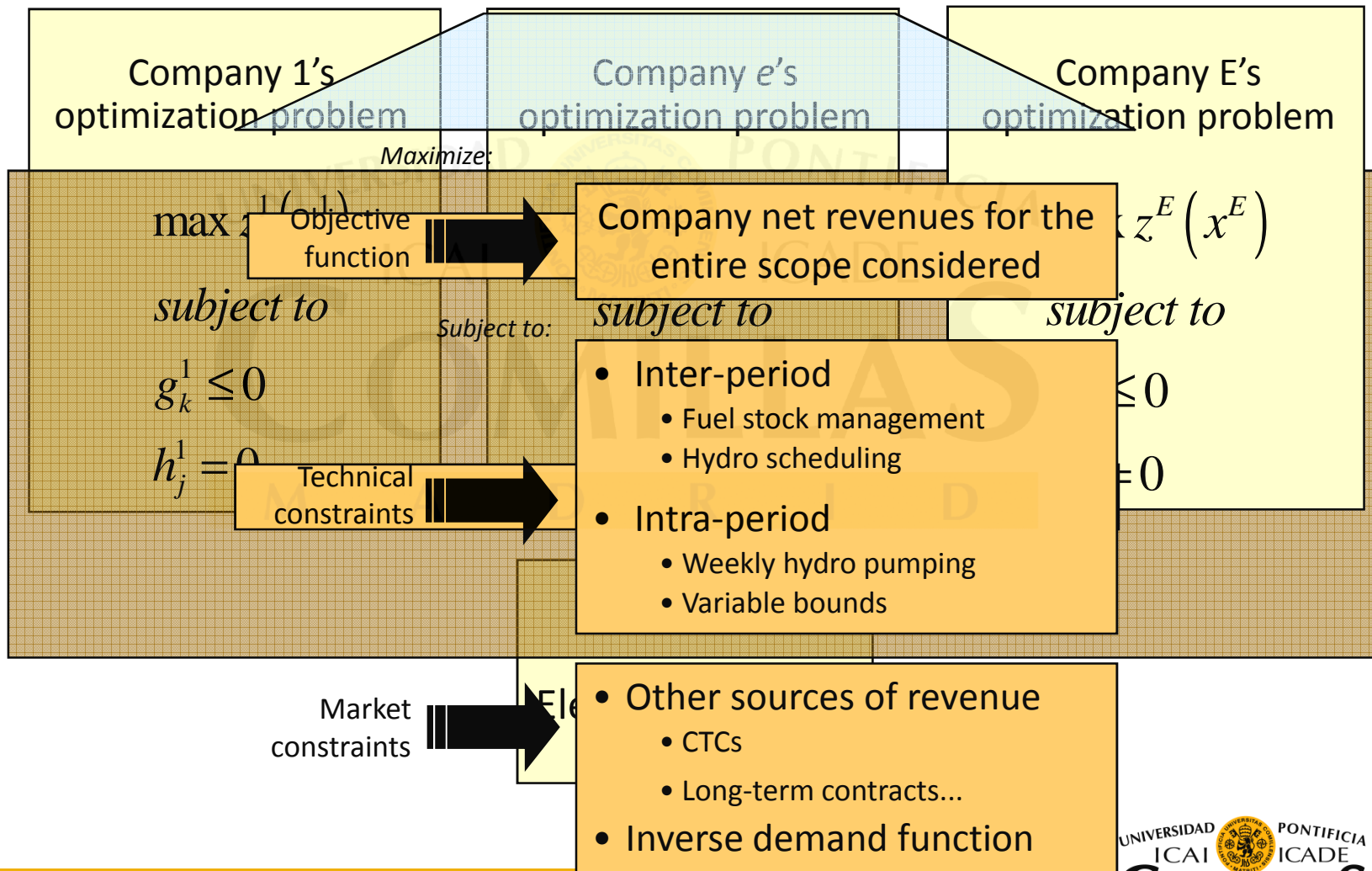*Maximize:*

$$\max z^1\left(x^1\right)$$

Objective function → Company net revenues for the entire scope considered

$$\max z^E\left(x^E\right)$$

subject to

subject to

subject to

Subject to:

$$g_k^1 \leq 0$$

$$h_j^1 = 0$$

$$\leq 0$$

$$= 0$$

Technical constraints →

- Inter-period
  - Fuel stock management
  - Hydro scheduling
- Intra-period
  - Weekly hydro pumping
  - Variable bounds

