Capacity Investments in a Stochastic Dynamic Game: Good News Principle

Talat Genc, Georges Zaccour

Dept of Economics, University of Guelph, Canada
Chair in Game Theory and Management, GERAD, HEC Montréal, Canada

April 2010

Outline

1. Motivation
   1. Why capital investments
   2. Previous Work
2. Our results/contribution
   1. Main results
   2. Model
3. Old work and work in progress

Capacity Investments Under Uncertainty

- In many industries capital or capacity investments are made under uncertainty.

Capacity Investments Under Uncertainty

- In many industries capital or capacity investments are made under uncertainty.
- Uncertainty may stem from the nature of production characteristics, demand, cost and macroeconomic conditions.

Capacity Investments Under Uncertainty

- In many industries capital or capacity investments are made under uncertainty.
- Uncertainty may stem from the nature of production characteristics, demand, cost and macroeconomic conditions.
- Uncertainties are industry specific and the degree of uncertainty may vary from industry to industry.

Capacity Investments Under Uncertainty

- In many industries capital or capacity investments are made under uncertainty.
- Uncertainty may stem from the nature of production characteristics, demand, cost and macroeconomic conditions.
- Uncertainties are industry specific and the degree of uncertainty may vary from industry to industry.
- Extensive literature, but:

Capacity Investments Under Uncertainty

- In many industries capital or capacity investments are made under uncertainty.
- Uncertainty may stem from the nature of production characteristics, demand, cost and macroeconomic conditions.
- Uncertainties are industry specific and the degree of uncertainty may vary from industry to industry.
- Extensive literature, but:
    - no much studies with stochastic demand

Capacity Investments Under Uncertainty

- In many industries capital or capacity investments are made under uncertainty.
- Uncertainty may stem from the nature of production characteristics, demand, cost and macroeconomic conditions.
- Uncertainties are industry specific and the degree of uncertainty may vary from industry to industry.
- Extensive literature, but:
  - no much studies with stochastic demand
  - no time-to-build concern

Capacity Investments Under Uncertainty

- In many industries capital or capacity investments are made under uncertainty.
- Uncertainty may stem from the nature of production characteristics, demand, cost and macroeconomic conditions.
- Uncertainties are industry specific and the degree of uncertainty may vary from industry to industry.
- Extensive literature, but:
  - no much studies with stochastic demand
  - no time-to-build concern
  - strategic type of interactions (precommitment versus no commitment, or open-loop versus closed-loop)

Capacity Investments Under Uncertainty

- Capacity expansion literature: Spence (1979), Dixit (1980), Fershtman and Muller (1984), Reynolds (1987), Cellini and Lambertini (1998), Garcia and Stacchetti (2008), Wu (2007), Ruiz-Aliseda and Wu (2008),Pacheco-de-Almeida and Zemsky (2003), Genc, Reynolds, and Sen (2007)

Capacity Investments Under Uncertainty

- Capacity expansion literature: Spence (1979), Dixit (1980), Fershtman and Muller (1984), Reynolds (1987), Cellini and Lambertini (1998), Garcia and Stacchetti (2008), Wu (2007), Ruiz-Aliseda and Wu (2008),Pacheco-de-Almeida and Zemsky (2003), Genc, Reynolds, and Sen (2007)
- Reynolds (1987): Markov strategies increase competition, i.e., Markov-perfect equilibrium investments exceed the open-loop ones.

Capacity Investments Under Uncertainty

- Capacity expansion literature: Spence (1979), Dixit (1980), Fershtman and Muller (1984), Reynolds (1987), Cellini and Lambertini (1998), Garcia and Stacchetti (2008), Wu (2007), Ruiz-Aliseda and Wu (2008),Pacheco-de-Almeida and Zemsky (2003), Genc, Reynolds, and Sen (2007)
- Reynolds (1987): Markov strategies increase competition, i.e., Markov-perfect equilibrium investments exceed the open-loop ones.
- Same result in Dockner (1992), Driskill and McCafferty (1989), Long et al. (1999), and Driskill (2001)

Capacity Investments Under Uncertainty

- Capacity expansion literature: Spence (1979), Dixit (1980), Fershtman and Muller (1984), Reynolds (1987), Cellini and Lambertini (1998), Garcia and Stacchetti (2008), Wu (2007), Ruiz-Aliseda and Wu (2008),Pacheco-de-Almeida and Zemsky (2003), Genc, Reynolds, and Sen (2007)
- Reynolds (1987): Markov strategies increase competition, i.e., Markov-perfect equilibrium investments exceed the open-loop ones.
- Same result in Dockner (1992), Driskill and McCafferty (1989), Long et al. (1999), and Driskill (2001)
- Opposite in van der Ploeg and de Zeeuw (1990), Melese and Michel (1991), Piga (1998), Figuières (2002).

