UNIVERSIDAD PONTIFICIA
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COMILLAS
MADRID
ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA

TWO STAGE STOCHASTIC MODELS FOR CONTRACTING DECISIONS OF AN INDUSTRIAL CONSUMER

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CONTENT

- Motivation and objective
- Deterministic approach
- Probabilistic approach
- Numerical application
- Conclusions
- Future developments

MOTIVATION and OBJECTIVE

❑ Motivation:

- ✓ Industrial consumers may negotiate with retailers price and format of the contracts they sign for supplying their energy needs
- ✓ Need for new mathematical tools for industrial consumers in liberalized markets

❑ Objective:

- ✓ Development of a decision support model for contracting and operation decisions in the medium term with the following features:

  - Integrated tool: contract and operation optimization and price generation modules
  - Single to parameterize models
  - Data easily available

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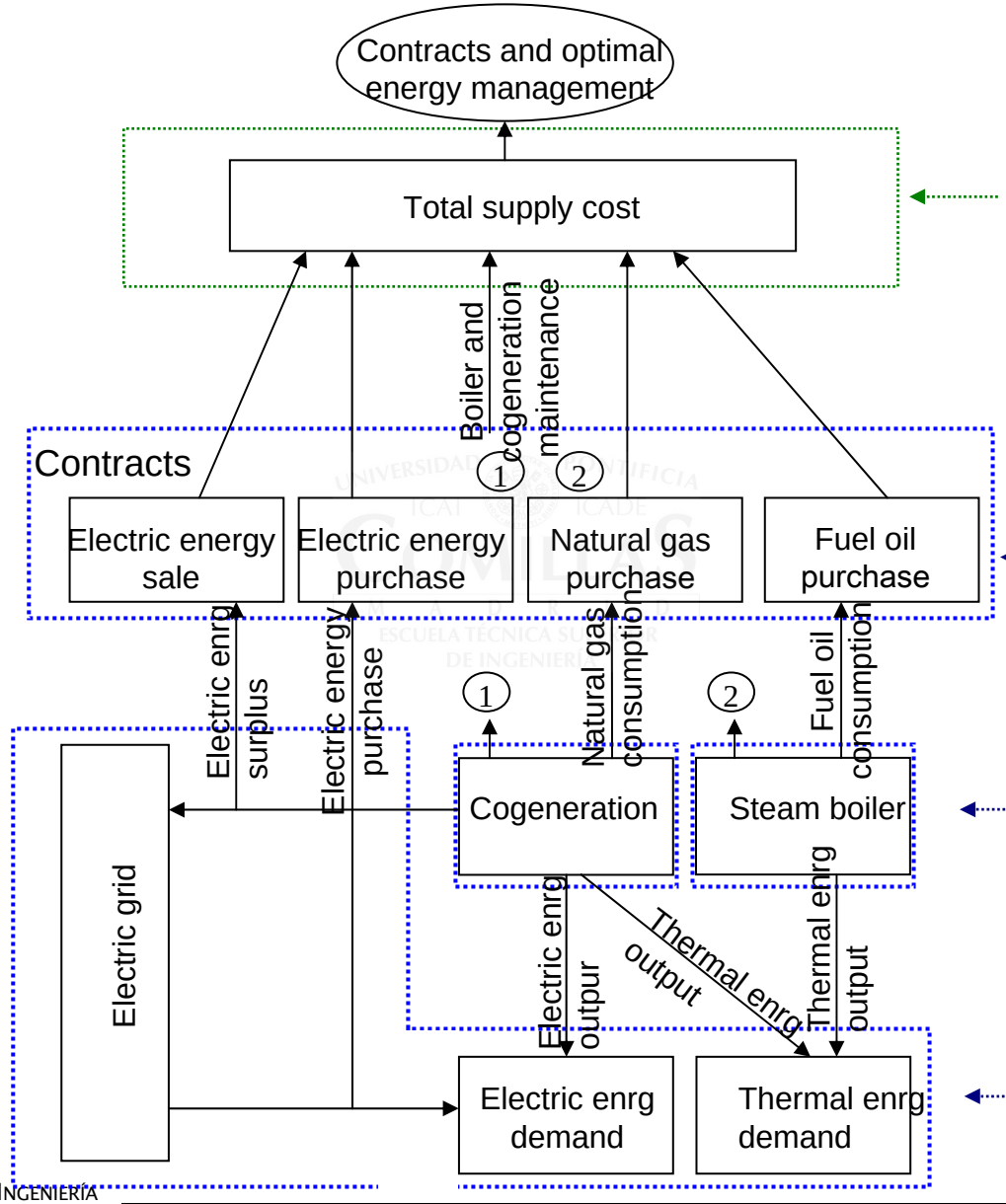
DETERMINISTIC APPROACH
General features

- **Medium term energy management**
  - ✓ Minimization of the supply cost
- **Yearly scope**
- **Industrial consumer with thermal and electric demand**
  - ✓ Cogeneration
  - ✓ Steam boiler
- **Decisions**
  - ✓ Contracts for energy supply
  - ✓ Boiler and cogeneration operation

DETERMINISTIC APPROACH
General features



Objective function

Constraints:

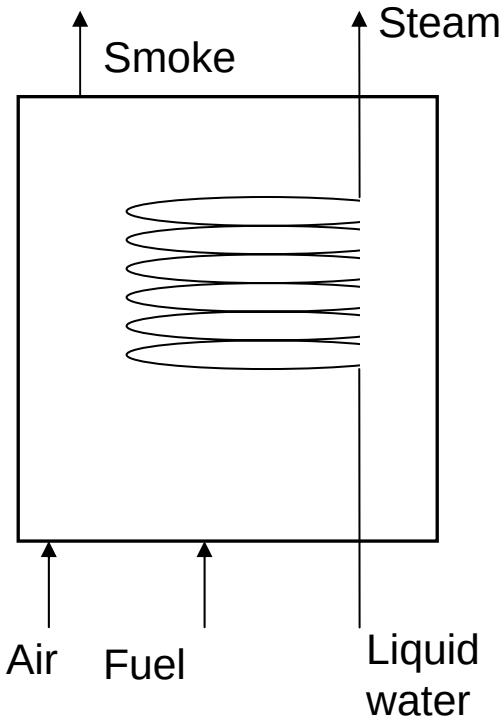
Contracts

Boiler and cogeneration operation

Energy balance

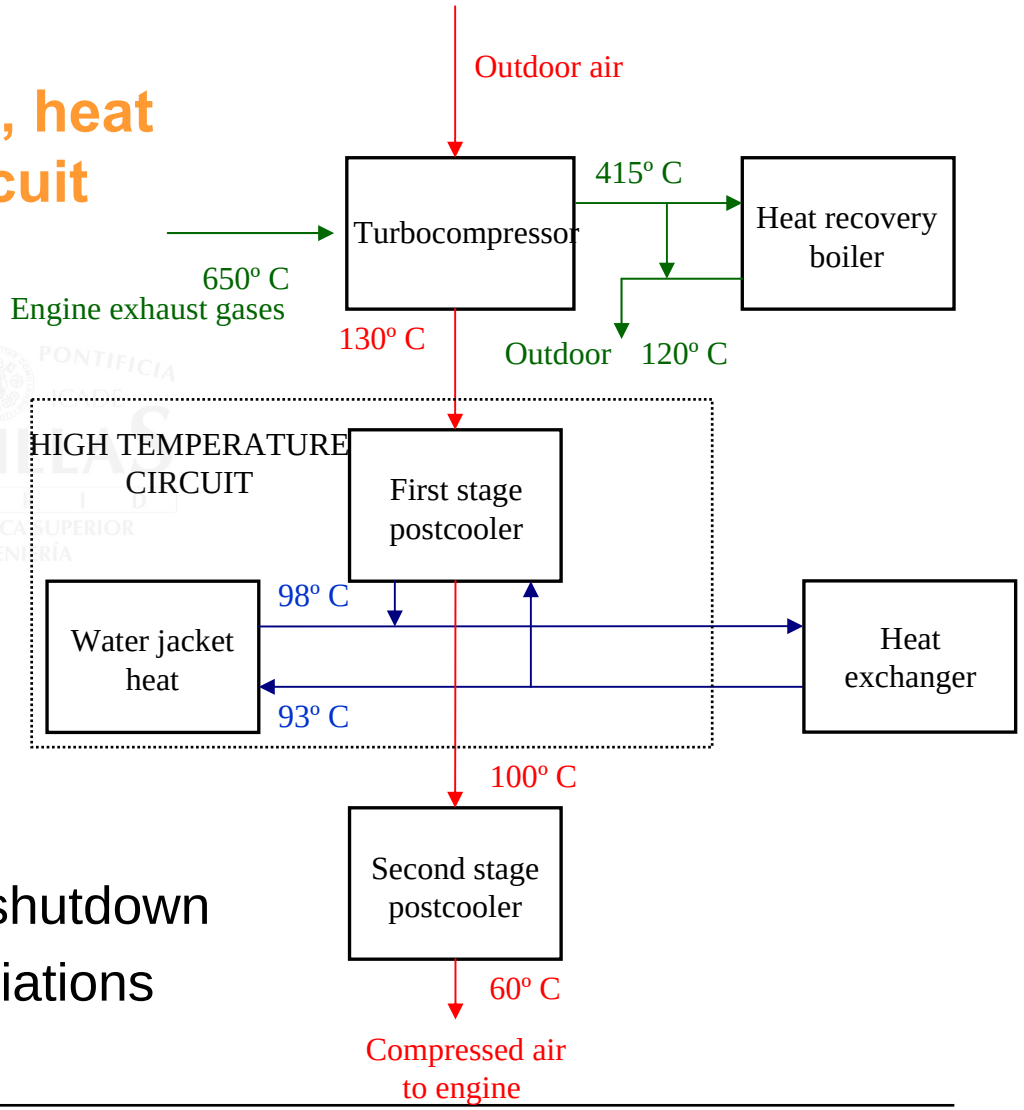
DETERMINISTIC APPROACH
Steam boiler

- Boiler fed by fuel oil
- Linear relation between fuel oil consumption and steam produced
- Operation limits
- Costs:
  - ✓ Fuel oil consumption
  - ✓ Operation cost per kg of fuel oil consumed
  - ✓ Yearly maintenance
- Simplifications:
  - ✓ Cost and time for startup and shutdown
  - ✓ Input and output enthalpies



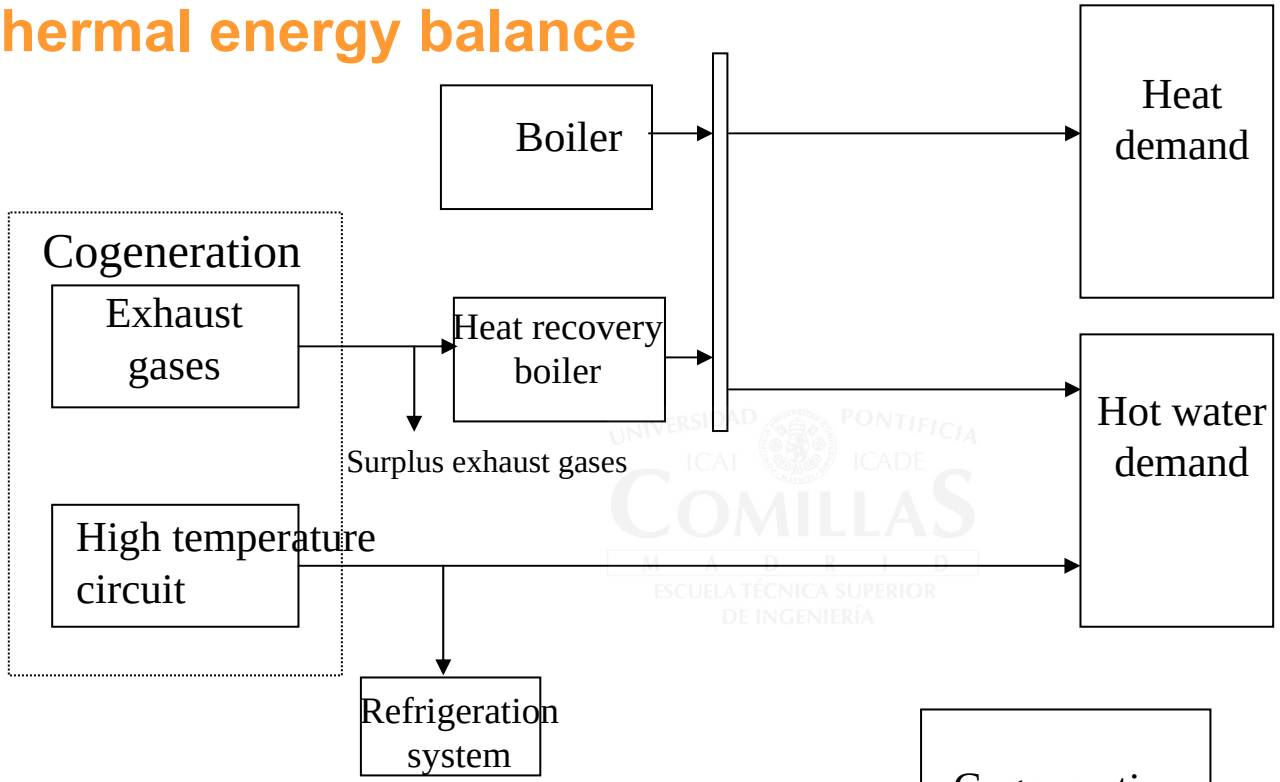
DETERMINISTIC APPROACH
Cogeneration

- Engine fed by natural gas
- Linear relation between gas consumption and: electricity, heat from exhaust gases, H.T. circuit
- Operation limits
- Special regime
- Costs:
  - ✓ Natural gas consumption
  - ✓ Operation cost per kWh of electricity generated
  - ✓ Yearly maintenance
- Simplifications:
  - ✓ Cost and time for startup and shutdown
  - ✓ Temperature and pressure variations