Market constraints → Ele

- Other sources of revenue
  - CTCs
  - Long-term contracts…
- Inverse demand function

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Stating the problem: Using the model

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

Company 1's optimization problem

$$\max z^1\left(x^1\right)$$

subject to

$$g_k^1 \leq 0$$

$$h_j^1 = 0$$

Company *e*'s optimization problem

$$\max z^e\left(x^e\right)$$

subject to

$$g_k^e \leq 0$$

$$h_j^e = 0$$

Company E's optimization problem

$$\max z^E\left(x^E\right)$$

subject to

$$g_k^E \leq 0$$

$$h_j^E = 0$$

Price−m(x)=0

Electric power market

MARKET RESULTS
- Market share
- Electricity prices
- Revenue and output per unit
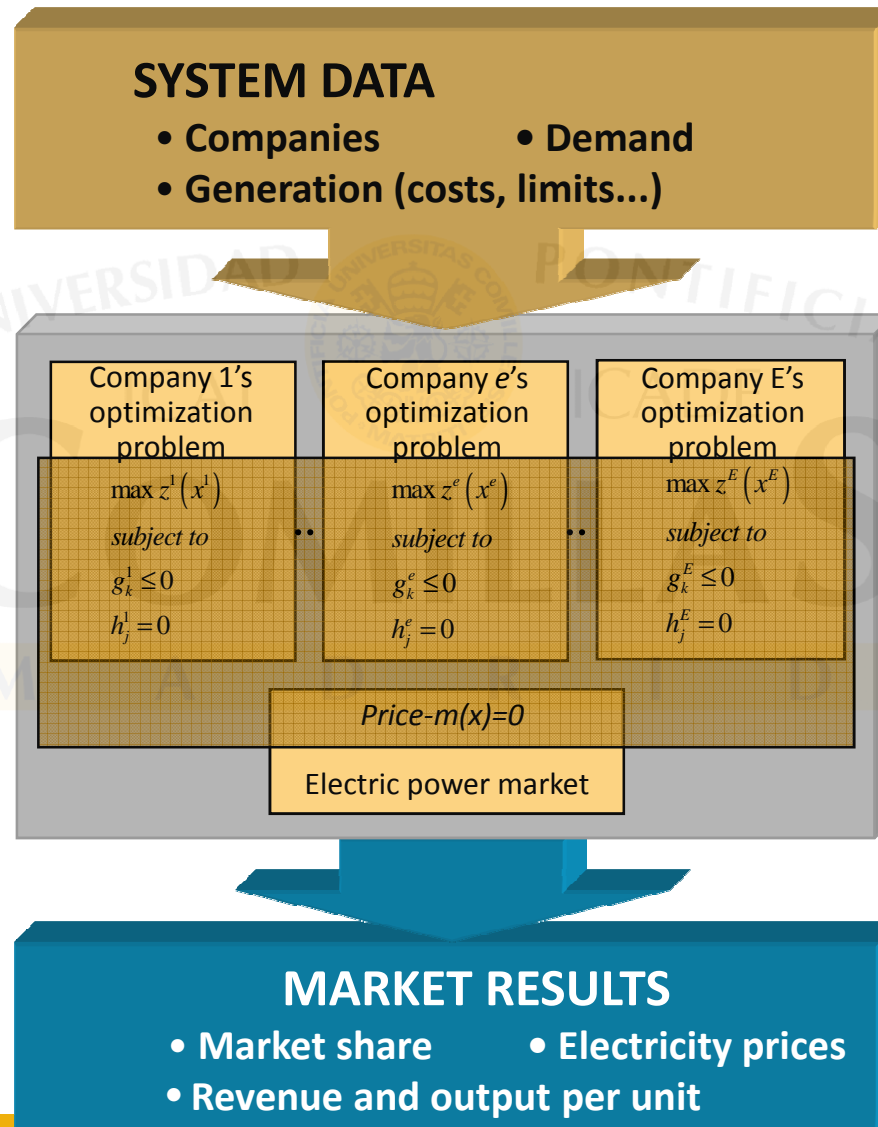
Mixed complementarity problem (MCP)