Capacity Investments Under Uncertainty

- Capacity expansion literature: Spence (1979), Dixit (1980), Fershtman and Muller (1984), Reynolds (1987), Cellini and Lambertini (1998), Garcia and Stacchetti (2008), Wu (2007), Ruiz-Aliseda and Wu (2008),Pacheco-de-Almeida and Zemsky (2003), Genc, Reynolds, and Sen (2007)
- Reynolds (1987): Markov strategies increase competition, i.e., Markov-perfect equilibrium investments exceed the open-loop ones.
- Same result in Dockner (1992), Driskill and McCafferty (1989), Long et al. (1999), and Driskill (2001)
- Opposite in van der Ploeg and de Zeeuw (1990), Melese and Michel (1991), Piga (1998), Figuières (2002).
- Figuières (2009) shows, using a model with reversible investments, that these contradictory findings are related to the concept of strategic substitutability and complementarity

Capacity Investments Under Uncertainty

- Recently the literature moved from a deterministic world to a stochastic one (Ruiz-Aliseda and Wu (2008), Wu (2007), and Garcia and Stacchetti (2008))

Capacity Investments Under Uncertainty

- Recently the literature moved from a deterministic world to a stochastic one (Ruiz-Aliseda and Wu (2008), Wu (2007), and Garcia and Stacchetti (2008))
- But are not concerned by the impact of the different equilibrium types (or information structures), nor do they explicitly study the role of state variables on equilibrium predictions.

Capacity Investments Under Uncertainty

- Recently the literature moved from a deterministic world to a stochastic one (Ruiz-Aliseda and Wu (2008), Wu (2007), and Garcia and Stacchetti (2008))
- But are not concerned by the impact of the different equilibrium types (or information structures), nor do they explicitly study the role of state variables on equilibrium predictions.
- **Capital Intensive Markets**

Capacity Investments Under Uncertainty

- Recently the literature moved from a deterministic world to a stochastic one (Ruiz-Aliseda and Wu (2008), Wu (2007), and Garcia and Stacchetti (2008))
- But are not concerned by the impact of the different equilibrium types (or information structures), nor do they explicitly study the role of state variables on equilibrium predictions.
- **Capital Intensive Markets**
    - Electricity generation industry

Capacity Investments Under Uncertainty

- Recently the literature moved from a deterministic world to a stochastic one (Ruiz-Aliseda and Wu (2008), Wu (2007), and Garcia and Stacchetti (2008))
- But are not concerned by the impact of the different equilibrium types (or information structures), nor do they explicitly study the role of state variables on equilibrium predictions.
- **Capital Intensive Markets**
    - Electricity generation industry
    - Telecomm and wireless Hotspot industry

Capacity Investments Under Uncertainty

- Recently the literature moved from a deterministic world to a stochastic one (Ruiz-Aliseda and Wu (2008), Wu (2007), and Garcia and Stacchetti (2008))
- But are not concerned by the impact of the different equilibrium types (or information structures), nor do they explicitly study the role of state variables on equilibrium predictions.
- **Capital Intensive Markets**
  - Electricity generation industry
  - Telecomm and wireless Hotspot industry
  - Natural gas transportation

Capacity Investments Under Uncertainty

- Recently the literature moved from a deterministic world to a stochastic one (Ruiz-Aliseda and Wu (2008), Wu (2007), and Garcia and Stacchetti (2008))
- But are not concerned by the impact of the different equilibrium types (or information structures), nor do they explicitly study the role of state variables on equilibrium predictions.
- **Capital Intensive Markets**
  - Electricity generation industry
  - Telecomm and wireless Hotspot industry
  - Natural gas transportation
  - Ethanol

This Paper

- Characterize and compare equilibrium investments under Closed-loop and S-adapted open-loop information structures.
- S-adapted open-loop information: Zaccour (1987), Haurie, Zaccour, Smeers (1990), Haurie, Zaccour, Legrand, Smeers (????),Haurie and Zaccour (2006)

Definition

S-adapted open-loop information: At any time each player's information set includes the current calendar time, the current demand state, the distribution of future demand, and the initial values of capacity states.

Definition

S-adapted closed-loop information: At any time each player's information set includes the current calendar time, the current states involving demand and capacity states, the distribution of future demand, and the history of the states.

