SCALE AND PROCESS INNOVATION: THE ADOPTION OF THE BASIC OXYGEN PROCESS BY CANADIAN STEEL FIRMS

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PREFACE

At the workshop on "Size and Productive Efficiency--The Wider Implications" held by the Management and Technology Area at IIASA in June 1979, one of the major topics of discussion was the relationship between scale and innovation, in particular the way in which the development and adoption of innovations are influenced by the size of the organization. It was, for example, suggested that for major process innovations there was an optimum organization size: not too small that there is an insufficient diversity of managerial experience, and not too large that there is bureaucratic rigidity and lack of common purpose.

However, rather than seeking an explanation in terms of organization behavioral characteristics it seems reasonable to first look for explanations which focus on the technical and economic characteristics of the competing processes. In this paper a specific major process innovation--the adoption of the basic oxygen process in steel making--is examined within the context of the decisions on timing, size and choice of process made by Canadian steel firms. A model of "rational" investment planning is used to evaluate the actual decisions and gain insight into the technical, economic and market factors which appear to support the proposition that there is an optimum "niche" for the introduction of major process innovations.

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INTRODUCTION

Economists have long been concerned with the process of technical change: the development, adoption and diffusion of innovations in products and processes. However, while a wide variety of theories have been proposed, their ability to predict the pattern of adoption and diffusion still seems to be rather limited. In part this is because the theories view the process of technical change from a macro perspective, either by estimating the rate of change of coefficients in production functions or by using general models of diffusion adapted from physical and biological sources. While perhaps adequate to describe the overall process of technical change in an economy, these theories do not give an adequate understanding of the process in the case of specific innovations.

The approach adopted in this paper is to both observe and model a specific process innovation, the replacement of the open hearth furnace by the basic oxygen furnace in the steel industry. First of all we describe the historic replacement process, the sequence of decisions on choice of process, size of unit and timing, in the specific context of the three major integrated steel producers in Canada. Significant differences in their behavior are observed. We then ask the question: can the behavior of each firm be explained by assuming that each firm made rational decisions on the basis of the technical and cost characteristics of the alternative processes and its expectations concerning future demand for steel? The differences in behavior are then primarily due to differences in commitment to the old technology (open hearth) at the time the new technology became available, initial technical limitations in the new technology and differences in size of firm and growth rate of demand.

In order to investigate this hypothesis a simplified decision model to represent the main factors involved in each decision of a firm is developed. The properties of the model are explored and the degree of success in predicting actual behavior is discussed. Finally the policy implications of the results are discussed.

The work described in this paper was carried out as part of the research task "Problems of Scale" in the Management and Technology Area at IIASA. It will be seen that the difference in scale characteristics of the technologies plays a signficiant role in the process of change. It is fortunate that there is information available on the scale characteristics of the two technologies--there are few other industries where such data is available.

1. THE SEQUENCE OF DECISIONS BY CANADIAN STEEL FIRMS

The basic oxygen process (BOP) was developed in Austria following World War II. The first commercial sized plants were installed in late 1952 in Linz and in 1953 in Donawitz, in both cases using 35 ton capacity vessels. The first Canadian plant, two 40 ton vessels in Dominion Foundries and Steel Ltd (DOFASCO), was authorized in 1953 and began operations in 1954. It was one of the first two plants outside Austria so, at least as far as the Canadian steel industry was concerned, there was very little delay in developing an awareness of the process. STELCO (The Steel Company of Canada Ltd) is located approximately one mile away from DOFASCO in Hamilton, Ontario and the level of commercial security in Canadian steel firms is such that it would have been fully aware of DOFASCO's plans. ALGOMA (The Algoma Steel Company Ltd) is located in Sault Ste. Marie, 400 miles from Hamilton and it is also unlikely that it would not have known of DOFASCO's decisions.

Table 1 lists the subsequent decisions on steel making process made by each of the three firms over the period 1953-1978. STELCO operates non integrated steel plants in Western Canada, using scrap fed electric furnaces. These decisions have been omitted from the table as their impact on decisions at the Ontario locations (Hamilton and Nanticoke) was probably minimal.

It will be noted that only STELCO still had open hearth capacity at the end of the period. ALGOMA closed down its last open hearth furnaces in 1973 while DOFASCO closed down its last open hearth furnace in 1960.

Table 2 shows the production of crude steel by each of the firms over the period 1951 to 1976 at five year intervals. It will be noted that there are significant differences in growth rates of different producers at different times. This is in part due to the relative growth of markets for different categories of steel. DOFASCO specialized in flat products and over most of the period this sector showed strong growth, linked to the growth of the automobile industry, particularly following