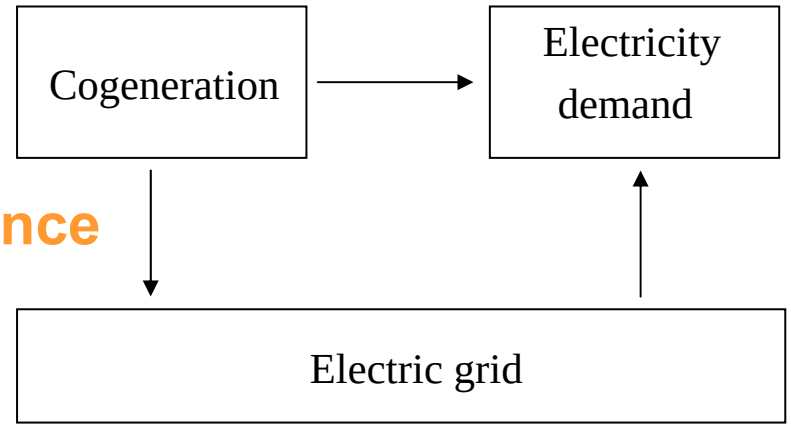


DETERMINISTIC APPROACH
Energy balance

Thermal energy balance

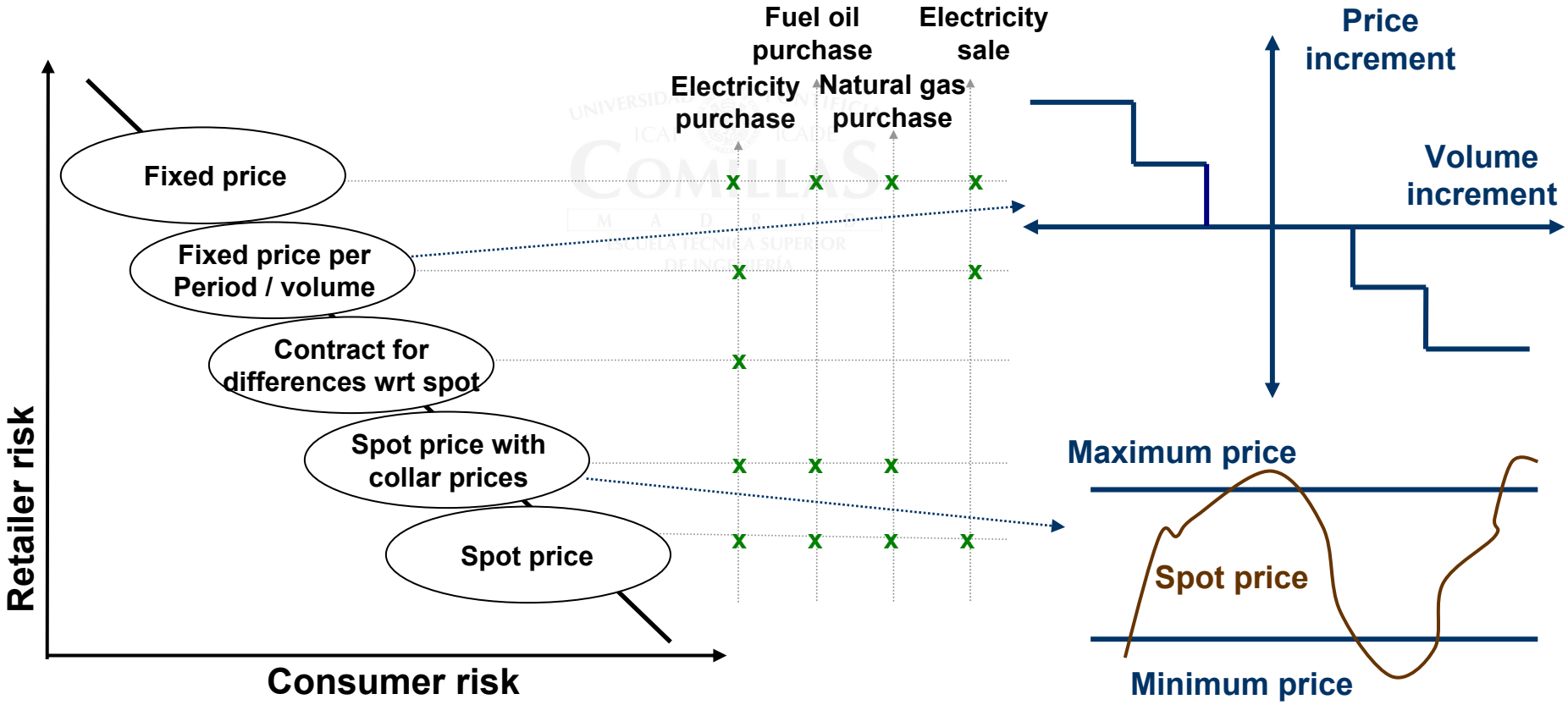


Electric energy balance



DETERMINISTIC APPROACH
Contracts

- Main decisions of the model
- Only one yearly contract is chosen per type
- Contract with different risk aversion are modeled



DETERMINISTIC APPROACH
State of the art

- **Industrial consumers with their own energy supply**

	Operation	Operation + Contract
Short term	McGregor,Lee,Botzauer	
Medium term	Ito	**Gómez-Villalva and Ramos**
Long term	Baugman	

- **Generation**

	Operation + Contract
Conventional generation	Fleten, Urgen, Bjorgan
Cogeneration	Illerhaus, Paravan

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STOCHASTIC APPROACH
General features

❑ Deterministic approach

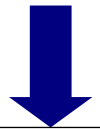
- ✓ Limited in uncertainty modeling

❑ Stochastic optimization

- ✓ Allows to take decisions explicitly considering the parameter uncertainty

❑ Risk sources for industrial consumers

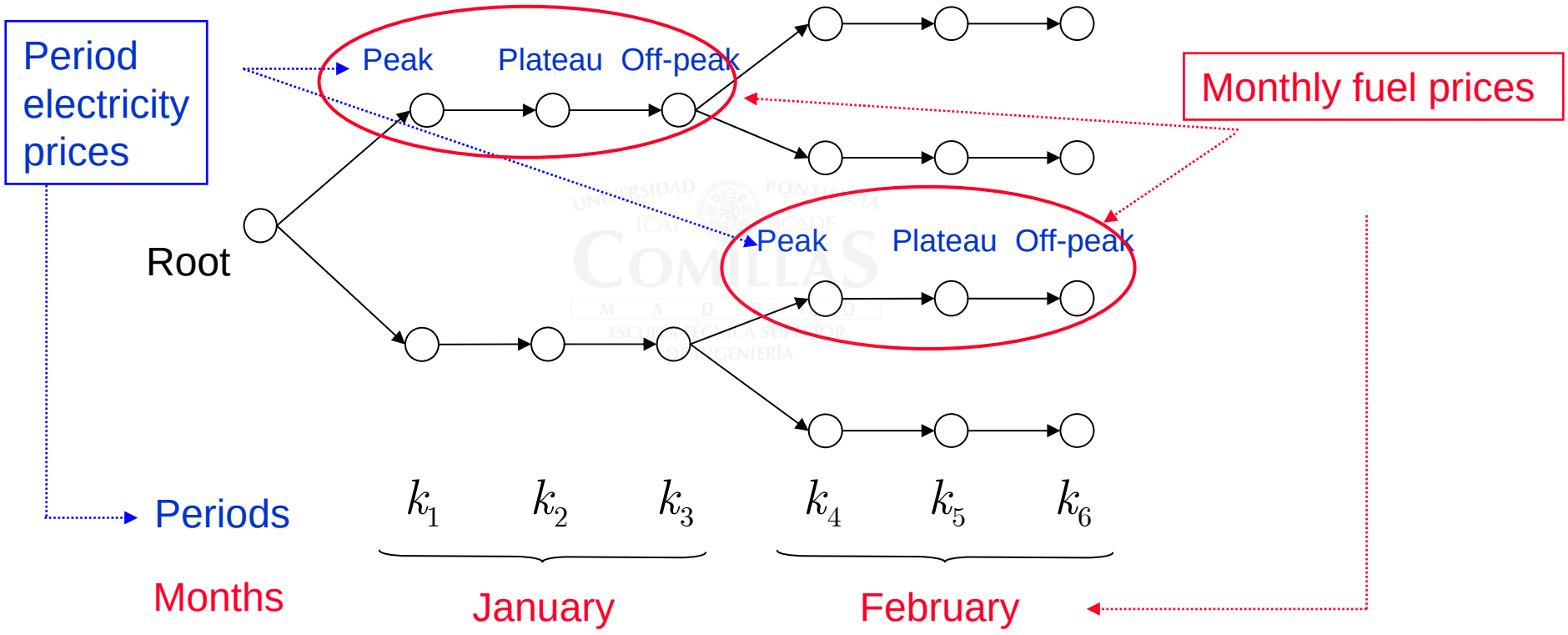
- ✓ **Price risk**
- ✓ Quantity risk: system failure or demand fluctuations
- ✓ Other risks: credit and regulatory



Stochastic parameter: sale and purchase prices of electricity, natural gas and fuel oil

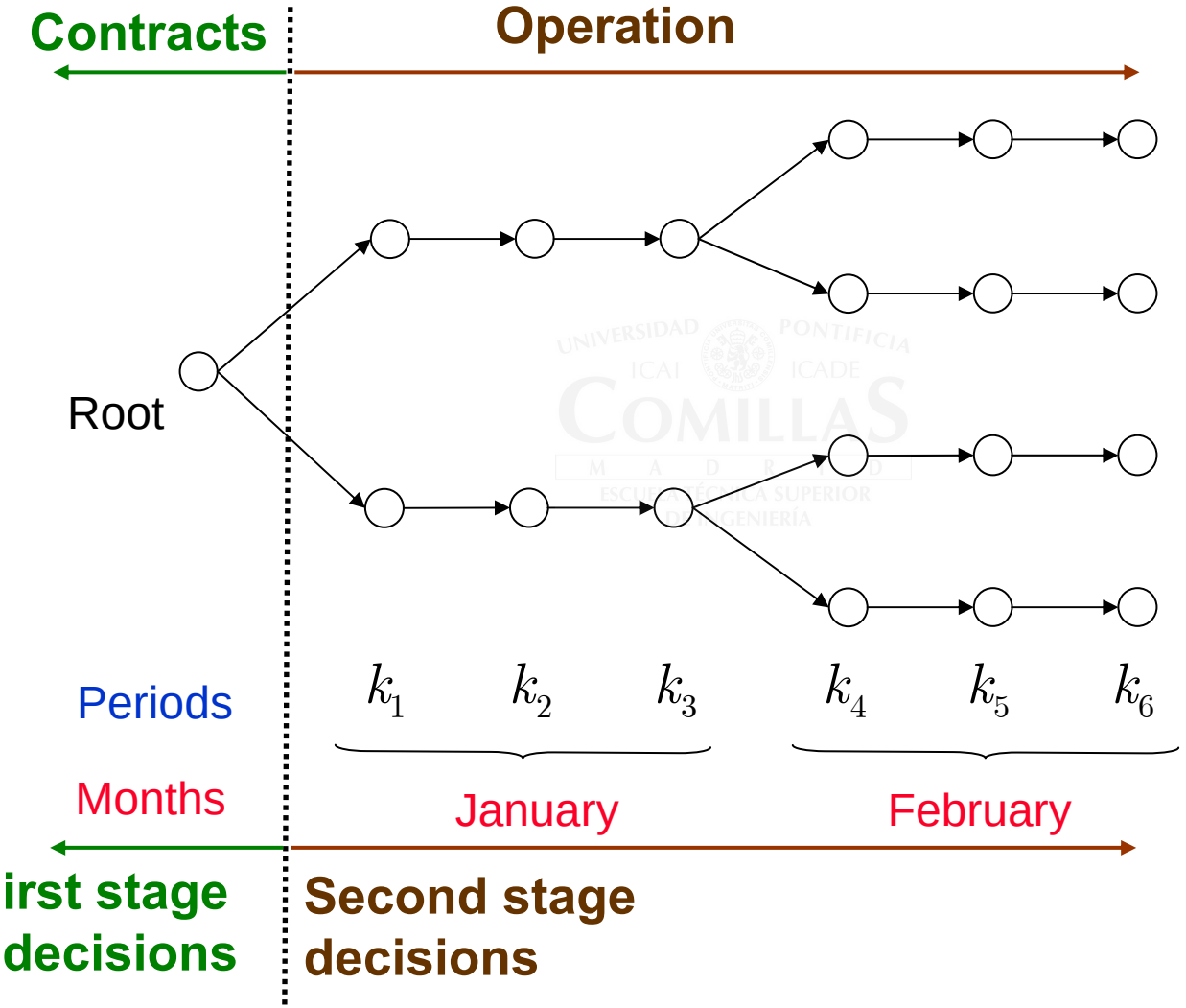
STOCHASTIC APPROACH
Uncertainty modeling

- **Discrete representation of the uncertainty: scenario tree**



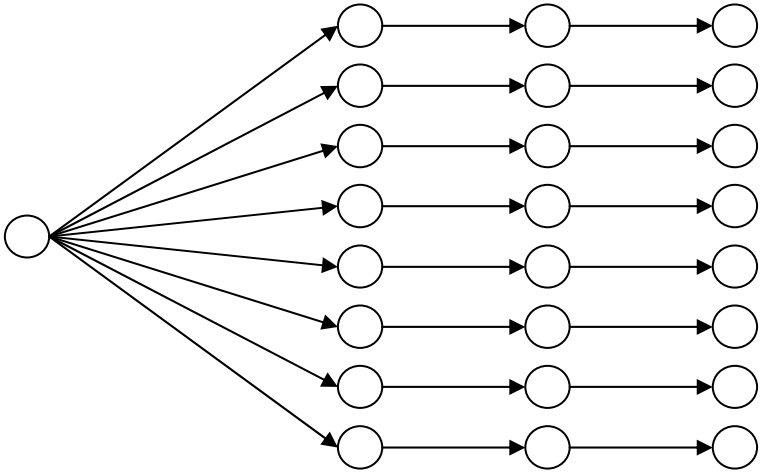
STOCHASTIC APPROACH
Uncertainty modeling

❑ Two-stage model



PRICE SCENARIO GENERATION

- **Scenarios for yearly prices of electricity, natural gas and fuel oil for industrial consumers**
  - ✓ Electricity prices for load levels
  - ✓ Monthly fuel prices
- **No significant correlation between the electricity and fuel prices in the Spanish energy market: independent forecasting algorithms**
- **Price series independent and equiprobable**