This Paper

- Two variations on model:

This Paper

- Two variations on model:
  - Two-period game.

This Paper

- Two variations on model:
  - Two-period game.
  - Extention to T-period game.

This Paper

- Two variations on model:
  - Two-period game.
  - Extention to T-period game.
- Questions:

This Paper

- Two variations on model:
  - Two-period game.
  - Extention to T-period game.
- Questions:
  - What is the ranking of investments under both equilibrium types?

This Paper

- Two variations on model:
  - Two-period game.
  - Extention to T-period game.
- Questions:
  - What is the ranking of investments under both equilibrium types?
  - How do initial conditions and degree of asymmetry affect the investment rankings?

This Paper

- Two variations on model:
  - Two-period game.
  - Extention to T-period game.
- Questions:
  - What is the ranking of investments under both equilibrium types?
  - How do initial conditions and degree of asymmetry affect the investment rankings?
  - What is the investment pattern under uncertainty?

This Paper

- Two variations on model:
  - Two-period game.
  - Extention to T-period game.
- Questions:
  - What is the ranking of investments under both equilibrium types?
  - How do initial conditions and degree of asymmetry affect the investment rankings?
  - What is the investment pattern under uncertainty?
  - How does available capacity affect the distribution of investments?

This Paper

- Two variations on model:
  - Two-period game.
  - Extention to T-period game.
- Questions:
  - What is the ranking of investments under both equilibrium types?
  - How do initial conditions and degree of asymmetry affect the investment rankings?
  - What is the investment pattern under uncertainty?
  - How does available capacity affect the distribution of investments?
  - What are the incentives to increase capacity

Main Results

- Firms may invest at a higher level in the open-loop equilibrium than in the closed-loop Nash equilibrium, contrary to what is established.

Main Results

- Firms may invest at a higher level in the open-loop equilibrium than in the closed-loop Nash equilibrium, contrary to what is established.
- The rankings of the investments depend on the initial capacities and on the degree of asymmetry between the firms.

Main Results

- Firms may invest at a higher level in the open-loop equilibrium than in the closed-loop Nash equilibrium, contrary to what is established.
- The rankings of the investments depend on the initial capacities and on the degree of asymmetry between the firms.
- Under no circumstances the (investing) players can achieve a higher payoff under an open-loop information structure than under a closed-loop information structure.

Main Results

- Firms may invest at a higher level in the open-loop equilibrium than in the closed-loop Nash equilibrium, contrary to what is established.
- The rankings of the investments depend on the initial capacities and on the degree of asymmetry between the firms.
- Under no circumstances the (investing) players can achieve a higher payoff under an open-loop information structure than under a closed-loop information structure.
- Contrary to the bad news principle of investment (Bernanke (1983)),firms may invest more as demand volatility increases and they invest as if high demand (i.e., good news) will unfold in the future.

Model

- Set of players J
- S^t the set of possible realizations of the stochastic process that affects market demand at period t.
- S^0 has only one element, s^0, which is the root of the event tree.
- At any subsequent period, $t \geq 1$, the set S^t contains N_t elements (nodes), i.e., $S^t = \left\{ s_1^t, \ldots, s_{N_t}^t \right\}$..
- $a\left(s_k^t\right) \in S^{t-1}$ is the unique predecessor of $s_k^t \in S^t$
- $B\left(s_k^t\right) \subset S^{t+1}$, $t = 0, \ldots, T-1$, the set of successors of node s_k^t in the event tree
- $\theta\left(s_k^t \mid a\left(s_k^t\right)\right)$ the conditional probability associated with the arc $\left(a\left(s_k^t\right), s_k^t\right)$ in the event tree with

$$\sum_{s_k^t \in S^t} \theta\left(s_k^t \mid a\left(s_k^t\right)\right) = 1.$$

Model

- Inverse demand:

$$P\left(\sum_i q_i\left(t, s_k^t\right)\right) = 1 + \phi\left(t, s_k^t\right) - Q\left(t, s_k^t\right),$$

where

$$\phi\left(t, s_k^t\right) = \phi\left(a\left(t, s_k^t\right)\right) + \tilde{\xi}, \quad \text{where } \tilde{\xi} = \begin{cases} \xi, & \text{if } s_k^t = u \\ -\xi, & \text{if } s_k^t = d \end{cases},$$

and ξ is a nonnegative parameter and $\phi(0,0) = 0$.