Table 1. Additions and retirements of steel making plant 1950-1978

Year	Decision	Start-up (shut down)
Steel Company of Canada Ltd		
1950	4 x 275 ton open hearth furnaces in No. 3 open hearth shop	1952
1959	1 x 400 ton open hearth in No. 3 open hearth shop	1961
	Equiping open hearth furnaces for volume oxygen	1961
1968	3 x 140 ton furnaces in No. 1 BOP plant	1971
	Closure of No. 2 open hearth plant	(1971)
1973	2 x 250 ton furnaces at Nanticoke (BOP)	1979-80
Dominion Foundries and Steel Ltd		
1953	2 x 40(50) ton furnaces in No. 1 BOP plant	1954
1955	1 x 50 ton furnace in No. 1 BOP plant	1956
1959	Enlarge 50 ton furnaces to 105 ton in No. 1 BOP plant	1960
	Closure of open hearth plant	(1960)
1965	Enlarge 105 ton furnaces to 150 tons in No. 2 BOP plant	1967-71
1974	2 x 280 ton furnaces in No. 2 BOP plant	1978
Algoma Steel Company Ltd		
1950	2 x 300 ton furnaces in No. 2 open hearth shop	1953
	Enlarge 4 x 135 ton furnaces to 4 x 165 in No. 2 open hearth	1954
1956	2 x 80(105) ton furnaces in No. 1 BOP shop	1958
	Closure of No. 1 open hearth	(1958)
1959	Enlarge No. 2 open hearth furnaces to 2 x 360 and 4 x 180	1959-61
1961	1 x 105 ton furnace in No. 1 BOP shop	1964
1965	2 x 260 ton furnaces in No. 2 BOP shop	1973
	Closure of No. 2 open hearth shop	(1973)

Note: Capacity of BOP vessels are those on start-up. Capacities in brackets are eventual capacity.

Sources: Schell (1979) from annual reports of companies; Ess (1964) and Kotsch (1979).

Table 2. Crude Steel Production by Major Canadian Steel Companies, 1951-76

Company	Crude steel production (million tons)						Share in national output (%)					
	1951	1956	1961	1966	1971	1976	1951	1956	1961	1966	1971	1976
STELCO	1.26	2.37	2.45	3.79	4.67	5.72	35.3	44.7	37.8	37.8	39.1	38.9
DOFASCO	.35	.63	1.13	1.88	2.47	3.34	9.8	11.9	17.4	18.8	20.7	22.7
ALGOMA	.79	1.10	1.65	2.35	2.36	2.89	22.1	20.8	25.4	23.5	19.7	19.6
Total of 3 largest	2.40	4.10	5.23	8.02	9.50	11.95	76.2	77.4	80.6	80.0	79.4	81.3
Others	1.17	1.20	1.26	2.00	2.46	2.74	32.8	22.6	19.4	20.0	20.6	18.7
Total	3.57	5.30	6.49	10.02	12.20	14.69	100.0	100.0	100.0	100.0	100.0	100.0

Source: Schell (1979) from
-- The Steel Company of Canada, Limited. Annual Report, various issues.
-- Dominion Foundries and Steel, Limited. Annual Report, various issues.
-- Algoma Steel Corporation, Limited. Annual Report, various issues.
-- Statistics Canada, Primary Iron and Steel. Cat. no. 41-001.

the signing of the auto pact with the US in 1964 which provided free trade in automobiles and parts between the US and Canada subject to certain conditions making it attractive for automobile assembly plants located in southern Ontario to be expanded. ALGOMA had, until 1952, specialized in structural steel and while it entered the flat products market, was in a somewhat unfavorable location to complete with DOFASCO and STELCO in supplying the automobile industry. The long period of depressed demand for structural steel which followed EXPO in 1967, together with the inroads of Japanese competition in Western Canada, accounts for the low growth of ALGOMA in the late 1960's.

There are a number of features of the decisions on steel making process which are worthy of comment.

Slow adoption of BOP by STELCO. Note that STELCO did not adopt the BOP process until 1971, 17 years after DOFASCO. As pointed out above this cannot have been due to lack of awareness of the BOP process. Note also that STELCO even installed open hearth capacity as late as 1961.

Two stage expansion. With the exception of STELCO's first BOP plant each firm built a two furnace plant initially, then expanded it by adding a third furnace some years later.

DOFASCO's expansion by rebuilding. During the 1960's DOFASCO expanded capacity by rebuilding, that is by replacing existing furnaces by larger furnaces. This was done in several stages, 50 ton furnaces were replaced by 105 ton furnaces and these in turn by 150 ton furnaces. Neither of the other producers used this approach for their BOP plants. However, they did at times rebuild open hearth furnaces, increasing capacity by 10% or so each time.

Poor markets affect timing not size. The steel industry is characterized by variations in demand related to the business cycle. There is a tendency to authorize expansion projects during periods of strong demand and to cancel, defer or delay them during periods of weak demand. For example ALGOMA's No.2 BOP plant was authorized in 1965, construction ceased in 1968, then resumed in 1970 and was completed in 1973. However, the size of plant was not affected by this delay. Similarly, STELCO's Nanticoke plant was authorized in 1973 for completion in 1976-77 but in 1975 when markets were poor construction was slowed down with completion planned for 1979-80. Again size of plant was not affected by poorer estimates of market growth.

Expansions primarily self financed. The predominant source of financing for expansion projects is depreciation and retained earnings. Canadian steel companies consider that their debt to equity ratio should not exceed 20% and for most of the period this ratio was around 10-15%. As far as possible it was considered desirable to have a return on equity competitive with other manufacturing firms, i.e., over the period 1965-1974 this implies about 12% although ALGOMA only reached this level in 1965, 1971 and 1974. However, it must be pointed out that

Canadian steel firms have had a return on equity about double that of US steel firms.