STOCHASTIC APPROACH
Risk neutral model

- **Total supply cost c_T^g for each scenario g :**
  - ✓ Contract cost for each scenario
  - ✓ Maintenance cost for each scenario
- **Constraints X : boiler and cogeneration operation, energy balance and contracts**
- **Risk neutral model**

$$\min \; E[c_T] = \sum_{g \in G} p^g c_T^g$$

$$c_T \in X$$

Expected total cost

Total cost of scenario *g*

Probability function of total cost

Probability of scenario *g*

STOCHASTIC APPROACH
Risk neutral model

- **Drawback**
  - **Does not perform any risk management**

- **Solution**
  - **Multiobjective stochastic programming**
    - Balance among risk and expected cost
    - Efficient frontier: set of optimal solutions

- **Risk definition for industrial consumers**
  - **POSSIBILITY OF HIGH COSTS**

STOCHASTIC APPROACH
Reference cost model

❑ Risk measure

Linear penalty for costs above a certain reference cost *R*

$$\min \sum_{g \in G} p^g c_T^{g^+}$$

$$c_T \in X$$

$$E[c_T] \leq S$$

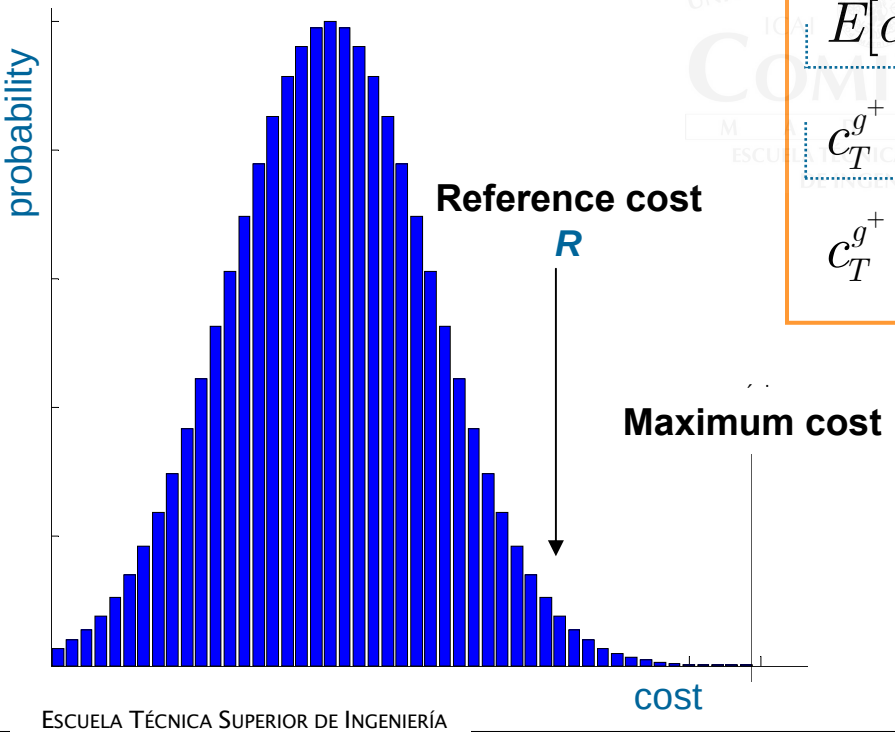
$$c_T^{g^+} \geq c_T^g - R \qquad \forall g \in G$$

$$c_T^{g^+} \geq 0 \qquad \forall g \in G$$

Risk measure

Expected cost limited by the risk aversion parameter *S*

Determine positive deviations wrt the reference *R*



STOCHASTIC APPROACH
Safety-first model

❑ Risk measure

Maximum cost of the distribution

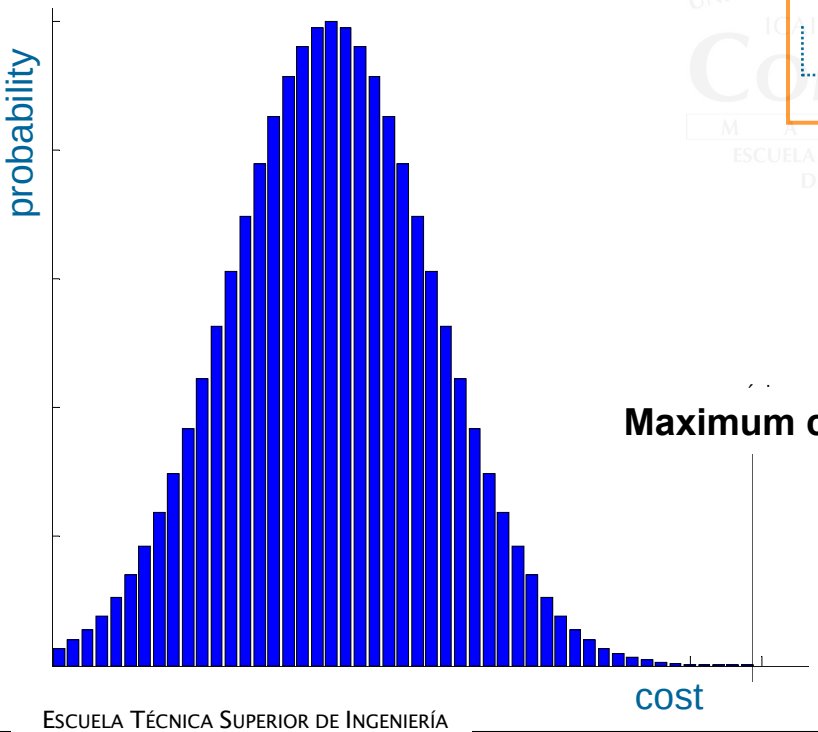
$$\min \quad E[c_T]$$

$$c_T \in X$$

$$c_T^g \leq S \qquad \forall g \in G$$

Expected total cost

Cost of any scenario *g* limited to a safety level *S* (risk aversion parameter)



STOCHASTIC APPROACH
Value at Risk (VaR) model

❑ Risk measure

Maximum cost for a certain confidence level α

$$\min \quad VaR_\alpha$$

$$c_T \in X$$

$$E[c_T] \le S$$

$$\sum_{g \in G} p^g \delta^g \le 1-\alpha \quad \forall g \in G$$

$$c_T^g \le VaR_\alpha + M\delta^g \quad \forall g \in G$$

Risk measure

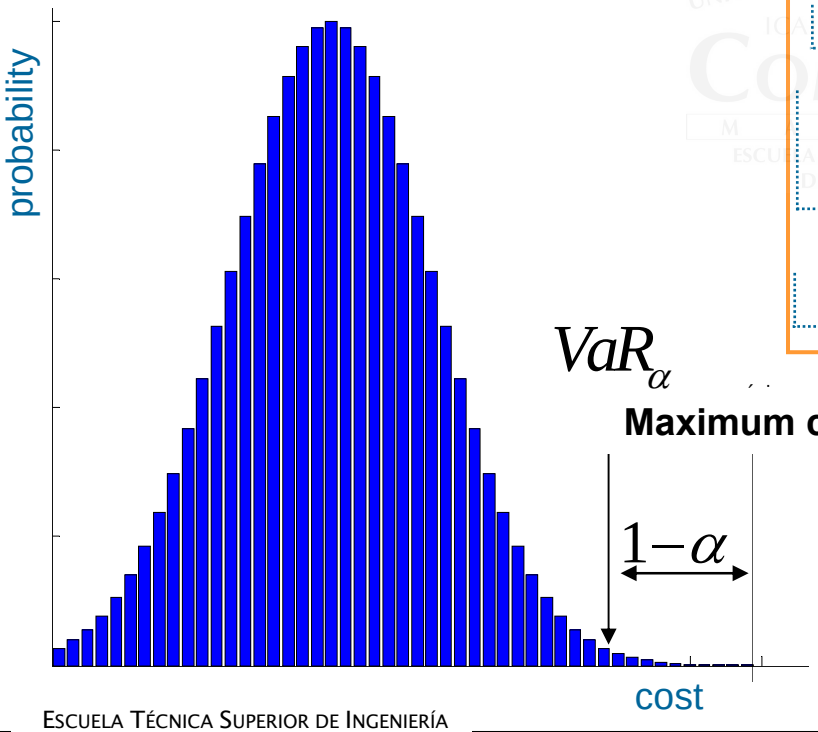
Expected cost limited by the risk aversion parameter *S*

Bounds the # of vars delta to the # of scenarios with value above VaR

Sets the VaR scenario

Auxiliary binary variable for each scenario *g*

Upper bound for any scenario



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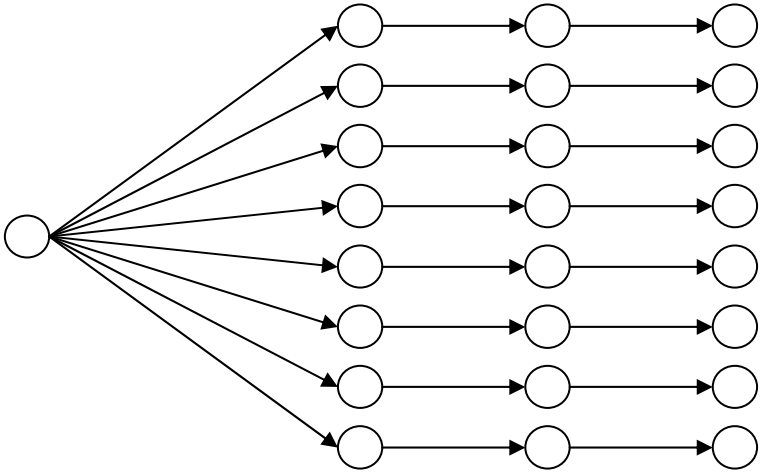


GENERATION OF NATURAL GAS AND FUEL OIL PRICES
Price formation

- **Natural gas prices**
  - ✓ Tipos de contratos: tarifas o libre mercado
  - ✓ Contratos a tarifa son una referencia para contratos en el libre mercado
  - ✓ Precios indexados a varios crudos y fuelóleos
- **Precios de fueloil**
  - ✓ Mercados de fueloil líquidos
  - ✓ Contratos a libre mercado
- **Coeficientes de correlación elevados (>0.95) con los precios spot de Brent**
  - ✓ Fueloil con precio medio spot de Brent del mes anterior
  - ✓ Gas natural con precio medio spot de Brent de 6 meses anteriores
- **Precios de combustibles determinados a través de los precios spot de Brent**

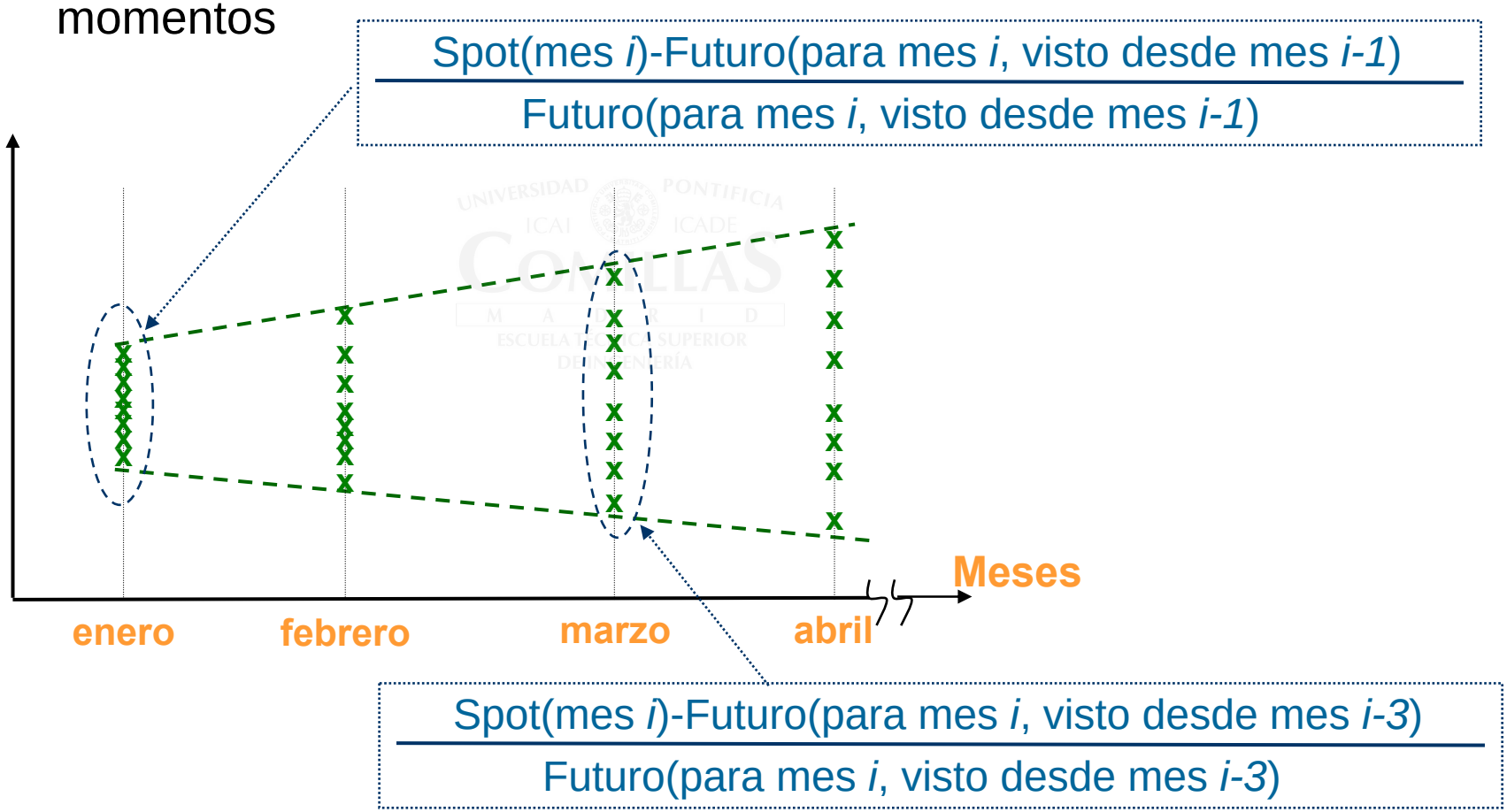
GENERACIÓN DE PRECIOS DE GAS Y FUELOIL

Precios spot de Brent. Metodología

- **Precios spot de Brent no estacionarios**
- **Nueva metodología basada en:**
  - ✓ Emplear precios de futuros de Brent para la predicción
  - ✓ **Hipótesis:** la diferencia relativa entre precios spot y futuros en años pasados se mantiene en el año de planificación
- **Ventajas método:**
  - ✓ Captura información de los precios spot contenida en los futuros
  - ✓ No se requiere aplicar tasa de descuento
  - ✓ No se requieren hipótesis de media y varianza
  - ✓ Correlación entre gas natural y fueloil generada automáticamente