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

- Generalization of the complementarity problem

System of equations

$$x \text{ free}$$
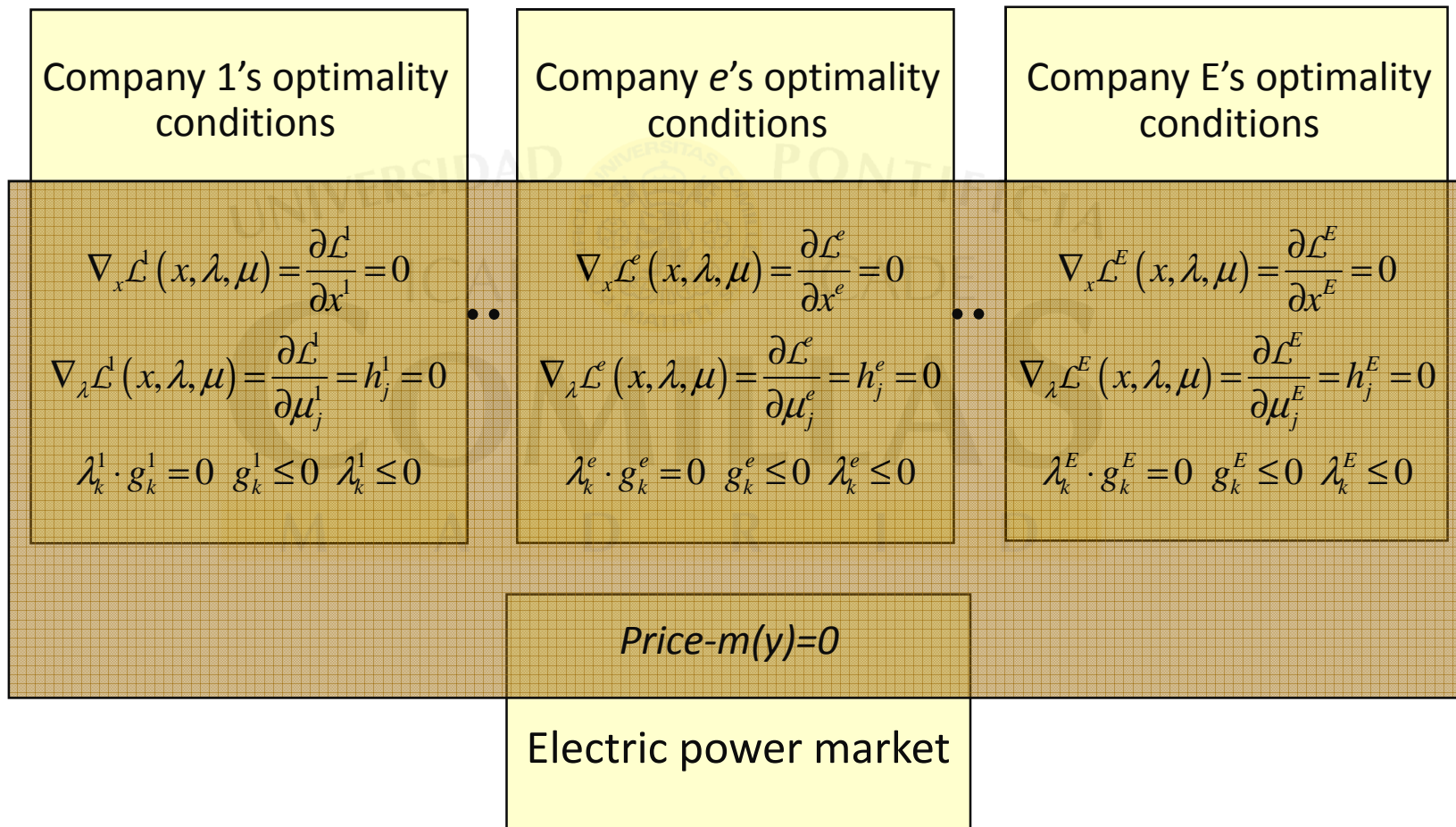$$\mu_j^e \text{ free}$$

$$\nabla_x \mathcal{L}^e(x, \lambda, \mu) = \frac{\partial \mathcal{L}^e}{\partial x^e} = 0$$

$$\nabla_\mu \mathcal{L}^e(x, \lambda, \mu) = \frac{\partial \mathcal{L}^e}{\partial \mu_j^e} = h_j^e = 0$$