The aggressiveness of DOFASCO vs. the cautiosness of STELCO. There is a general feeling that STELCO management is more conservative than DOFASCO's and this would appear to be supported by the slowness of STELCO and the rapidity of DOFASCO in adopting the BOP process. However, since Canadian steel companies have technically competent managers and there appears to be little political and other external influences over their decisions it could be that the behavior of the management of each firm was quite rational in the light of the perceived situation confronting the firm. Furthermore, in the adoption of other innovations, such as continuous casting, there does not seem to have been a significant difference between the behavior of the firms.

2. THE MODEL OF PROCESS CHOICE

The basis of the model of process choice is that firms make decisions on the choice of process and size of plant using a planning approach in which they determine how to meet their expectations of the growth of demand for steel on the basis of the technical and cost characteristics of the available processes and their desired financial objectives.

That is, the firm develops an investment plan for the successive installations of new capacity and retirements of old capacity. The plan covers the period from the present up to some time horizon for planning T years hence. On the basis of this long term plan the firm will then commit itself to the immediate projects. Subsequently, it will revise its investment plan in accordance with changed perceptions on available processes or market growth and only commit itself to new capacity if it is in accordance with the revised plan.

Thus the purpose of the model is to determine the choice and timing of additions and retirements. It is assumed that the firm's objective is to minimize the present worth of the costs related to the investment plan. Selling prices and revenues of the firm are assumed not to be related to the timing and magnitude of the additions and retirements. There is probably sufficient competition and sufficient lack of coordination of investments amongst the Canadian steel firms for this to be a reasonable assumption.

The magnitude of each steel making project and the growth rate of demand is such that it is highly unlikely that a firm would consider building more than one steel making plant of a given process in one year. Thus each plant addition can be identified by the year in which it was built, the type of process and the size of the plant. However, there is some interrelationship between additions. For example, it is common to build a two vessel BOP plant and then add a third vessel to the plant at a future date. The three vessel plant will then operate as a single production unit. This introduces an interdependence between projects which must be allowed for.

All steel making processes are discontinuous. That is, steel is made in some vessel of capacity G tons and a batch of size G is produced at periodic intervals. Thus the "size" of a plant can be identified by the number of vessels and their capacity in tons or the maximum possible output of the plant in tons per year. Over time a given plant will change its capacity. For example, there may be improvement in operating practices which will reduce the mean time between the production of successive batches or alternatively, by minor rebuilding and adjustments the capacity of each vessel in tons can be increased. It will be assumed that firms do not allow for the automatic occurrence of such improvement. However, in so far as the capacity of existing plant affects their decisions it will be assumed that they base their decisions on the present actual capacity (the results of this improvement having occurred in the past).

Thus a given investment plan will show, for each year from now to the planning horizon

- the amount of capacity of each process to be added in each year,
- which units of plant are to be retired in each year,

together with information required to identify interdependencies between additions, retirements and existing capacity.

To evaluate the investment plan the firm will require the following information

- the capital cost of each plant addition
- the total operating cost in each year for producing the required production from the plant available in that year
- the cost of each plant retirement.

The nature of these costs will be discussed in the next section. In some cases it may also be appropriate to include depreciation, this is also discussed in the next section.

It must be pointed out that the evaluation of the investment plan requires a further set of sub-problems to be solved: how to allocate the required production in a year to the different units of plant and hence determine the total operating cost. When there are a variety of units of plant and processes available some units are more suitable to certain metallurgical requirements or order sizes than others. However for investment planning purposes it will be assumed that this allocation will be done so as to minimize the variable costs of production. That is the units of plant are ranked so that $v_1 < v_2 < \ldots < v_n$ where v_i is the variable cost per ton of plant unit i, Then if x_i is the capacity of plant unit i and P the total required production, then the production of plant unit i will be given by

$$P_i = \min\left(P - \sum_{k=1}^{i-1} P_k,\ x_i\right)$$

and the total variable costs of this allocation

$$V(P) = v_1 P + \sum_{i=2}^{n} (v_i - v_{i-1}) \max\left(0, P - \sum_{k=1}^{i-1} x_k\right) \quad .$$

Such an allocation of production may not minimize total operating costs if the fixed operating costs associated with each plant unit do not follow the same ordering as the variable operating costs. When demand is low it may be possible to termporarily shut down plant units and avoid the fixed operating costs. However, since open hearth plants have both a higher fixed operating cost and higher variable operating costs than BOP plants the above allocation will be reasonable if a firm has both types of plant. The electric furnace has a lower fixed operating cost and a higher variable operating cost but it is unlikely that a firm with a mixture of electric furnaces and the BOP could operate without any BOP in service.

The formulation of the basic model is given in appendix 1 and a dynamic programming version is presented.

If no plant retirements are permitted the model is similar to models of capacity expansion due to Manne (1961) and Erlenkotter (1967). Thus some key results can be obtained using the properties of the optimal solutions for their models.

It will be assumed that the required production is known, thus there is no consideration of uncertainty concerning future demand. It is also assumed that the firm must meet the required demand from its own facilities. That is, no imports or purchases from other firms are permitted.

3. COSTS OF ALTERNATIVE STEEL PRODUCTION PROCESSES

The source of the data on alternative steel production process is Schenck (1970). This book gives detailed costs for the major steel production processes (BOP, open hearth, electric furnace) for FRG as of mid 1968.