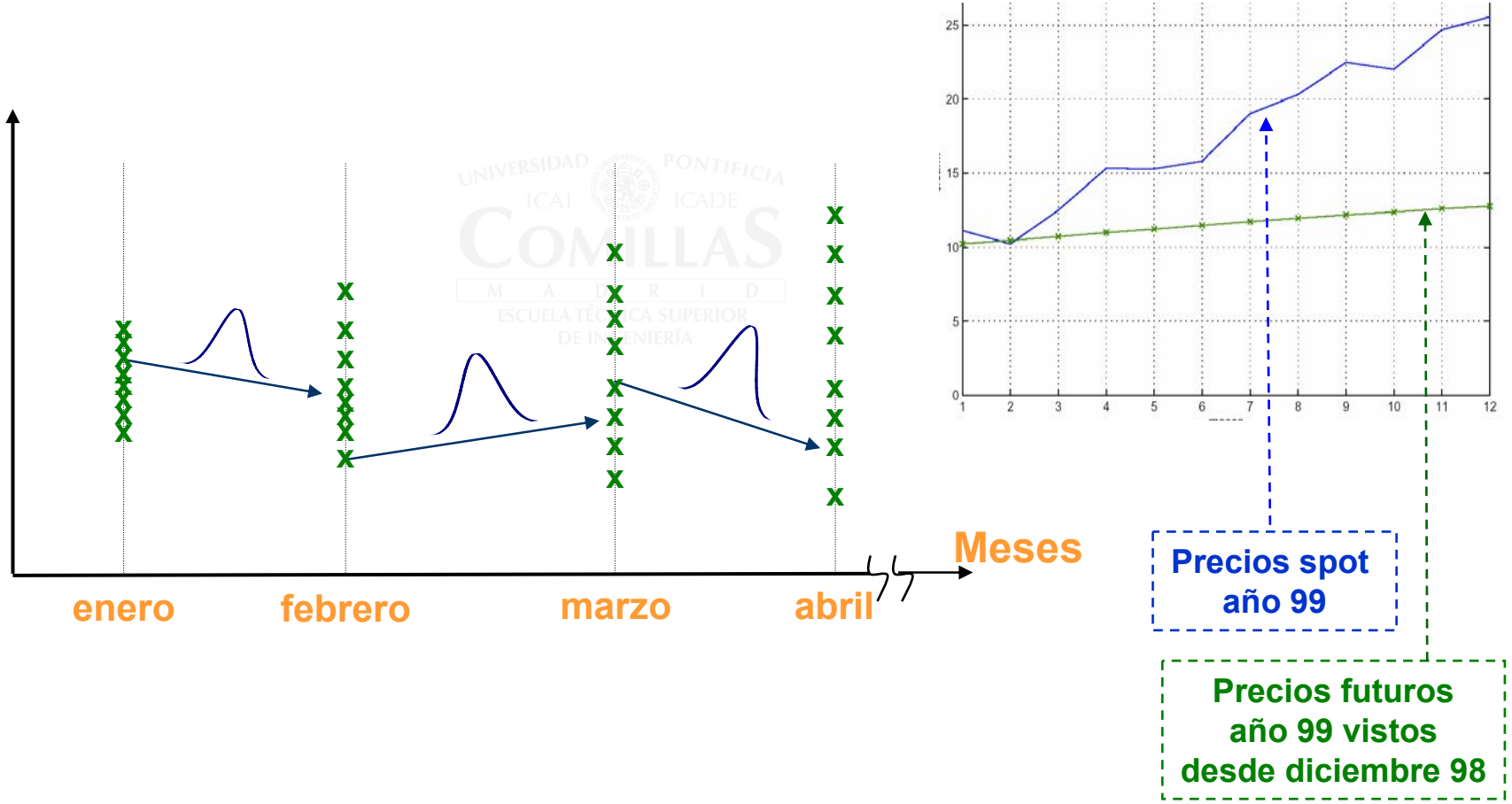
GENERACIÓN DE PRECIOS DE GAS Y FUELOIL
Algoritmo

- **Formación de las distribuciones de diferencias relativas entre precios spot y futuros**
  - ✓ Muestras generadas validadas mediante la comparación de momentos



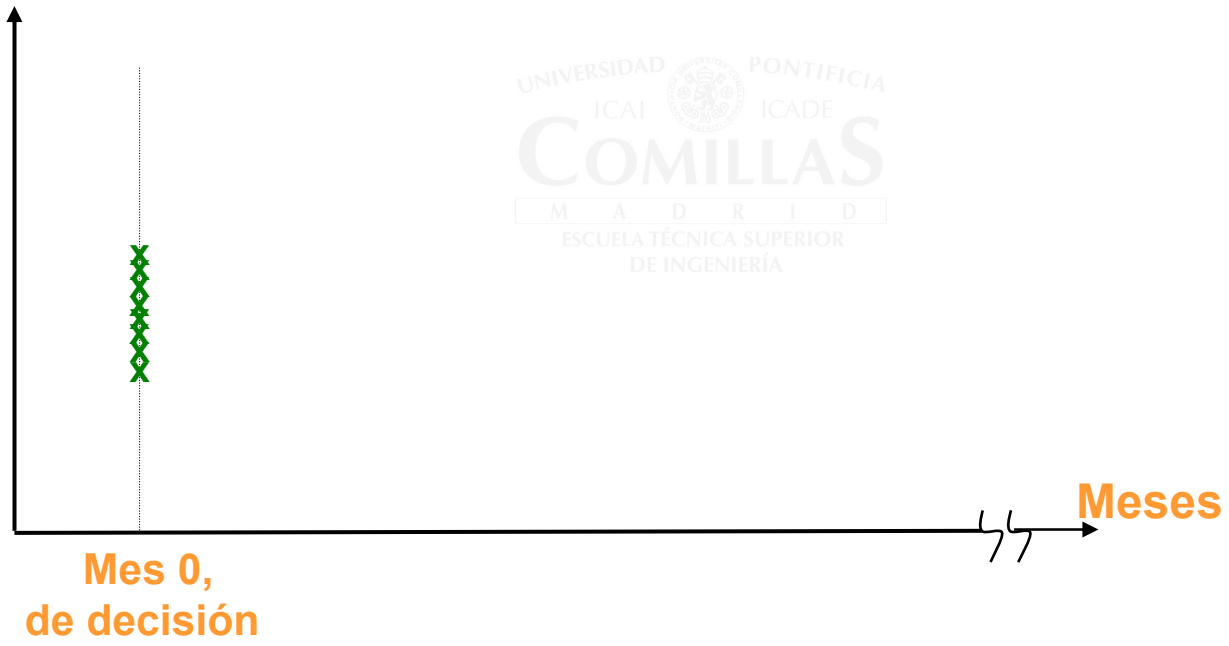
GENERACIÓN DE PRECIOS DE GAS Y FUELOIL
Algoritmo

- **Regresiones lineales entre muestras de periodos consecutivos**
  - ✓ Muestreos de las distribuciones empíricas de residuos



GENERACIÓN DE PRECIOS DE GAS Y FUELOIL
Algoritmo

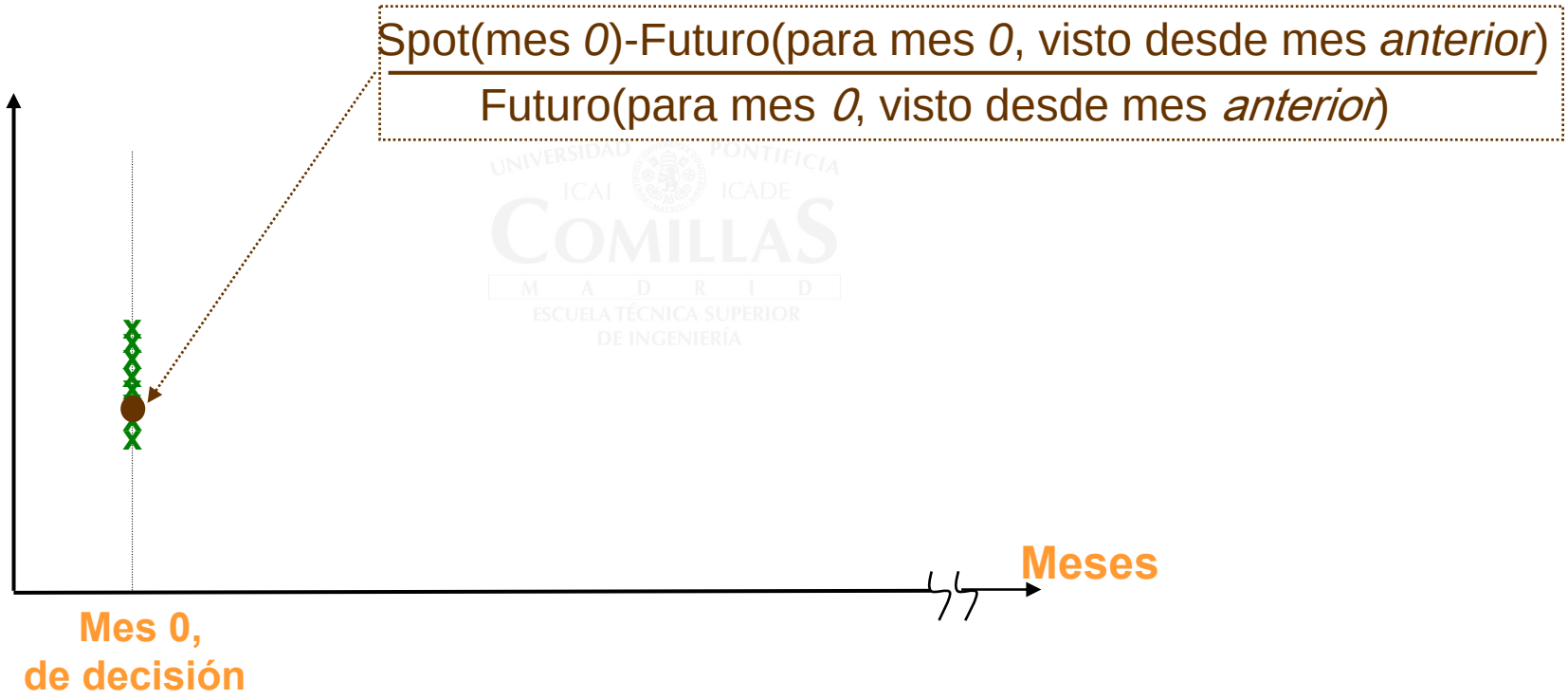
- **Determinación de muestras del primer periodo**
  - ✓ Generación de muestras de diferencias spot-futuros a 1 mes



GENERACIÓN DE PRECIOS DE GAS Y FUELOIL
Algoritmo

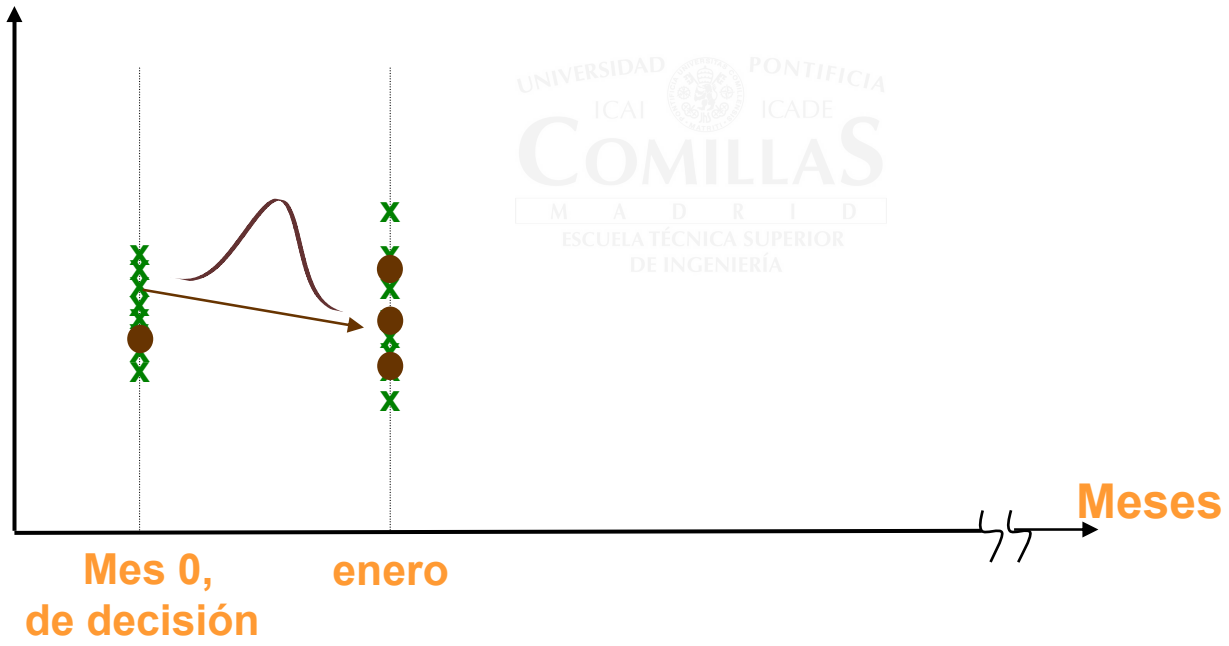
❑ Determinación de muestras del primer periodo