Model

- Inverse demand:

$$P\left(\sum_i q_i\left(t, s_k^t\right)\right) = 1 + \phi\left(t, s_k^t\right) - Q\left(t, s_k^t\right),$$

where

$$\phi\left(t, s_k^t\right) = \phi\left(a\left(t, s_k^t\right)\right) + \tilde{\xi}, \quad \text{where } \tilde{\xi} = \begin{cases} \xi, & \text{if } s_k^t = u \\ -\xi, & \text{if } s_k^t = d \end{cases},$$

and ξ is a nonnegative parameter and $\phi\left(0, 0\right) = 0$.

- Capacity accumulation:

$$K_i\left(t, s_k^t\right) = K_i\left(t-1, a\left(s_k^t\right)\right) + I_i\left(t-1, a\left(s_k^t\right)\right), \ \forall t, \ \forall s_k^t \in S^t,$$

with $K_i\left(0, s^0\right) = K_{i0}$.

Model

- Investment and production costs

$$F_i\left(I_i\right) = 1/2f\, I_i^2, \qquad C_i\left(q_i\right) = cq_i,$$

Model

- Investment and production costs

$$F_i\left(I_i\right) = 1/2f\, I_i^2, \qquad C_i\left(q_i\right) = cq_i,$$

- Player i's optimization problem:

$$\max \pi_i = P\left(Q\left(0, s^0\right)\right) q_i\left(0, s^0\right) - C_i\left(q_i\left(0, s^0\right)\right) - F_i\left(I_i\left(0, s^0\right)\right)$$
$$+\sum_{t=1}^{T} \delta^t \sum_{s_k^t \in S^t} \theta\left(s_k^t \mid a\left(s_k^t\right)\right)\left[P\left(Q\left(t, s_k^t\right)\right) q_i(\cdot) - C_i\left(q_i(\cdot)\right) - F_i(I_i(\cdot))\right]$$

subject to capacity accumulation and

$$q_i\left(t, s_k^t\right) \geq 0, \quad I_i\left(t, s_k^t\right) \geq 0, \quad t = 1, \ldots, T, \forall s_k^t \in S^t,$$

Some General Results

Lemma

At any node $s_k^t \in S^t, t = 0, \dots, T$, whenever capacities of the players are symmetric, Nash equilibrium outputs are unique and symmetric.

Lemma

In any set $B\left(s_k^t\right)$, $q_i\left(t+1, d\right) \leq q_i\left(t+1, u\right)$.

Some General Results

Lemma

If at any node $s_k^t \in S^t, t = 0, \ldots, T-1, I_i\left(t, s_k^t\right) > 0$, then in any set $B\left(s_k^t\right)$, player i produces at maximal capacity in the upstate demand case, i.e., $q_i\left(t+1, u\right) = K_i\left(t+1, u\right)$. Further, if $I_i\left(t, s_k^t\right) = 0$, then $q_i\left(t+1, u\right) < K_i\left(t+1, u\right)$.

- This result is an illustration of the good news principle, stipulating that a decision-maker is investing as if the optimistic scenario will materialize in the following period.
- This result will not necessarily hold if we had a large fixed cost or indivisibility of investment.

Lemma

In a symmetric game, in any set $B\left(s_k^t\right)$, $s_k^t \in S^t, t = 0, \ldots, T-1$, if $I_i\left(t, u\right) = 0$ then necessarily $I_i\left(t, d\right) = 0$.

Equilibria in Two-Period Model

Proposition

In the absence of uncertainty, closed-loop Nash equilibrium and open-loop Nash equilibrium investments coincide.

- Closed-loop and open-loop Nash equilibrium state vectors at each stage coincide. Rollback solution is identical to the forward solution.
- Alternatively, as the investment cost is sunk for the second period and the effect of investment is to provide an upper bound for the production level, the two types of equilibria coincide in the two-period model with deterministic demand.
- Result holds for any given initial production capacities, and in particular for equal ones.

Equilibria in Two-Period Model

- Switch to a stochastic demand (i.e., $\tilde{\xi} > 0$).
- In period 1, the production capacity is the same in both states u and d. We simplify the notation: $K_i\left(1, s_k^1\right) = K_{i1}$ and $I_i\left(0, s^0\right) = I_{i0}$.
- Depending on the model parameters' values, different cases may arise, namely:
  - Case 1: $I_{i0} = 0$ and (by Lemmas 2 and 3) $q_i\left(1, d\right) < q_i\left(1, u\right) < K_{i1}$.
  - Case 2: $I_{i0} > 0$ and $q_i\left(1, d\right) < q_i\left(1, u\right) = K_{i1}$.
  - Case 3: $I_{i0} > 0$ and $q_i\left(1, d\right) = q_i\left(1, u\right) = K_{i1}$.