Each of the cost components will be reviewed and then the question of their applicability to Canadian conditions will be discussed.

3.1 Cost of Plant Additions

As mentioned above the cost of a unit of plant with a given production capacity is determined by two factors:

(i) the capital cost of building a plant using process j which consists of m vessels each of size G tons
(ii) the maximum production which can be achieved from the plant which uses process j and has m vessels each of size G tons. This is influenced by the number of vessels which can operated simultaneously and the time between the production of successive batches of steel from an operating vessel.

Schenck gives sufficient data so that it is possible to determine the capital cost of a plant using process j of m vessels each of size G tons in the form:

$$k(m,G,j) = c^1(m,j)\ G^{a(m,j)} \quad .$$

Alternatively, a linear model can be fitted to the data

$$k(m,G,j) = d(m,j) + b^1(m,j),G \quad .$$

Over the range of plant sizes for which data is given in Schenck the difference between the power law and linear model is small. However outside the range there can be larger differences. In this study the power law model will generally be used.

Table 3 shows the values of the parameters $c^1(m,j)$, $a(m,j)$; $d(m,j)$,$b^1(m,j)$ when G is in tons and $k(m,G,j)$ in million of DM.

It will be noted that the BOP process is characterized by a significantly lower value of $a(m,j)$ than the other processes, indicating higher economies of scale. However, it must be pointed out that the costs on which table 3 are based are the sum of various cost components and not all cost components show the same scale characteristics.

In particular, for the open hearth process with two ovens

Buildings, foundations and steel work cost = $.059\ G^{1.07}$

Remaining costs = $1.35\ G^{.55}$

and if G = 300 tons the building, foundation and steel work cost is 45% of the total cost.

It seems to be typical of all the processes that there is very little economy of scale in the buildings, foundations and

Table 3. Coefficients in Formulae for Capital Cost of m Vessel Plant each of Size G tons

(cost in millions of DM)

Process	m	Power law c'(m,j)	a(m,j)	Linear law d'(m,j)	b'(m,j)
BOP	2	4.63	.60	34.5	.37
	3	5.73	.63	43.8	.57
Open hearth	2	0.79	.75	9.2	.16
	4	1.18	.79	13.7	.31
Electric furnace	1	0.46	.77	2.14	.14
	2	0.72	.79	3.40	.24

steel work costs; the economies of scale come from the vessels themselves with an exponent of about 0.50.

The second factor determining the capital cost of a given production capacity is the productivity of process j with m vessels each of size G tons.

Schenck assumes that the times between production of successive batches of steel from an operating vessel are as follows:

BOP	: 40 minutes
open hearth	: 5.67 hours
electric furnace (UHP*)	: 2.6 hours

These data seem to agree with other estimates although the open hearth times assume that that oxygen injection was used, a development which occurred in the 1950's, more or less in parallel with the development of the BOP. STELCO fitted oxygen injection to its open hearth furnaces in 1959 while ALGOMA apparently did not ever use it. Without oxygen injection the above time would be approximately eight to nine hours (Ess 1964:A-13).

*UHP = ultra high power

UHP electric furnaces were not developed until the early 1960's when they started to replace HP furnaces. Schenck has data on HP furnaces but they have not been considered as a process option in this study.

Using these times and making allowance for necessary down times (Schenck 1970:66-120) it is possible to determine the relationship between capital cost and annual production capacity

$$k(m,P,j) = c(m,j)\ P^{a(m,j)}$$

or

$$k(m,P,j) = d(m,j) + b(m,j) \cdot P$$

where $k(m,P,j)$ is in millions of DM and P in millions of tons per year.

Table 4 gives the values of the various parameters.

It should be noted that with the BOP process the production capacity of a three vessel plant in which two vessels are operating (3/2 plant) is double the production capacity of a 2/1 plant. Thus it is cheaper to expand a two vessel plant to three vessel plant rather than construct a new plant.

Table 4. Coefficients in Formulae for Capital Cost of m Vessel Plant with Production Capacity of P million tons per Year

(cost in millions of DM)

Process	m	Power law c(m,j)	Power law a(m,j)	Linear law d(m,j)	Linear law b(m,j)
BOP	2(1 operating)	62.9	.60	34.5	28.7
	3(2 operating)	57.1	.63	43.8	22.1
Open hearth	2	68.3	.75	9.2	62.8
	4	76.9	.79	13.7	58.8
Electric furnace	1	40.3	.77	2.14	44.5
	2	39.8	.79	3.40	39.0

For the purposes of this study it will be assumed that the cost of the expansion of the 2/1 plant to a 3/2 plant by adding a third vessel of the same size as the existing two vessels so that the expanded plant has capacity P is

$$k(2 \rightarrow 3,P,BOP) = c(3,BOP)\ P^{a(3,BOP)} - c(2,BOP)(P/2)^{a(2,BOP)}$$

which is usually about 50% of the cost of the initial 2/1 plant.

It will be noted that the cost of building a two vessel open hearth shop to meet a given constant demand P will be less than the BOP or electric furnace only if P is in the range 400,000 < P < 750,000 tons per year (using the linear cost model.