Complementarity problem

$$\lambda_k^e \cdot g_k^e = 0 \quad g_k^e \leq 0 \quad \lambda_k^e \leq 0$$

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Equivalent mixed complementarity problem for all the companies

Company 1's optimality conditions

$$\nabla_x \mathcal{L}^1 (x, \lambda, \mu) = \frac{\partial \mathcal{L}^1}{\partial x^1} = 0$$

$$\nabla_\lambda \mathcal{L}^1 (x, \lambda, \mu) = \frac{\partial \mathcal{L}^1}{\partial \mu_j^1} = h_j^1 = 0$$

$$\lambda_k^1 \cdot g_k^1 = 0 \quad g_k^1 \le 0 \quad \lambda_k^1 \le 0$$

Company e's optimality conditions

$$\nabla_x \mathcal{L}^e (x, \lambda, \mu) = \frac{\partial \mathcal{L}^e}{\partial x^e} = 0$$

$$\nabla_\lambda \mathcal{L}^e (x, \lambda, \mu) = \frac{\partial \mathcal{L}^e}{\partial \mu_j^e} = h_j^e = 0$$

$$\lambda_k^e \cdot g_k^e = 0 \quad g_k^e \le 0 \quad \lambda_k^e \le 0$$

Company E's optimality conditions

$$\nabla_x \mathcal{L}^E (x, \lambda, \mu) = \frac{\partial \mathcal{L}^E}{\partial x^E} = 0$$

$$\nabla_\lambda \mathcal{L}^E (x, \lambda, \mu) = \frac{\partial \mathcal{L}^E}{\partial \mu_j^E} = h_j^E = 0$$