✓ Inclusión precio spot Brent



GENERACIÓN DE PRECIOS DE GAS Y FUELOIL
Algoritmo

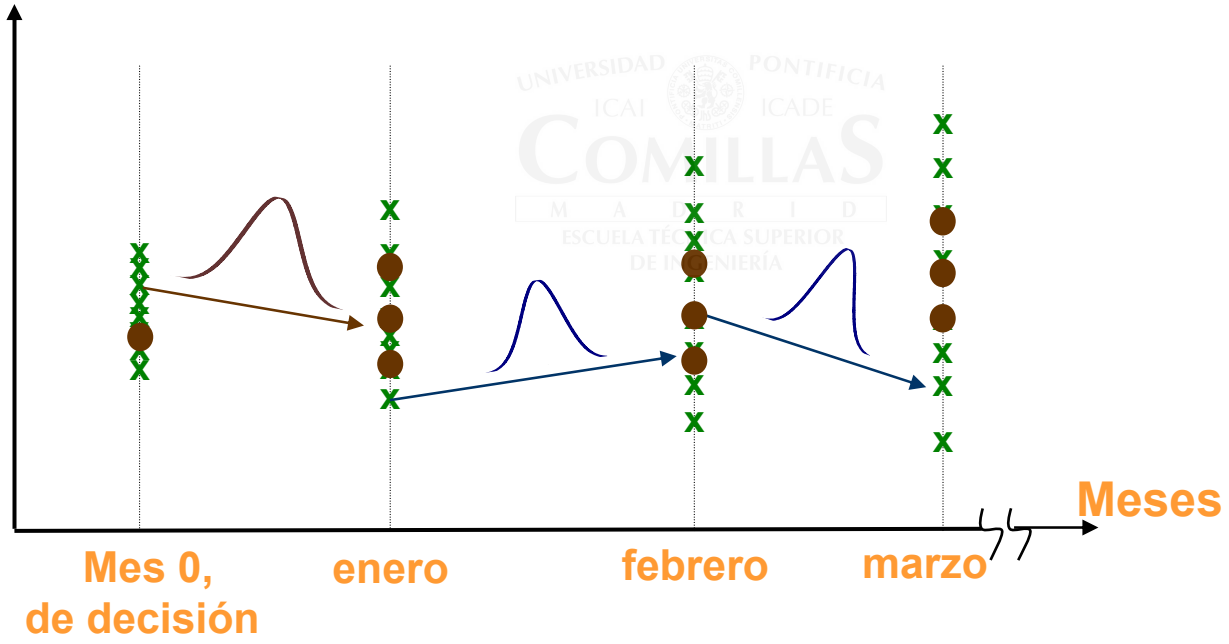
- **Determinación de muestras del primer periodo**
  - ✓ Transformaciones lineales



GENERACIÓN DE PRECIOS DE GAS Y FUELOIL
Algoritmo

- **Determinación de muestras del primer periodo**

- **Determinación de muestras del resto de periodos**
  - ✓ Correlaciones lineales entre periodos consecutivos



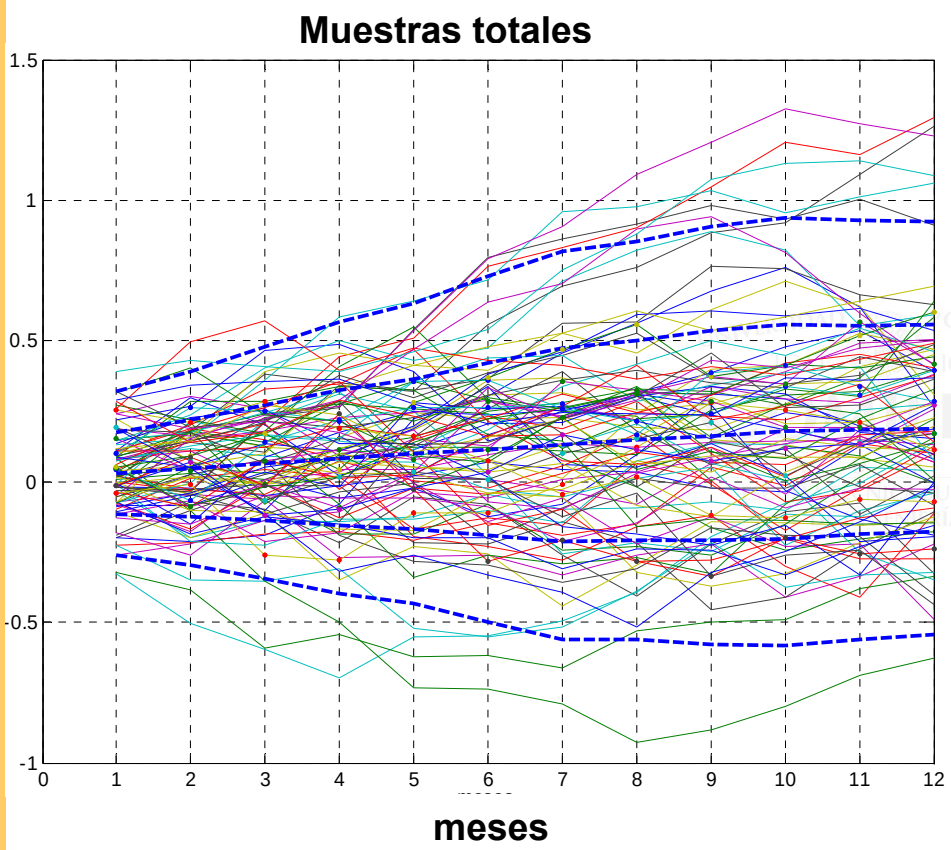
GENERACIÓN DE PRECIOS DE GAS Y FUELOIL
Caso ejemplo

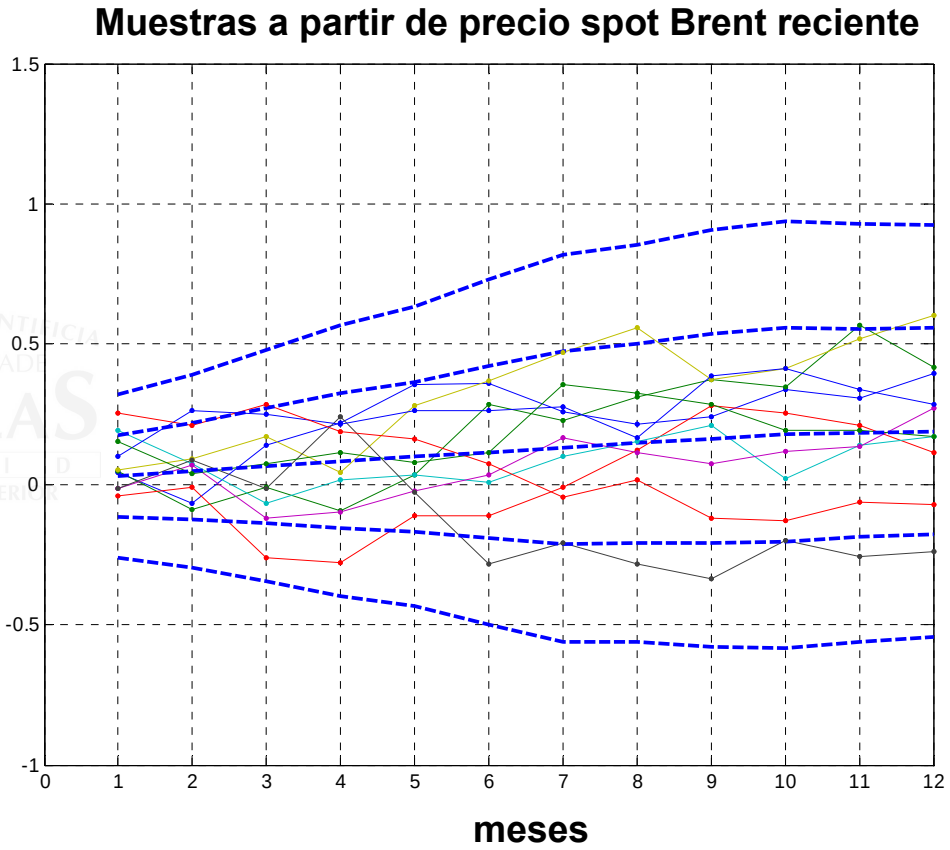
- **Previsión de precios de gas natural y fueloil para el año 2003**
- **Generación de 10 escenarios**
- **Datos de entrada:**
  - ✓ Precios spot de Brent (1999-2002)
  - ✓ Precios futuros de Brent (1999-2003)
  - ✓ Precios de gas natural y fueloil (1999-2002)

- **Correlación muy alta entre Brent y combustibles:**
  - ✓ Gas natural (0.99)
  - ✓ Fueloil (0.97)
- **Correlación media alta (0.92) entre las muestras de distribuciones de errores consecutivos**

GENERACIÓN DE PRECIOS DE GAS Y FUELOIL
Caso ejemplo

- Muestreas de las distribuciones de diferencias spot-futuros

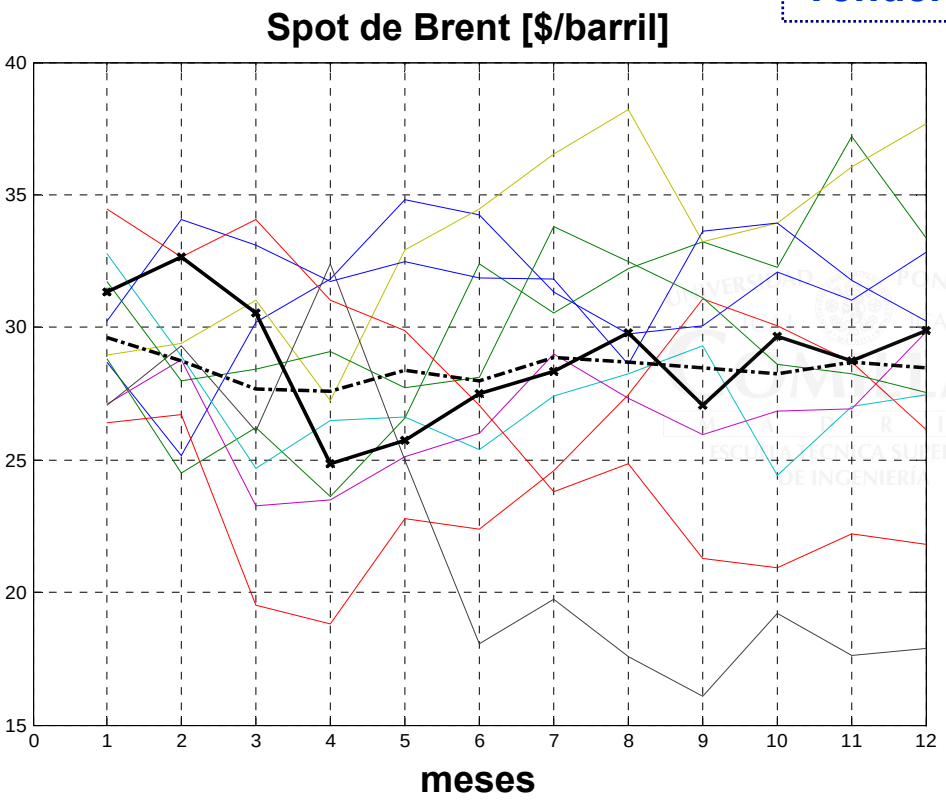


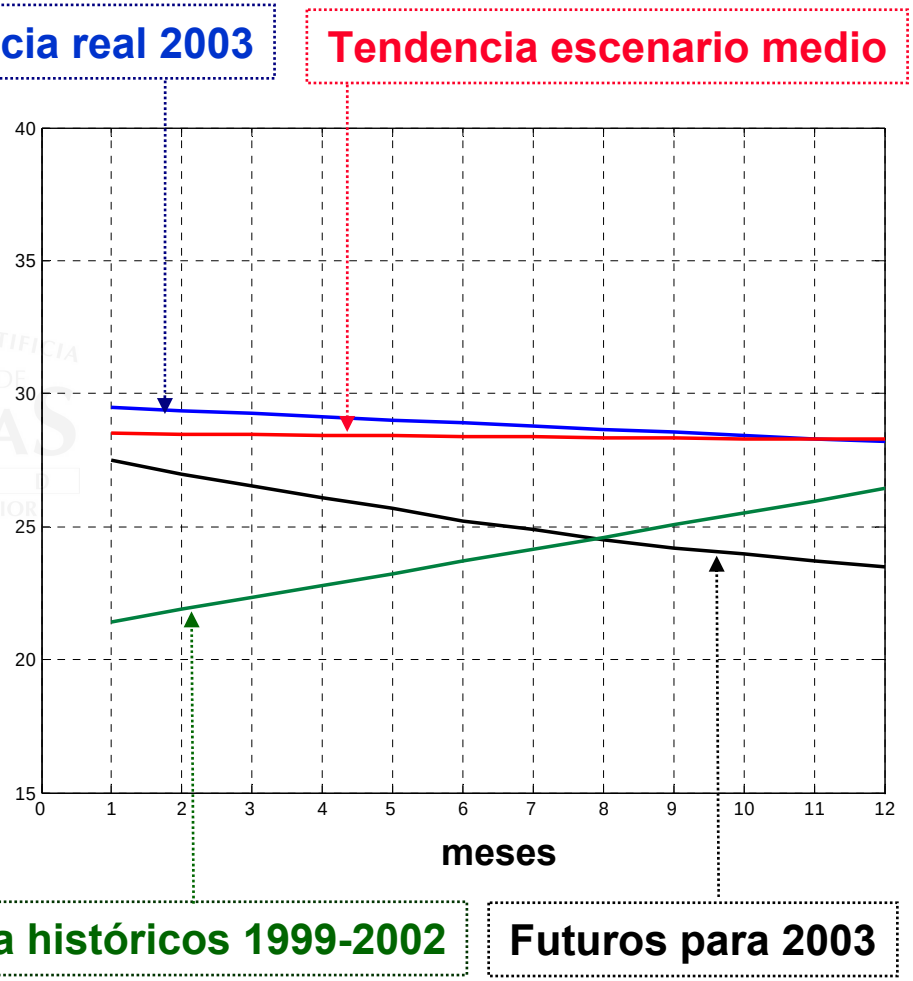


Líneas - - - -
- Media
- Media ± desviación típica
- Media ± 2 x desviación típica