3.2 Operating Costs

Schenck has an extensive discussion of the operating costs of the different processes. Many components of operating cost, such as energy or oxygen are dependent solely on the production rate. However, other components are dependent on the capacity of the plant.

In particular, it would appear that the labor costs of a plant using process j and consisting of m vessels each with capacity G tons are dependent solely on m and j and independent of the production rate and G. In the case of integrated steel plants the steel production process is linked with other continuous processes (iron making, finishing) and hence it is necessary to use three shift operation. It is only in the case of scrap fed electric furnaces that it is customary for the plant to close down over weekends or, during the start up phase of its life, operate only for one shift.

Thus it will be assumed that the operating costs of an m vessel plant for a given process are made up of the following components:

v_j variable operating cost (millions of DM per million tons produced)

L_{mj} annual labor cost (millions of DM).

Table 5 shows the values of v_j and L_{mj}.

On the basis of the costs v_j, index 1 will be used to denote the BOP, index 2 the open hearth and index 3 the electric furnace.

Not included in these operating costs are the repair costs. Schenck assumes that repair costs per year amount to 3% of the capital cost of the plant.

Table 5. Operating Costs of the Various Processes

Process	m	v_j (DM per ton)	L_{mj} (millions of DM per year)
BOP	2	25	5.2
	3	25	7.0
Open hearth	2	41	5.6
	4	41	9.2
Electric furnace	1	74*	3.3
	2	74*	4.7

* of which electricity is 30 DM per ton at a price of 0.055 DM/KWh.

It must be noted that the operating costs do not allow for differences in the costs of the hot metal:scrap mixture input to the process. Typical Canadian practice has been to have hot metal:scrap ratio as 75:25 for the BOP and 55:45 for the open hearth. Electric furnaces usually have 100% scrap input.

Although scrap prices declined over most of the period 1953 to 1978 (although showing considerable short term fluctuations), this appears to be associated with reductions in the cost of hot metal due to reductions in the price of iron ore delivered to the plant (see Manners 1971) and improvements in blast furnace operation and raw materials preparation. Since there is no data available on the cost of hot metal to the firms, it is not possible to assess how much is the difference, if any, in the raw materials cost. Since some substitution of scrap for hot metal is possible in the open hearth, yet the North American hot metal:scrap ratio has shown no significant change over the period it is unlikely that, at least as between the open hearth and the BOP there was a significant difference in input materials cost (cf. Meyer and Herreyat 1974:60). However, the cost of scrap input for electric furnace plants may have been less (up to $3).

3.3 Depreciation

Assuming the plant investment is made out of the firm's own cash resources the only other cost to be considered is depreciation. Insofar as depreciation is just an accounting charge there is no cash flow associated with it, however since depreciation reduces the taxable profits of the firm and hence the firm's tax liability there is a cash flow to the firm amounting to the saving in tax.

That is, if D is the depreciation provision in a given year and t the tax rate of the firm there is a net cash flow of -tD. Since t will be affected by whether or not the firm is profitable in the year the estimation of the effect of depreciation can become complex.

There have been a number of changes in the tax laws over the period 1953-1978 and it has not been possible to come up with a reasonable treatment of depreciation, in particular to determine the cash flow and tax effects of plants being scrapped prior to their depreciated book value becoming negligible.

If the firm used the declining balance method to calculate depreciation the value of the plant at age ℓ would be $K\beta^{\ell}$ where K is the initial cost and $(1 - \beta)$ the depreciation rate. The depreciation cash flow is then $-t(1 - \beta)K\beta^{\ell}$ and with a discount factor of α the present worth (for an infinite life) is thus $-t(1 - \beta)K/(1 - \alpha\beta)$.

For typical values of t (40 to 50%) and $1/(1 - \beta)$ (15 to 20 years) the present worth of depreciation and repair costs are approximately equal. Thus repair costs and depreciation have been ignored in the models.

3.4 Applicability of Cost Data

The cost data given in Schenck applies for FRG in mid 1968. Thus the question arises: to what extent are they applicable to Canadian conditions over the period 1953 to 1978?

First of all, it must be recognized that as far as the models are concerned it is not the absolute value of the costs that matters but the relative value. Thus if all cost components are affected equally by inflation and changes in exchange rates then none of the results will be affected.

Schenck based his labor cost calculation on a labor cost per hour of 8.1 DM or approximately \$2.3 at the then exchange rates. In mid 1968 the average hourly earnings of Canadian steel company employees was \$3.3 (Wittar 1968).

Thus at that time Canadian labor costs were approximately 50% greater than the FRG. It is probable that many components of capital and operating cost would have also been in this ratio, the only cost where there was probably a significant relative difference was the cost of electricity. Schenck assumed a cost of .055 DM/kwh or about 1.4 cents/kwh. Ontario costs at that time would have been about 0.6 cents or so. Thus it is likely that the relative costs of the open hearth and BOP under Canadian conditions were similar to the FRG but the relative operating cost of the electric furnace was significantly less.

The major factor which would limit the applicability of the data to the whole of the period is the impact of significant changes and improvements in the processes. Thus UHP electric furnaces were not available prior to the early 1960's and not using oxygen injection in open hearths would increase the capital cost for a given production capacity (although its effect on their operating cost would be insignificant).

