Capacity Expansion

Objectives of Presentation:

- Explore the theory governing economics of capacity expansion (builds on assignment)
- Identify the fundamental tradeoffs
- Illustrate the sensitivity of the results for optimal policy – in deterministic conditions
- Provide a basis for understanding how results will change when future is uncertain

The Issue

- Given a system with known capacity
- We anticipate growth in future years

Year	0	1	2	3	4	5	6	…	N
Demand increase	0	5	10	15	20	25	30	…	5N

- The question is:
  What size of capacity addition
  minimizes present costs ?

Consider "infinite" horizon

- If growth is steady (e.g.: constant annual amount or percent),
- Does optimal policy change over time?

- Policy should not change -- Best policy now should be best at any other comparable time
- If we need addition now, and find best to add for N years, then best policy for next time we need capacity will also be an N year addition
- Best policy is a ***repetitive cycle***

Cost assumptions

- Cost of Capacity additions is:
  - Cost = K (size of addition) ^{a}
  - If a < 1.0 we have economies of scale

- Cost of a policy of adding for N years, C(N), of growth annual growth "Δ" is:
  - Initial investment = $K (N \Delta)^{a}$
  - Plus Present Values of stream of future additions. Value in N years is C(N), which we discount:

$$C(N) = K (N \Delta)^{a} + e^{-rN} C(N)$$

If Constant Returns to Scale

- This means exponent a = 1
- Thus for example

Year	0	1	2	3	4	5	6	…	N
Demand Increase	0	5	10	15	20	25	30	…	5N
Capacity Addition	15			15			15	…	
Proportional Cost	15			15			15	,,,	
Present Value at 10% = C(t=0) + C/r (for period)	15 + 15(/0.33) = 60								

- Present Value for cyclical payments in Excel is:
  = PV(DR over cycle beyond year 0, number of cycles, amount/cycle)

- How does present cost vary over longer cycles?

Optimal policy in linear case

- The general formula for the present value of a series of infinite constant amounts is:

  PV = (Constant Amount)[1 = 1 / (DR over period)]
- In linear case:
  - Constant Amount = K (N Δ)
  - DR over period = N (annual DR)
  - PV = K(N Δ) [1 + 1 / N (annual DR)] =
    = K(Δ) [N + 1 / (annual DR)]
- In this case, contributions of future cycles is irrelevant. Only thing that counts is first cost, which [= f (N Δ)] that we minimize.

Consider diseconomies of scale

- In this case, it is always more expensive per unit of capacity to build bigger – that is meaning of diseconomies of scale
- Thus, incentive to build smaller
- Any countervailing force?

- No !
- In this case, shortest possible cycle times minimize present costs

… and economies of scale?

- Economies of scale mean that bigger plants => cheaper per unit of capacity
- Thus, incentive to build larger
- Any countervailing force?

- Yes!
- Economies of scale are a power function so advantage of larger units decreases, while they cost more now
- Best policy not obvious

Manne’s analysis

- **Alan Manne developed an analytic solution for the case of constant linear growth**

- **Reference:**

Manne, A. (1967) <u>Investments for Capacity Expansion: Size, Location and Time-phasing</u>, MIT Press, Cambridge, MA

Here’s the picture (from Manne)

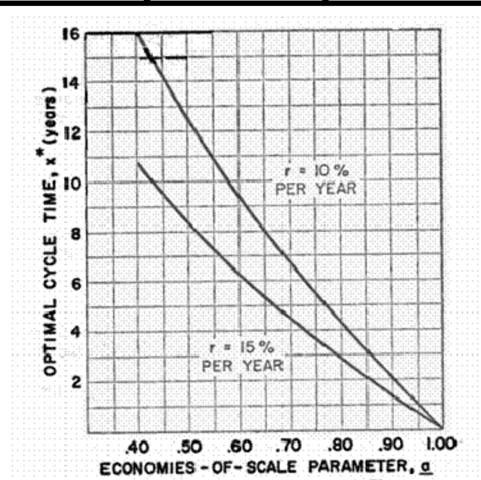


Figure 2.4.—Cross-Plot for Optimal Cycle Time

Design implications

- For industries with Economies of Scale, such as electric power, chemical processes
- For conditions assumed (constant steady growth forever) …
  - Small plants (for small N) are uneconomical
  - Optimum size in range of between 5 and 10 years
  - Corresponding to maybe 30 to 50% expansion
  - Results not especially sensitive to higher N
  - Which is good because forecasts not accurate.

What if assumptions wrong? (1)

- Growth assumed "for ever" …
- Is this always so?

- Not always the case:
  - Fashion or technology changes
  - Examples –
    - Analog film -- once digital cameras came in
    - Land lines – once everyone had cell phones

Optimal policy if growth stops

- What is the risk?
- Building capacity that is not needed

- What can designer do about it?
- Build smaller, so less reliance on future

- What is the cost of this policy?
- Tradeoff: extra cost/unit due to small plants, vs. saving by not paying for extra capacity

What if assumptions wrong? (2)

- Growth assumed steady…(no variability)
- Is this always so?

- Generally not correct.
  - Major economic cycles are common
  - Examples:
    - Airline industry
    - Consumer goods of all sorts
    - Industrial products….