GENERACIÓN DE PRECIOS DE GAS Y FUELOIL
Caso ejemplo

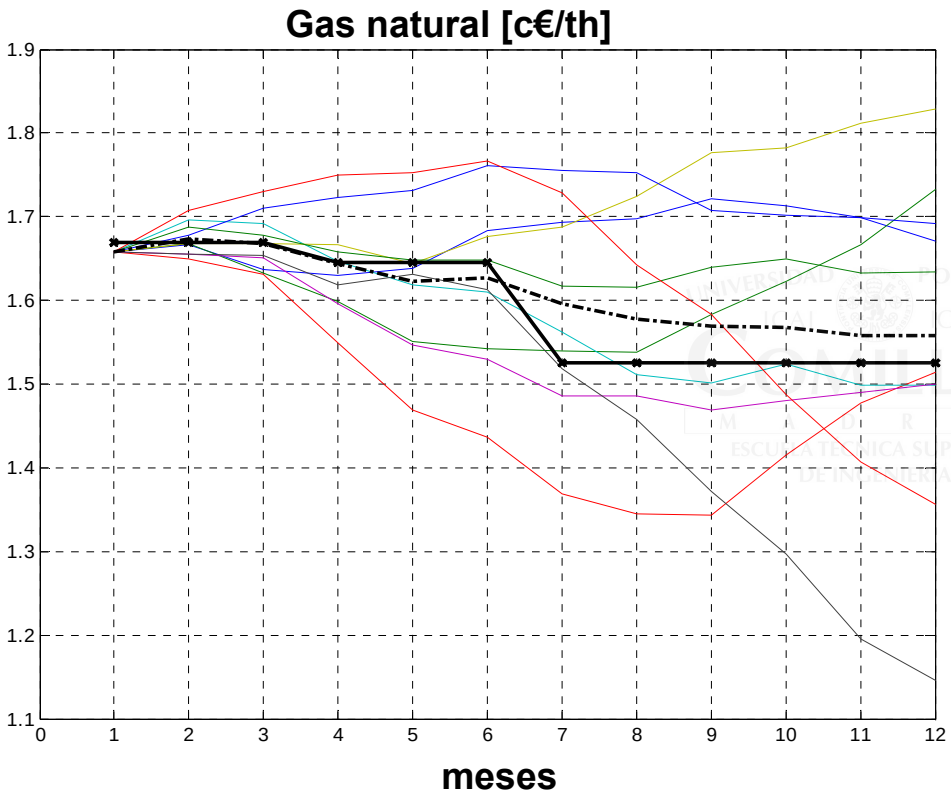
❑ Precios spot de Brent

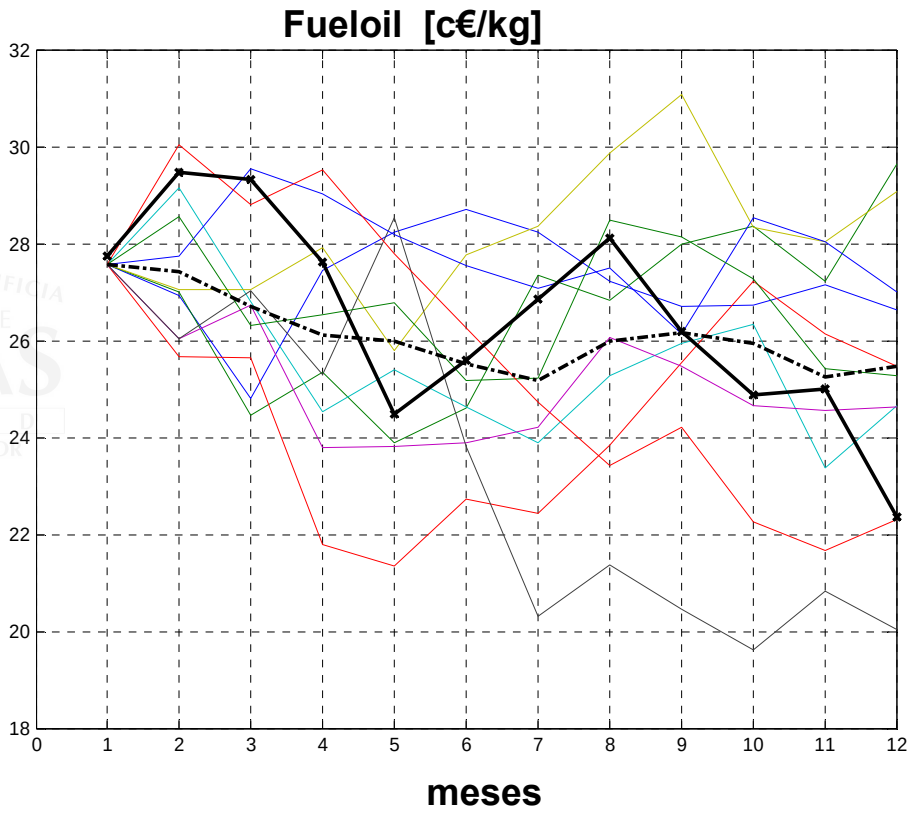




GENERACIÓN DE PRECIOS DE GAS Y FUELOIL
Caso ejemplo

- Precios de gas natural y fueloil para consumidores





GENERACIÓN DE PRECIOS DE ELECTRICIDAD
Características y modelos de precios

- **Modelos cuantitativos: no proporcionan buenos resultados**
  - ✓ Basados fundamentalmente en la serie de precios
  - ✓ Orientados principalmente al corto plazo
- **Modelos fundamentales: son complejos de parametrizar**
  - ✓ Basados en el conocimiento del mercado y el sistema eléctrico
  - ✓ Orientados al medio-largo plazo
- **Precios en España difíciles de predecir a medio plazo**
  - ✓ Posible poder de mercado
  - ✓ Ingresos de las eléctricas no sujetos exclusivamente al mercado
  - ✓ Entrada progresiva de nuevos agentes y cambios regulatorios
- **Modelo propuesto**
  - ✓ **Compra electricidad:** Muestreo de años históricos
  - ✓ **Venta electricidad:** Regresión lineal anual entre precios de compra y venta (coeficientes de correlación superiores a 0.99)

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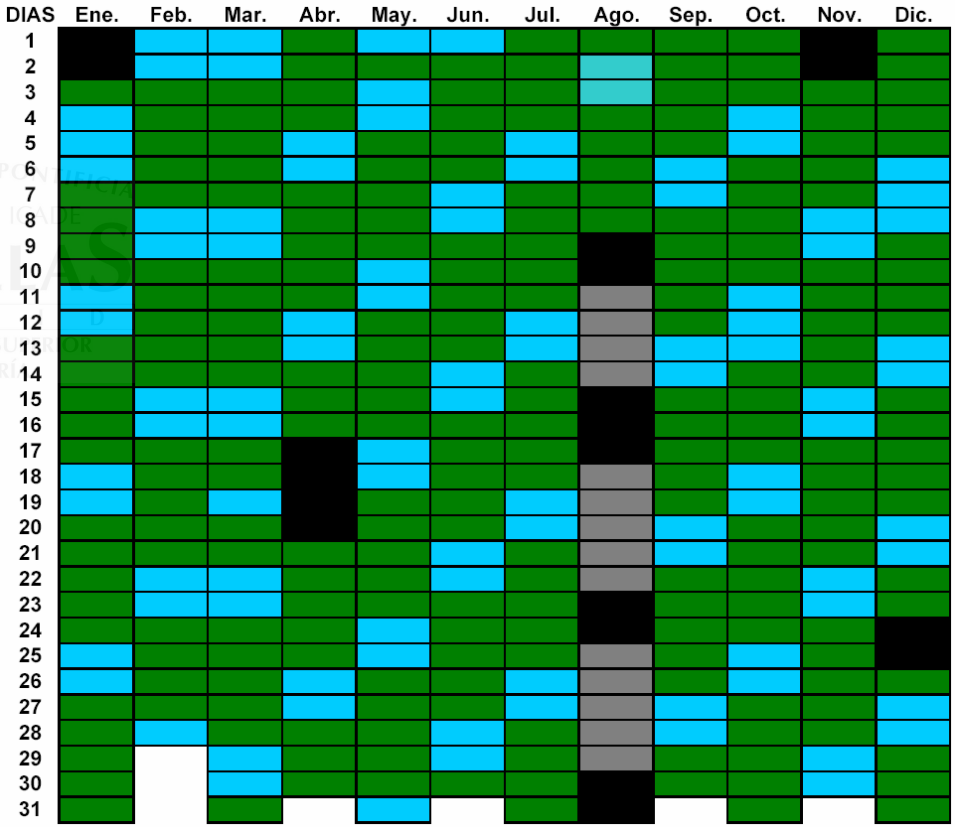
NUMERICAL APPLICATION
Input data

- **Cellulose paper factory**
- **Day type:** Weekday/Producing Weekday/Stopped
  Weekend/Producing **Weekend/Stopped**
- **3 periods/day type:**
  90 periods
- **15 price scenarios:**
  - ✓ 5 fuel scenarios
  - ✓ 3 electricity scenarios
- **1350 nodes**
- **23 contracts:**
  - ✓ 12 purchase of electricity
  - ✓ 4 purchase of natural gas
  - ✓ 4 purchase of fuel oil
  - ✓ 3 sale of electricity



NUMERICAL APPLICATION
Size and solution

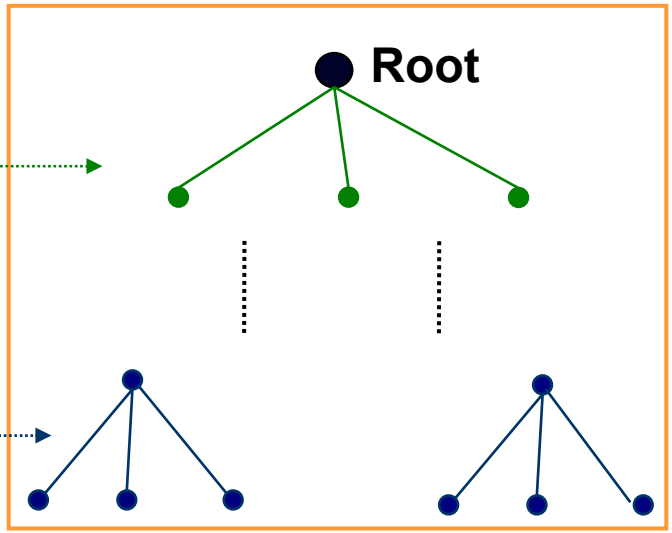
- Coded in GAMS, solved by CPLEX 9.0
- Size

	Deterministic	Stochastic
Constraints	5.883	88.035
Variables	8.677	129.879
Binary	1.087	16.043
Non zero coef.	32.887	492.818

- Branch&Bound algorithm: branching priorities

Contracts (first level branching)

Boiler and cogeneration state (last level branching)

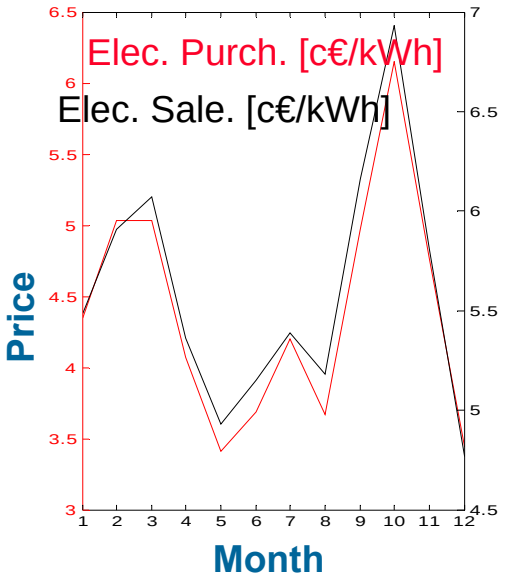


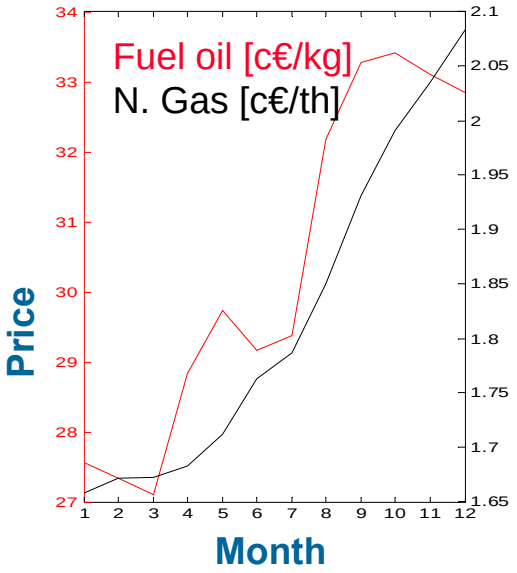
NUMERICAL APPLICATION
Deterministic: Operation 1 scenario

- **Cogeneration operation: 7032 h/year**
  - ✓ Performance: 55.1%, exports 65% of the output
- **Boiler operation: 936 h/year**

Sold or consumed quantities

Mes	Fueloil [t]	Gas natural [km^3]	E^a eléctrica adquirida [MWh]	E^a eléctrica vendida [MWh]
1		468.9	0.5	1196.9
2		458.3		1180.5
3		513.0		1331.5
4		418.9	1.0	1066.5
5	15.0	440.0	86.0	1120.5
6	44.4	320.2	258.1	843.1
7	46.0	332.8	266.7	879.7
8	11.9	86.1	74.4	228.0
9		481.3		1146.5
10		500.8		1277.6
11		450.6	0.5	1146.5
12	57.5	257.5	313.3	670.9
Total	174.8	4728.3	1000.5	12088.4





NUMERICAL APPLICATION

Deterministic: Contracts for the 15 scenarios

❑ Portfolios of different contracts

CONTRACT COST [k€]

	Scenario	Elect. (purchase)		Fuel oil	Natural gas		Elect. (sale)		Objective function
High fuel prices	1		0.3			1024.5		827.3	658.0
	2	30.4		50.9		903.3	754.0		650.6
	3		0.3			1022.8	917.8		565.0
Electricity price:	4		0.3		992.1			827.3	625.7
	5		0.3		979.6		816.5		618.9
	6		0.3		990.7		917.9		532.8
low	7		0.3		911.6			827.3	545.1
medium	8		0.3		911.5		832.4		539.4
high	9		0.3		912.0		917.7		454.3
	10		0.3		893.8			827.2	527.3
	11		0.3		894.1		832.7		521.7
	12	0.3			895.4		918.8		437.0
Low fuel prices	13		0.3		831.8			824.1	467.7
	14		0.3		834.1		831.1		462.9
	15	0.3			836.9		918.2		379.1

Fixed price
Indexed fixed price
Contract for differences
Market price
Market price + collar
Fixed price