However, the assumption that the FRG cost data can be used to determine Canadian decisions will be discussed in the context of specific decisions.

4. GENERAL RESULTS

The results will be presented in three parts. In this section results are obtained for the optimal decisions of a hypothetical steel firm confronted with an arithmetic increasing demand of g million tons per year. These results make various assumptions concerning the available choice of process, initial capacity, whether or not plant retirements are permitted, etc. These results enable some general features of the optimum decision to be seen.

In section 5 the effect of the introduction of a new process option is considered. It is assumed that the hypothetical steel firm has only open hearth capacity at the time the BOP process becomes available. The optimum process of introduction of the new technology is then considered, and in particular the way this process is affected by the limited experience and development of the new process.

Finally in section 6 the actual decisions of each steel firm are compared with the general results in order to see the extent to which the general results predict the behavior of the firms.

4.1 Assumptions

Results will be derived for values of g equal to 0.05, 0.10 and 0.20 million tons per year. These three values cover the range of historical growth rates of the three firms considered. Some results will also be given for growth rates of 0.02 and 0.40 million tons per year.

A key parameter is the discount factor α. This is assumed to be 0.85 throughout. This is consistent with the firms desired return on investment of 12 to 15% (Schell 1979).

Because of the assumption that labor costs are independent of production rate the appropriate way to allow for them is to set the cost of an addition of m vessels of process j and with capacity P as

$$L_{mj}/(1 - \alpha) + c(m,j)P^{a(m,j)} \quad .$$

That is, capital costs are increased by the present worth of labor costs.

The time horizon will be taken to be very large. In practice this means that the results are generally unaffected if T is more than 30 years.

In this section it will be assumed that there is neither an upper nor lower limit on the size of plant that can be built for any process. Some of the results imply plant sizes which would not be considered feasible.

4.2 Only One Process Can be Used--No Retirements

Manne's results on capacity expansion demonstrate that the optimal plan consists of equal sized additions installed when the surplus capacity is zero.

The optimum time between additions for an m vessel plant of process j when the demand growth is g is found by determining the minimum present worth of the capital and fixed operating costs, i.e.,

$$f(m,g,j) = \min_{\tau} \{(L_{mj}/(1 - \alpha) + k(m,g\tau,j))/(1 - \alpha^{\tau})\} \quad .$$

Table 6 shows the optimum value of τ and the present worth of the optimal plan for each process for the different values of g. Also shown on table 6 are the optimum values of τ and the present worth of two step expansion plans for the BOP and the electric furnace. That is, in the case of the BOP the first step is building a 2/1 plant while the second step at time τ later is the addition of a third vessel so the plant becomes a 3/2 plant with double the production capacity. The next expansion would be another, unrelated, 2/1 plant at time 2τ.

The optimum value of τ is found from

$$\begin{aligned} f(2 \to 3,g,1) = \min_{\tau} \{ & [L_{21}/(1 - \alpha) + k(2,g\tau,1) \\ & + \alpha^{\tau}((L_{31} - L_{21})/(1 - \alpha) + k(2 \to 3,2g\tau,1))] \\ & /(1 - \alpha^{2\tau})\} \ . \end{aligned}$$

Table 6. Optimal Expansion Plans Using Only One Process

g	BOP				Open hearth		Electric furnace			
	2/1		2/1 then 3/2		2		1		1 then 2	
	τ	PW	τ	PW	τ	PW	τ	PW	τ	PW
.4	8	221	6	190	6	271	6	162	5	146
.2	9	162	6	140	7	184	7	109	6	98
.1	10	121	7	107	9	131	8	77	7	70
.05	12	94	8	84	10	97	10	57	8	52
.02	14	71	10	65	13	71	13	41	10	39

(PW--Present worth in millions of DM of optimal plan, τ--optimal time between expansions (years), g--growth rate in millions of tons per year.)

A similar approach is used for the electric furnace with one furnace built at time 0 and a second furnace built at time τ. In this case most of the benefits of two step expansion are due to the labor costs then only increasing by about 50%.

If a firm were required to choose only one process and had no existing capacity at the time this decision was made then it would be necessary to also consider relative operating costs. That is, it is necessary to add a further term to the present worth of process j of

$$(v_j - v_1) g\ \alpha/(1 - \alpha)^2 \quad .$$

From table 5 it can be seen that $v_j - v_1$ is

open hearth = 16 million DM per million tons
electric furnace = 49 million DM per million tons.

However, as mentioned above, lower electricity prices in Canada almost certainly mean that the relative operating cost differential of the open hearth and electric furnace processes are less than the above. Thus three possible values of $v_3 - v_1$ have been considered, 16, 32 and 48 million DM per million tons.

Table 7 shows the resulting optimum choice of process and size of vessel for each growth rate

From the data of table 6 it can be seen that there is no positive value of $v_2 - v_1$ such that the open hearth would be preferred to the BOP for growth rates greater than 0.02 million tons per year.

4.3 Mixture of Processes Can Be Used--No Retirements

If the firm has available a mixture of processes then, rather than expanding as soon as the lowest operating cost capacity is fully utilized, it is preferable for it to defer expansion and use some of the higher cost capacity for a while.