Optimal policy if growth varies

- What is the risk?
- Building capacity not needed for long time

- What can designer do about it?
- Build smaller, more agile response to future

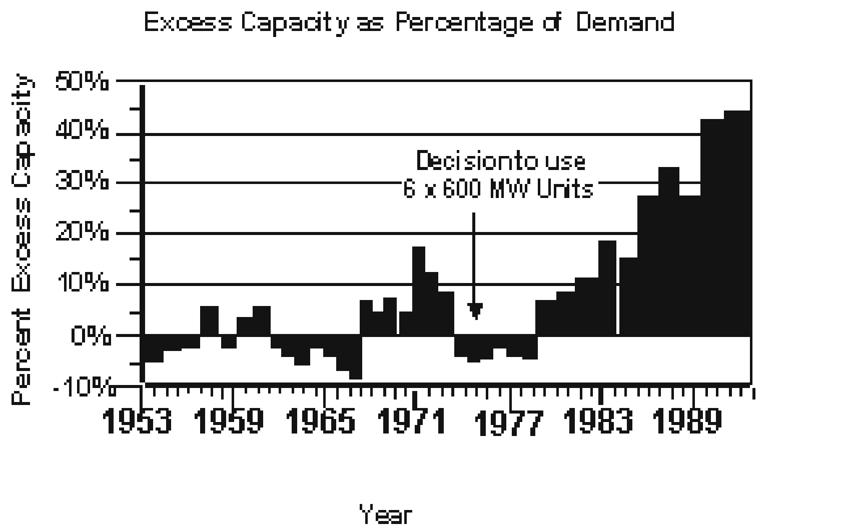
- What is the cost of this policy?
- Tradeoff: extra cost/unit due to small plants, vs. saving by not paying for extra

Example: Power in S. Africa

- Eskom, power generator for South Africa, adopted Manne's model in mid-1970s
- They committed to units of 6 x 600 MW
- This led them to over 40% overcapacity within 15 years – an economic disaster!

- Aberdein, D. (1994) "Incorporating Risk into Power Station Investment Decisions in South Africa, S.M. Thesis, MIT, Cambridge, MA.

Expansion of Established Industry
Power Station Investment in South Africa



Why did oversupply persist?

- Build up of oversupply was not sudden, lasted over a decade
- Why did system managers let this happen?
- Not clear. Some likely explanations:
  - Managers committed to plan – thus it was too shameful to admit error of fixed plan
  - They had locked themselves in contractually – no possibility to cancel or defer implementation
- In any case, system was inflexible

What could have been done?

- They would have been better off (less unnecessary or premature construction) if they had:
  - not committed themselves to a fixed plan, but had signaled possibility of change
  - contractual flexibility to cancel orders for turbines, defer construction (they would have had to pay for this, of course)
  - Planned for smaller increments
- In short, they should have been flexible

General Cap. Expan. Problem

- How should system designers "grow" the system over time?
- Main tensions:
  - For early build – if economies of scale
  - For delays –
    - defer costs, lower present values
    - resolution of uncertainties
- Need for flexible approach

Summary

- Capacity Expansion Issue is a central problem for System Design
- Deterministic analysis offers insights into major tradeoffs between advantages of economies of scale and of deferral
- In general, however, the uncertainties must be considered
- A flexible approach is needed
  - How much? In what form?
- This is topic for rest of class

Appendix

- Details on Calculations and results from Alan Manne
- These replicate what you found in homework exercise (optimal capacity expansion)

Applications of M's Analysis

- Still widely used
- In industries that have steady growth
- In particular in Electric power
- See for example

- Hreinsson, E. B. (2000) "Economies of Scale and Optimal Selection of Hydropower projects," Proceedings, Electric Deregulation and Restructuring of Power Technologies, pp. 284-289.

Details of Manne's analysis (1)

- Cost of Stream of replacement cycles is:

$$C(N) = K (N \Delta)^a + e^{-rN} C(N)$$

- Thus: $C(N) = K (N \Delta)^a / [1 - e^{-rN}]$

- This can be optimized with respect to N, decision variable open to system designer

Details of Manne's analysis (2)

- It's convenient to take logs of both sides

  $\log [C(N)] = \log [K (N \Delta)^a] - \log [1 - e^{-rN}]$

  $= \log [N^a] + \log [K (\Delta)^a] - \log [1 - e^{-rN}]$

  $d(\log [C(N)]) / dN = a/N - r / [e^{-rN} - 1] = 0$

- So: $a = rN^* / [e^{-rN^*} - 1]$
- Optimal cycle time determined by (a, r)
  -- for assumed conditions

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Key results from Manne

- There is an optimal cycle time…
- It depends on
  - Economies of scale: lower "a" ➔ longer cycle
  - Discount rate: higher DR ➔shorter cycle
- It does not depend on growth rate!
- Higher growth rate ➔ larger units
- However, this is driven by cycle time
  Capacity addition = (cycle time)(growth rate)

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Graphical View of Results

- **Manne's present costs versus cycle time**
  - **steep for small cycle times**
  - **quite flat at bottom and for larger cycle times**
- **See following figure…**
- **What are implications?**

Sensitivity of results (Manne)

- **Total Cost vertically**
- **Cycle Time, N, horizontally**
- **Optimum is flat, around 6.75 years for a = 0.7 and r = 0.1 = 10%**

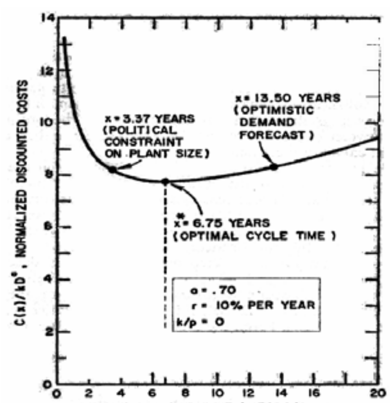

Figure 2.6.—Discounted Cost Function