NUMERICAL APPLICATION
Deterministic: Multiattribute scenario analysis

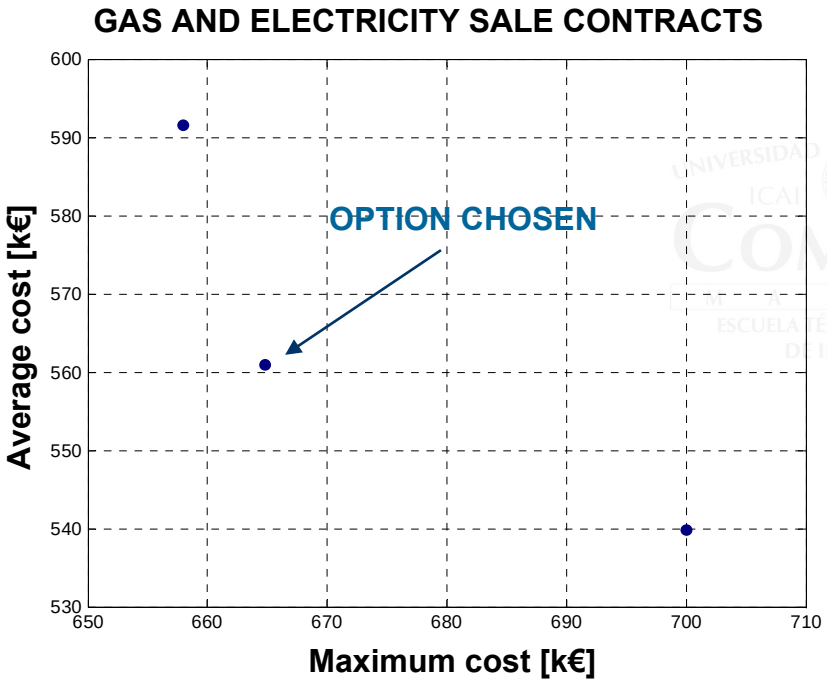
❑ Determining the contract in two stages

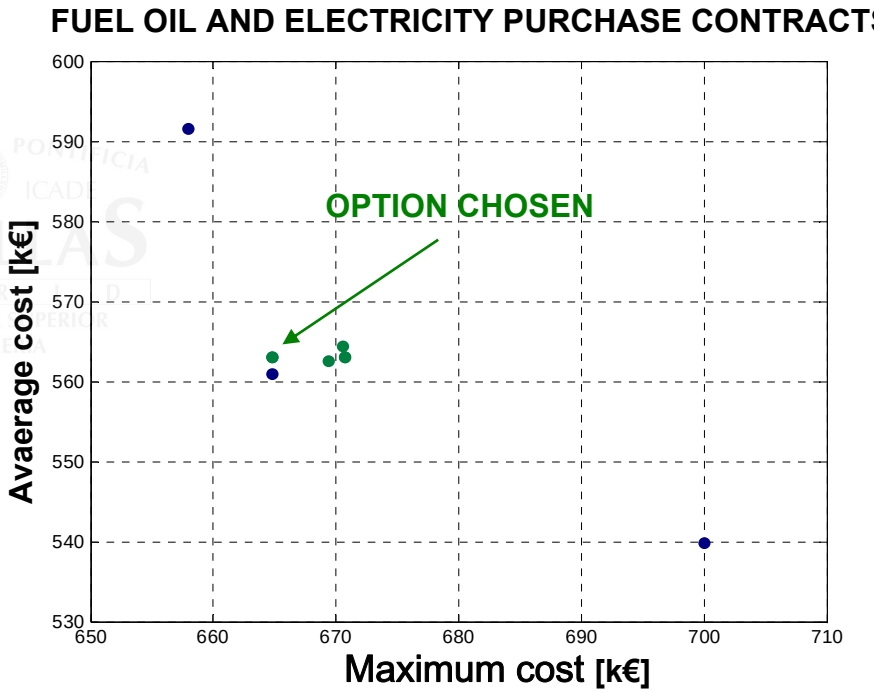
- ✓ **Stage 1:** Contracts with high coefficient in the objective function: Gas and electricity purchase contracts
- ✓ **Stage 2:** Contracts with low coefficient in the objective function : Fuel oil and electricity sale contracts

❑ For each stage:

- ✓ Solve the model for each scenario
- ✓ Select the solution: risk neutral, low aversion attitude and high aversion attitude
- ✓ Solve for each scenario and each solution
- ✓ Select the compromise solution in risk measure and attitude

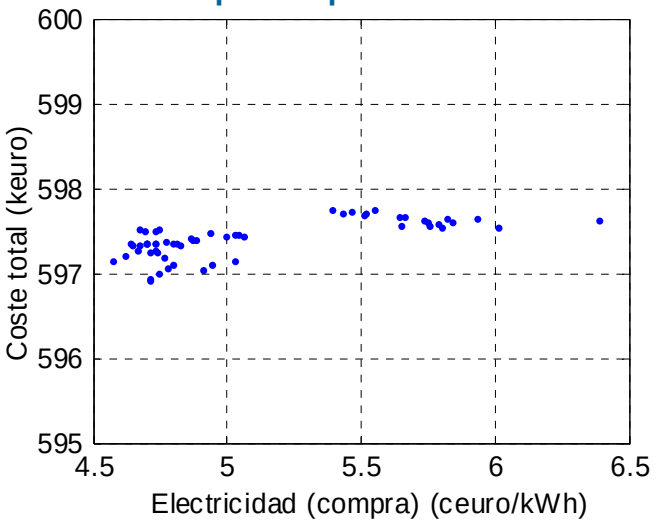
NUMERICAL APPLICATION
Deterministic: Multiattribute scenario analysis



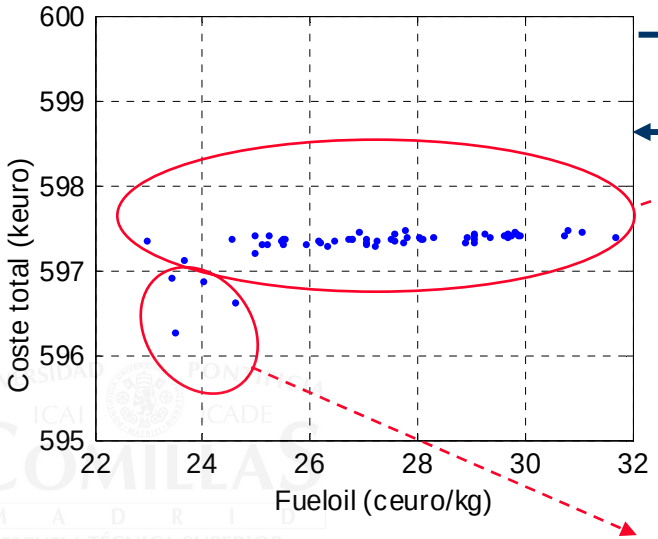


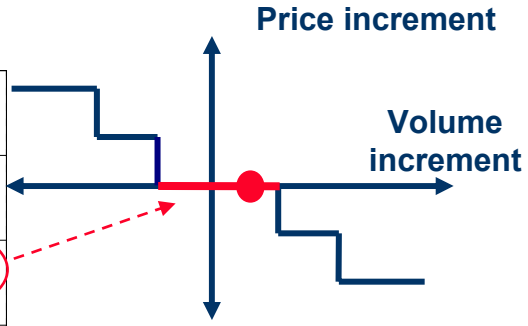
NUMERICAL APPLICATION
Deterministic: Sensitivity analysis

Market price + price bounds

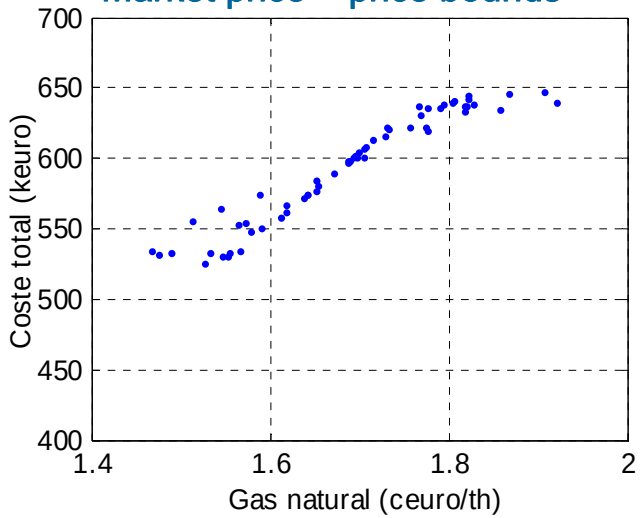


Market price + quantity discount

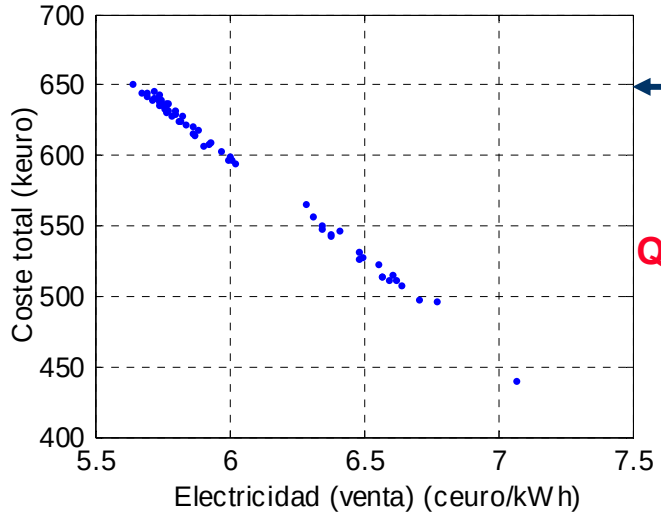


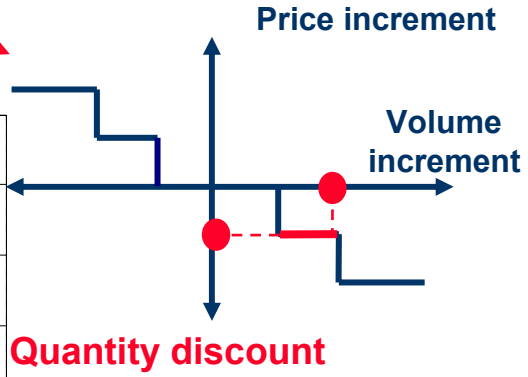


Market price + price bounds



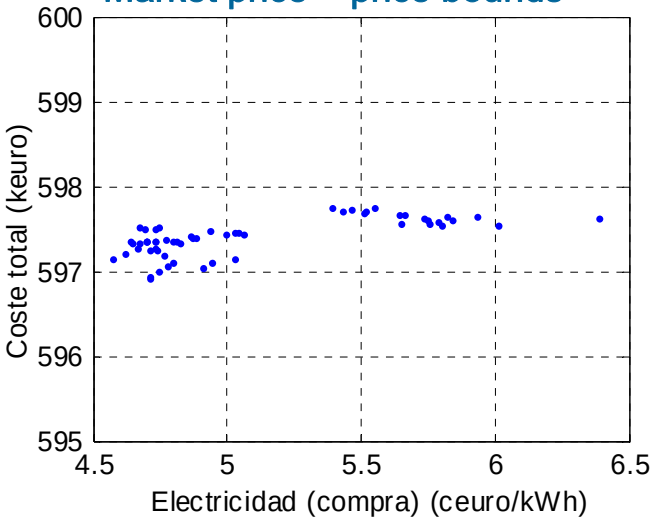
Market price



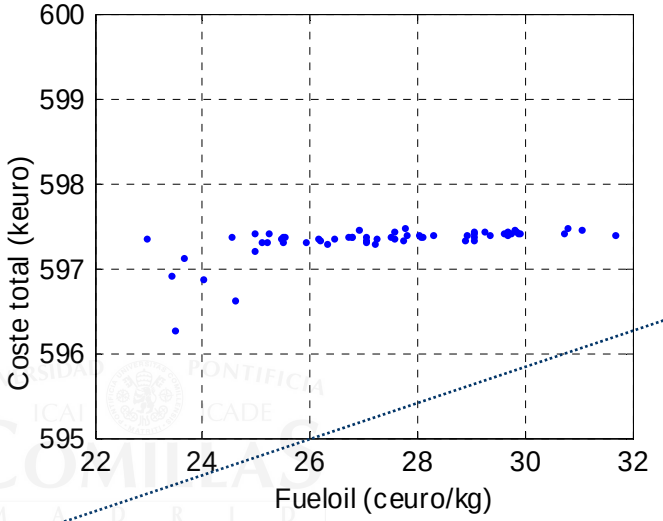


NUMERICAL APPLICATION
Deterministic: Sensitivity analysis

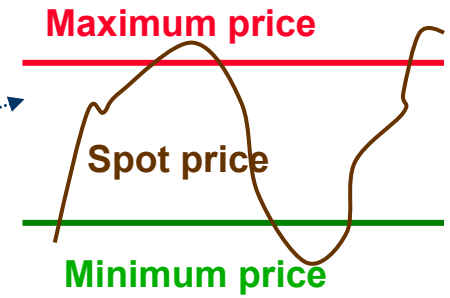
Market price + price bounds



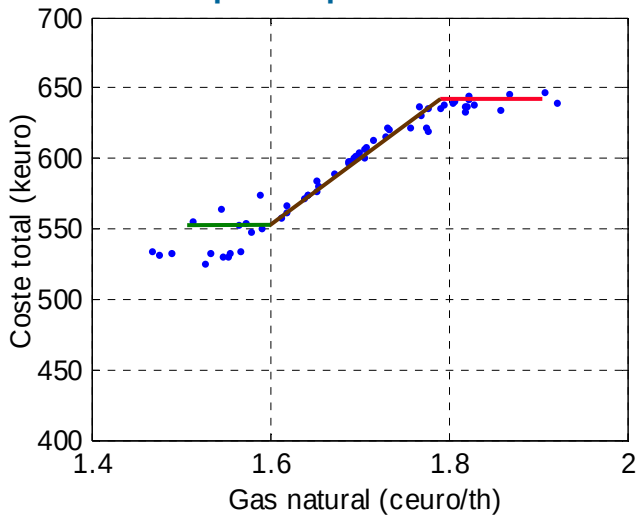
Market price + quantity discount



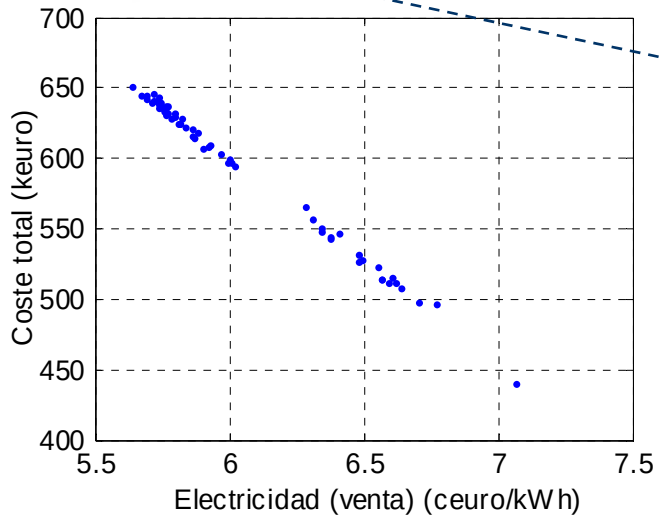
- Straight line:
  Δ 0.1 c€/th →
  Δ 33 k€ cost