The optimum policy can be found using Erlenkotter's model of capacity expansion with imports (Erlenkotter 1967:151). "Imports" in this case means the use of the higher cost process. Erlenkotter shows that the optimum policy with arithmetic growth in demand will consist of equal sized additions.

Suppose sg is the available capacity of the higher operating cost process j. Then if all capacity additions use the lowest operating cost process 1 then the optimum time between additions can be found from (cf. Erlenkotter 1967:159)

Table 7. Optimal Process and Vessel Size If Only One Process Is Used and No Retirements

g	Process	Vessel size tons	Sequence	
.4	BOP	200	Staggered:	2 vessels then third
.2	BOP	100	"	"
.1	BOP	60	"	"
.05	Electric furnace	130	Staggered:	1 vessel then second
.02	Electric furnace	65	"	"

$$f(m,s,g,1) = \min_{\tau, s' \leqslant s} \{[(v_j - v_1)\frac{g\alpha}{1-\alpha}(\frac{1-\alpha^{s'}}{1-\alpha} - s'\alpha^{s'})$$
$$+ \alpha^{s'} (L_{m1}/(1-\alpha) + k(m,g\tau,1))]/(1-\alpha^{\tau})\}$$

where $f(m,s,g,1)$ is the present worth of the optimal plan from an instant when the total capacity of process 1 and demand are equal.

Table 8 gives some results for 2/1 BOP plants for various values of s, g and $v_j - v_1$. If s is sufficiently large there is an optimum value of s' for given τ given by (Erlenkotter 1967: 159)

$$s' < \frac{(1-\alpha)(L_{m1}/(1-\alpha) + k(m,g\tau,1))}{(v_j - v_1)\alpha g} < s' + 1$$

and hence a minimum value of $f(m,s,g,1)$ can be found

$$f(m,I,g,1) = \min_{s>0} f(m,s,g,1) \quad .$$

Table 9 gives the values of gs, τ and $f(m,I,g,1)$ for various values of g and $v_j - v_1$ for expansions using only 2/1 plants, using only 3/2 plants and using step wise expansion, i.e., first a 2/1 plant and then converting it to a 3/2 plant. Erlenkotter's equation for determining the overall cycle time 2τ must then be modified to

$$f(2 \rightarrow 3,I,g,1) = \min_{s} f(2 \rightarrow 3,s,g,1)$$

where
$$f(2 \rightarrow 3,s,g,1) = \min_{\tau, s', s'' \leqslant s} \{[(v_j - v_1)\frac{g\alpha}{1-\alpha}(\frac{1-\alpha^{s'}}{1-\alpha} - s'\alpha^{s'})$$
$$+ \alpha^{s'}(L_{21}/(1-\alpha) + k(2,g\tau,1))$$
$$+ \alpha^{\tau}((v_j - v_1)\frac{g\alpha}{1-\alpha}(\frac{1-\alpha^{s''}}{1-\alpha} - s''\alpha^{s''})$$
$$+ \alpha^{s''}((L_{31} - L_{21})/(1-\alpha) + k(2 \rightarrow 3,2g\tau,1)))]$$
$$\div (1 - \alpha^{2\tau})$$

Table 8. Optimal 2/1 BOP Expansion Policy When Capacity of Higher Operating Cost Plant is sg tons per Year

g	$v_j - v_1$			$v_j - v_1$					
	16 DM/ton			32 DM/ton			48 DM/ton		
	s	τ	PW	s	τ	PW	s	τ	PW
.4	0	8	221	0	8	221	0	8	221
	1	9	195	1	9	203	1*	9	210
	2	9	179	2*	10	198			
	4	11	166						
	5*	12	164						
.2	0	9	162	0	9	162	0	9	162
	1	9	141	1	10	144	1	10	148
	2	10	126	2	10	135	2*	11	144
	4	11	109	3*	11	132			
	6	13	102						
	8*	15	100						
.1	0	10	121	0	10	121	0	10	121
	2	11	92	2	11	97	2	11	101
	4	12	75	4	13	87	3*	12	98
	6	13	66	6*	15	85			
	8	15	61						
	10	17	58						
	14*	21	57						
.05	0	12	94	0	12	94	0	12	94
	4	12	55	4	13	61	4	14	66
	8	15	39	8	17	53	6*	16	64
	12	18	33	10*	19	52			
	16	22	31						
	20	27	30						
	26*	33	30						
.02	0	14	71	0	14	71	0	14	71
	10	15	21	10	18	27	10	20	34
	20	25	13	22*	31	24	13*	23	33
	30	35	12						
	40	46	12						
	60*	66	12						

* for s greater than this value plant addition should occur once production from old capacity reaches this level.

(PW--present worth of optimal policy, τ--optimal time between new plants.)