$$\lambda_k^E \cdot g_k^E = 0 \quad g_k^E \le 0 \quad \lambda_k^E \le 0$$

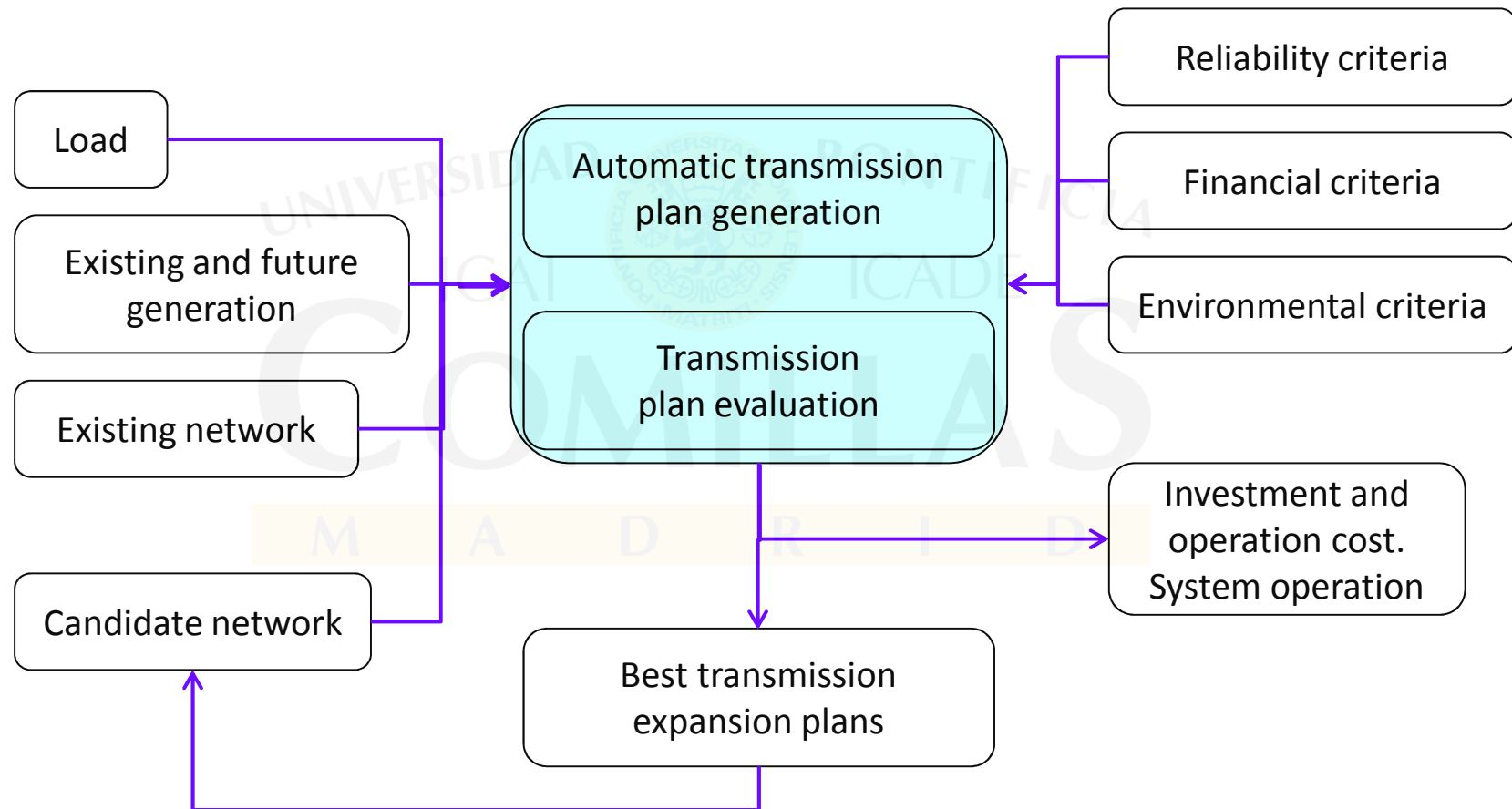*Price-m(y)=0*

Electric power market

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.

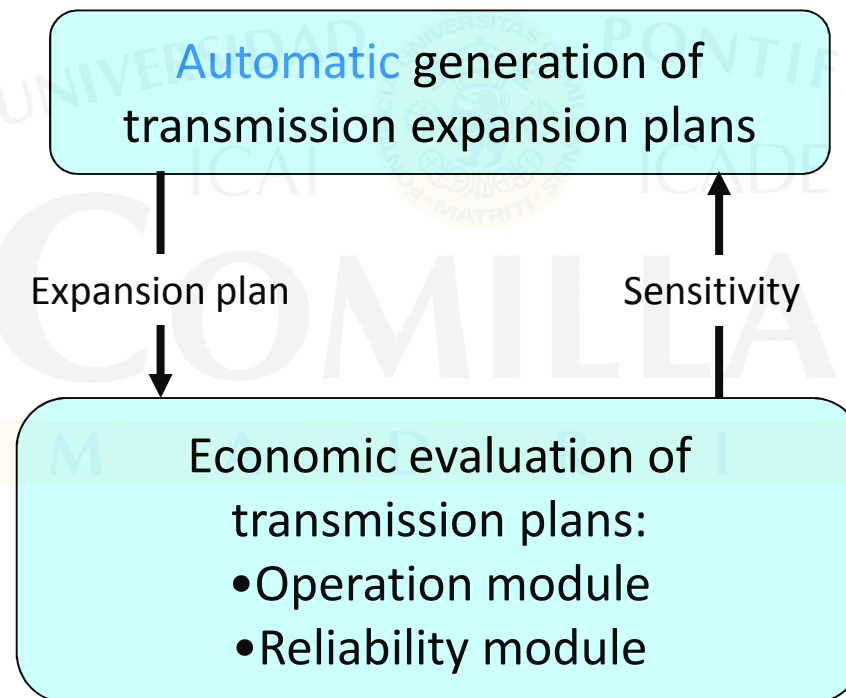- Stated as a *MIP* solved by *Benders' decomposition*

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Transmission expansion planning model

Load → Existing and future generation → Existing network → Candidate network

Automatic transmission plan generation

Transmission plan evaluation

Reliability criteria

Financial criteria

Environmental criteria

Investment and operation cost. System operation

Best transmission expansion plans

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Transmission expansion planning model

- Dynamic tactical transmission planning

Automatic generation of transmission expansion plans

Expansion plan

Sensitivity

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

The famous Spanish strategy for playing football

and the winner is …

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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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