Market price + price bounds



Market price



- High linear correlatio
- High risk
- Δ 0.5 c€/kwh →
  saving 72k€

NUMERICAL APPLICATION
Stochastic: efficient frontier

❑ Safety-first model

✓ **Obtaining the efficient frontier:**

- **First iteration:** solve the risk neutral model to obtain max cost
- **Remaining iterations** (while the problem is feasible): decrease the risk aversion parameter

✓ **In each iteration we obtain:**

- Optimal solutions for variables of both stages
- Different contract portfolios

❑ VaR model

✓ Optimal solution for the first stage

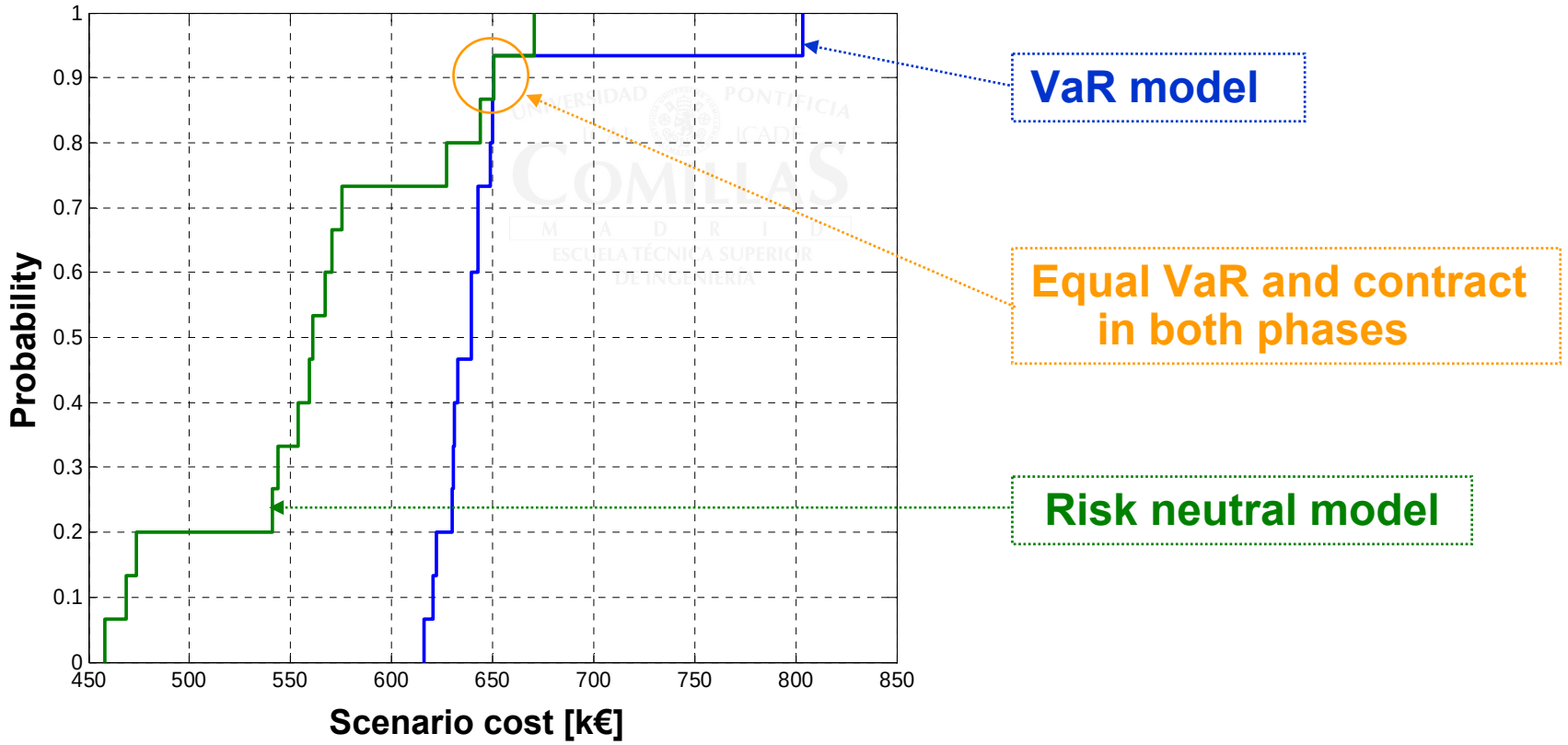
✓ Optimal solution for the second stage only for the VaR scenario

✓ **Drawbacks:**

- Not always a different contract solution can be obtained when diminishing the risk aversion parameter
- Optimal plant operation difficult to obtain (not included in the o.f.)

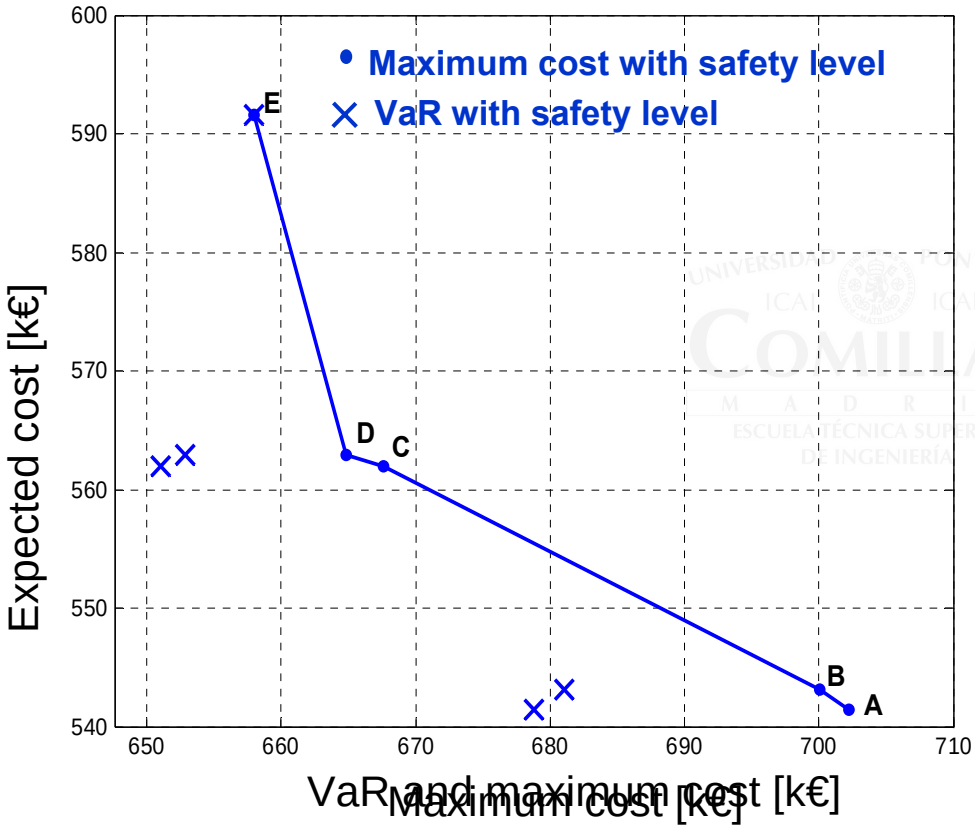
NUMERICAL APPLICATION
Stochastic: Methodology to determine eff. frontier with VaR model

- **Phase 1: Solving VaR models**
  - ✓ Determine contracts (**first stage variables**)
- **Phase 2: Solving risk neutral models**
  - ✓ Determine operation (**second stage variables**)

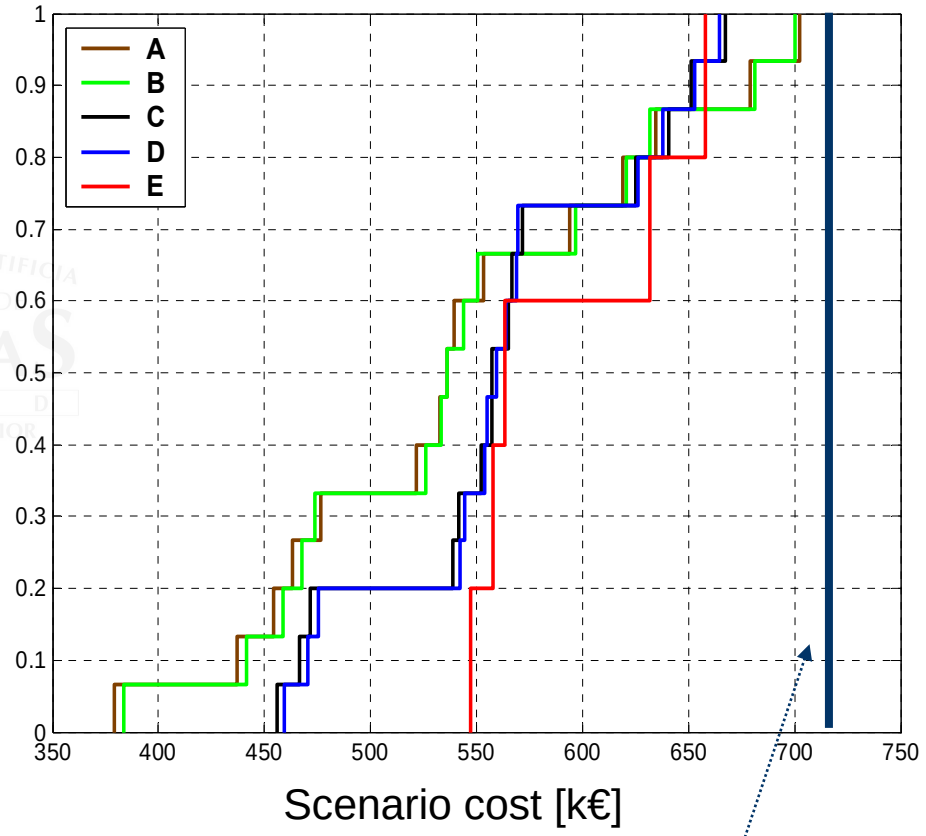


NUMERICAL APPLICATION
Stochastic: efficient frontier

❑ **Safety-first and VaR models (confidence level 0.9)**



Distribution function. Safety-first model



Solution 1 = A
Solution 3 = C

Fixed price contract

CONTENT

- Motivation and objective
- Deterministic approach
- Probabilistic approach
- Numerical application
- Conclusions
- Future developments

CONCLUSIONS

❑ Aplications:

✓ The tool developed allows the consumers to:

- Decrement the energy bill
- Control the assumed risk

✓ Other applications:

- Retailers: analysis of new contracting possibilities
- Factory design

❑ Optimization models:

	Solution time (*)	**Risk management**
Deterministic	Reduced (20 s)	Limited
Safety-first level	Reasonable (6 h)	Powerful, low flexibility
VaR	High (22 h)	Powerful, high flexibility

(*) Pentium IV 3 GHz

APORTACIONES

❑ Planteamiento determinista

[*Optimal Energy Management of an Industrial Consumer in Liberalized Markets. IEEE Transactions on Power Systems, Vol 18, No 2, May 2003*]

- ✓ **Optimización a medio plazo de contratación y operación para consumidores industriales**
- ✓ **Contratos:**
  - 4 tipos de bienes a contratar
  - Cantidad de contratos: recorren abanico de riesgos
  - Complejidad de contratos: tramos de precios y volumen
- ✓ **Operación:**
  - Modelado cogeneración: circuito alta temperatura
  - Régimen especial: balance energía y restricciones régimen especial
- ✓ **Metodología de decisión bajo incertidumbre con modelo determinista: análisis de escenarios multiatributo**

APORTACIONES

❑ Planteamiento estocástico

- ✓ **Modelos sin gestión del riesgo:**
  - **Modelo neutral al riesgo**
    - – Extensión del modelo determinista
- ✓ **Modelos con gestión del riesgo:**
  - **Planteamiento y análisis de 8 modelos de riesgo para consumidores industriales**
  - **Modelo coste de referencia**
    - – Planteamiento
  - **Modelo nivel de seguridad**
    - – Aplicación a mercados eléctricos
  - **Modelo VaR**
    - – Aplicación a mercados eléctricos
- ✓ **Metodología para determinar fronteras eficientes en problemas bietapa donde no estén penalizadas en la f.o. todas las variables**

APORTACIONES

❑ Generación de escenarios de precios de fueloil y gas

[*An algorithm for the mid-term forecast and scenario generation of natural gas and fueloil prices. IEEE Transactions on Power Systems, March 2004, TPWRS-00124-2004, en revisión*]

- ✓ **Determinación de precios finales a consumidores a través del precio spot de Brent**
- ✓ **Utilización de cotizaciones de futuros para hallar precios spot de Brent**

CONTENT

- Motivation and objective
- Deterministic approach
- Probabilistic approach
- Numerical application
- Conclusions
- Future developments

FUTURE DEVELOPMENTS

- **Extension of proposed models**
  - ✓ **Join optimization of several factories with interannual contracts: multistage stochastic programming**
  - ✓ Different plant configuration
  - ✓ New type of contracts

- **Solution methods for MIP**
  - ✓ Analysis of matrix structure
  - ✓ Decomposition techniques

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Andrés Ramos