Equilibria in Two-Period Model

Assumption A1: $K_{i0} = K_{j0} = K_0$, $i \neq j$, and $I_{i0} > 0$, $i = 1, 2$.

Proposition

Under assumption A1 and if $q_i(1, d) < q_i(1, u) = K_{i1}$, *then*

1. *Symmetric S-adapted open-loop (OL) and closed-loop (CL) Nash equilibrium investments are given by*

$$I_{i0}^{OL} = \frac{\delta p (1 + \xi - c - 3K_{i0})}{f + 3\delta p} > I_{i0}^{CL} = \frac{\delta p (1 + \xi - c - 4K_{i0})}{f + 4\delta p}, \quad i = 1, 2.$$

2. *The equilibrium profits compare as follows*

$$\pi_i^{OL} < \pi_i^{CL}, \quad i = 1, 2.$$

3. *An asymmetric equilibrium in investment strategies is not possible.*

Equilibria in Two-Period Model

Corollary

Under assumption A1 and assuming $q_i(1,d) = q_i(1,u) = K_{i1}, i = 1,2,$ *then*

1. *Symmetric S-adapted open-loop (OL) and closed-loop (CL) Nash equilibrium investments are given by*

$$I_{i0}^{OL} = \frac{\delta\left(1-\xi-c-3K_{i0}+2p\xi\right)}{f+3\delta} > I_{i0}^{CL} = \frac{\delta\left(1-\xi-c-4K_{i0}+2p\xi\right)}{f+4\delta}$$

2. *The equilibrium profits compare as follows*

$$\pi_i^{OL} < \pi_i^{CL}, \quad i = 1,2.$$

3. *An asymmetric equilibrium in investment strategies is not possible.*

Equilibria in Two-Period Model

Assumption 2: Suppose that $K_{i0} < K_{j0}$, and $I_{i0} > 0$, $I_{j0} = 0$, $i \neq j$.

Proposition

Under assumption A2, firm i's OLNE and CLNE investments are given by

$$I_{i0}^{OL} = \frac{\delta p[1 + \xi - c - 3K_{i0}]}{2f + 3\delta p} < I_{i0}^{CL} = \frac{\delta p[1 + \xi - c - 2K_{i0}]}{2f + 2\delta p}.$$

Further,

$$\begin{aligned} \pi_i^{OL} &< \pi_i^{CL}, \\ \pi_j^{OL} &> \pi_j^{CL}. \end{aligned}$$

A Generalization

Proposition

Assume the T stage extension of Assumption 1. For $T \geq 2$ period extension of the game, T is finite, equilibrium investment under the open-loop structure is higher than the one under the closed-loop structure; that is $I_i^{OL}(T-1, s_k^{T-1}) > I_i^{CL}(T-1, s_k^{T-1})$ at any node s_k^{T-1} on the event tree.

- Setting is restrictive: equal initial capacities and positive investment at each period. However:

A Generalization

Proposition

Assume the T stage extension of Assumption 1. For $T \geq 2$ period extension of the game, T is finite, equilibrium investment under the open-loop structure is higher than the one under the closed-loop structure; that is $I_i^{OL}(T-1, s_k^{T-1}) > I_i^{CL}(T-1, s_k^{T-1})$ at any node s_k^{T-1} on the event tree.

- Setting is restrictive: equal initial capacities and positive investment at each period. However:
    - The symmetry assumption insures that any difference in the investment strategies is due, and only due, to the information structure.

A Generalization

Proposition

Assume the T stage extension of Assumption 1. For $T \geq 2$ period extension of the game, T is finite, equilibrium investment under the open-loop structure is higher than the one under the closed-loop structure; that is $I_i^{OL}(T-1, s_k^{T-1}) > I_i^{CL}(T-1, s_k^{T-1})$ at any node s_k^{T-1} on the event tree.

- Setting is restrictive: equal initial capacities and positive investment at each period. However:
  - The symmetry assumption insures that any difference in the investment strategies is due, and only due, to the information structure.
  - The investment positivity assumption is not severe in a context where investment is divisible and the cost is quadratic.

Summary

The goal: Characterize and compare OL and CL investment strategies in a dynamic game with a stochastic demand. Assuming (most of the cases) symmetry, the main conclusions are:

- The dynamics of investment is governed by the good news principle, i.e., the players invest in their productive capacities as if the upstate-demand scenario is going to unfold in the next period.

Summary

The goal: Characterize and compare OL and CL investment strategies in a dynamic game with a stochastic demand. Assuming (most of the cases) symmetry, the main conclusions are:

- The dynamics of investment is governed by the good news principle, i.e., the players invest in their productive capacities as if the upstate-demand scenario is going to unfold in the next period.
- The rankings of open-loop and closed-loop investment equilibrium levels depend on initial capacities.

Summary

The goal: Characterize and compare OL and CL investment strategies in a dynamic game with a stochastic demand. Assuming (most of the cases) symmetry, the main conclusions are:

- The dynamics of investment is governed by the good news principle, i.e., the players invest in their productive capacities as if the upstate-demand scenario is going to unfold in the next period.
- The rankings of open-loop and closed-loop investment equilibrium levels depend on initial capacities.
- When investment is positive, then under no circumstances (parameter values) can a player achieve a better outcome in an open-loop equilibrium than in its closed-loop counterpart. This result constitutes a strong defense in favor of the closed-loop information structure.

Old work and work in progress

- European gas market (Zaccour (1986), Haurie, Zaccour, Legrand, Smeers (????), Breton and Zaccour (2001))
  - four suppliers (Algeria, Netherlands, Norway, Russia)
  - six buyers (Belgium-Lux, France, Germany, Italy, Netherlands, UK)
  - 25-year planning horizon
  - control variables: quantities and investments
  - state variables: production capacities and reserves
- Haurie and Zaccour (2006) look at realizations vs predictions: RMSE between 3-9%

Old work and work in progress

- Electricity industry in Finland; 3 players: Fortum, PVO and P3

Old work and work in progress

- Electricity industry in Finland; 3 players: Fortum, PVO and P3
- Forty-year horizon (eight five-year periods)

Old work and work in progress

- Electricity industry in Finland; 3 players: Fortum, PVO and P3
- Forty-year horizon (eight five-year periods)
- Two market segments: Peak load, base load.

Old work and work in progress

- Electricity industry in Finland; 3 players: Fortum, PVO and P3
- Forty-year horizon (eight five-year periods)
- Two market segments: Peak load, base load.
- Two different technologies: Peak load (thermal, renewable,...), base load (hydro, nuclear,...)

Old work and work in progress

- Electricity industry in Finland; 3 players: Fortum, PVO and P3
- Forty-year horizon (eight five-year periods)
- Two market segments: Peak load, base load.
- Two different technologies: Peak load (thermal, renewable,...), base load (hydro, nuclear,...)
- Low, Medium, High growth demand

Old work and work in progress

- Electricity industry in Finland; 3 players: Fortum, PVO and P3
- Forty-year horizon (eight five-year periods)
- Two market segments: Peak load, base load.
- Two different technologies: Peak load (thermal, renewable,...), base load (hydro, nuclear,...)
- Low, Medium, High growth demand
- Non-linear (non-quadratic) investment cost functions

Old work and work in progress

- Electricity industry in Finland; 3 players: Fortum, PVO and P3
- Forty-year horizon (eight five-year periods)
- Two market segments: Peak load, base load.
- Two different technologies: Peak load (thermal, renewable,...), base load (hydro, nuclear,...)
- Low, Medium, High growth demand
- Non-linear (non-quadratic) investment cost functions
- Production costs: linear (base load) and non-linear cost (peak load)

Old work and work in progress

- Electricity industry in Finland; 3 players: Fortum, PVO and P3
- Forty-year horizon (eight five-year periods)
- Two market segments: Peak load, base load.
- Two different technologies: Peak load (thermal, renewable,...), base load (hydro, nuclear,...)
- Low, Medium, High growth demand
- Non-linear (non-quadratic) investment cost functions
- Production costs: linear (base load) and non-linear cost (peak load)
- Constraints...

Old work and work in progress

- Genc et al. (2004, 2007): Ontario electricity industry

Old work and work in progress

- Genc et al. (2004, 2007): Ontario electricity industry
- 3-5 players

Old work and work in progress

- Genc et al. (2004, 2007): Ontario electricity industry
- 3-5 players
- Different technologies, ...

Old work and work in progress

- Closed-loop or feedback strategies

Old work and work in progress

- Closed-loop or feedback strategies
- Different lags (technologies)

Old work and work in progress

- Closed-loop or feedback strategies
- Different lags (technologies)
- Joint (environmental and transportation) constraints