Table 9. Optimal Policy with Surplus Capacity of Higher Operating Cost Process ($v_j - v_1$ = 16 DM/ton)

g	2/1			3/2			2/1 → 3/2			
	s*g	gτ	f	s*g	gτ	f	s*g	s'g	gτ	f
.4	2.2	4.8	164	2.3	5.2	166	1.9	.8	3.6	153
.2	1.7	3.0	100	1.8	3.4	101	1.5	.6	2.2	96
.1	1.4	2.1	57	1.5	2.3	57	1.3	.5	1.7	56
.05	1.3	1.65	30	1.4	1.75	30	1.3	.5	1.55	30
.02	1.2	1.36	12	1.3	1.44	12	1.2	.5	1.32	12

s*g: maximum production of process j (millions of tons) (in two step expansion--as 2/1 plant installed)
s"g: maximum production of process j as third vessel installed in two step expansion
gτ : optimum BOP plant capacity (millions of tons)
f = f(m,I,g,1): present worth of optimum policy (millions of DM)

4.31 Two Phase Expansion

The reduction in present worth which can be achieved through using the higher operating cost process to defer plant additions suggests that if the firm had no existing capacity of the higher cost process it might still be worth its while installing some. That is, the firm's investment plan would consist of a first phase during which it instals some higher operating cost capacity and then a second phase during which it will only instal the lower operating cost plant but it will use the available higher cost plant to defer additions. Shapiro and Wagner's turnpike expansion theorem suggests that once the firm starts installing the lower cost plant it would never be economical to revert to the installation of the higher cost plant (Shapiro and Wagner 1967).

Let h(s,j) be the cost of the optimal expansion plan whereby sg capacity of process j is installed over a period of s years. That is, the plan may consist of just one plant of capacity sg built at time zero or, alternatively, it could consist of a number of smaller plants with installation staggered over the period s.

Then the present worth of the overall investment plan will be given by

$$f(m,M,g,1) = \min_{s,j} (f(m,s,g,1) + h(s,j))$$

and

$$h(s,j) = \min_n h_n(s,j)$$

$$h_n(s,j) = \min_{1<s'<s,m} h_{n-1}(s',j) + \alpha^{s'} (L_{mj}/(1 - \alpha)$$

$$+ k(m,g(s - s'),j))$$

Table 10 shows the resultant optimal investment plans. It will be noted that at low growth rates it is preferable to instal electric furnace capacity before adding any BOP capacity. If a firm were to follow such an investment plan and had no hot metal capacity (i.e., was not an integrated producer) then the high capital costs of converting to being an integrated producer (e.g., the costs of a blast furnace and coke ovens) would almost certainly delay the transition beyond the point shown in table 9. In fact, it is quite likely that as long as scrap supplies are adequate it may never be justifiable to switch to becoming an integrated producer.

Table 10. Optimal Two Phase Expansion Plans When Only 2/1 BOP Plants are Used in Second Phase

g	$v_j - v_1$		
	16 DM/ton	32 DM/ton	48 DM/ton
.2	2 x 140 ton BOP	2 x 140 ton BOP	2 x 140 ton BOP
.1	staggered installation of 2 x 100 ton EF followed by 2 x 100 ton BOP (4%)*	2 x 80 ton BOP	2 x 80 ton BOP
.05	staggered installation of 2 x 75 ton EF followed by 2 x 60 ton BOP (15%)*	staggered installation of 2 x 50 ton EF followed by 2 x 60 ton BOP (1%)*	2 x 50 ton BOP

* Reduction in present worth through using a two phase policy.

4.4 Retirements Permitted

While the results in the capacity planning literature enable one to say that the expansion policies assumed in sections 4.2 and 4.3 are optimal, there are no general results concerning the characteristics of the optimum expansion plan with retirements permitted.

So the approach has been to assume that the expansion plans have certain features, corresponding to the strategies of the companies considered, and derive the optimum parameters. However, it is possible that more complex expansion plans are preferable.

4.41 Only One Process Can Be Used

Because labor costs are independent of the plant production capacity a strategy such as that followed by DOFASCO in 1953-1966 could be sometimes optimal. That is, plant capacity is expanded by rebuilding, replacing vessels of capacity G by vessels of capacity G'. In practice such a strategy requires careful coordination in order to ensure that continuity of production is achieved and it would be desirable to time the rebuilding to coincide with cyclical down turns in the industry. No data is available for the cost of rebuilding but a somewhat pessimistic assumption would be that it costs as much as the cost of building a new plant. However, the labor cost will not increase.

Thus, if P is the capacity of the existing plant and $P + g\tau$ the capacity of the new plant the cost of the addition will be $k(m,P + g\tau,1)$.

Since $k(m,P + g\tau,1)$ increases with P there will be some value of P such that it will be cheaper to add a new plant rather than expand by replacement. If $f(m,g,1)$ is the present worth of expansion by addition then the critical value of P will be such that

$$f(m,g,1) = \min_{\tau} [k(m,P + g\tau,1) + \alpha^{\tau} f(m,g,1)] \quad .$$

Since expansion by addition would be step wise and expansion by replacement would probably only be used with a 3 vessel shop, the above equation is specialized to

$$f(2 \rightarrow 3,g,1) = \min_{\tau} \left[\frac{k(3,P + g\tau,1)}{1 - \alpha^{\tau}}\right] \quad .$$

The critical value of P is approximately independent of g and is about 850,000 tons.

It is possible to examine the expansion process in more detail. Suppose it is assumed that the firm first builds a 2/1 plant followed by an addition making it a 3/2 plant. Subsequently it replaces and enlarges the 3/2 plant until some size is reached where it is appropriate to begin a completely new plant. Such an expansion plan can be analyzed and the optimum sequence of times between expansions found. However, replacement is only worth using if g is less than .05 and at g equal to .02 the present worth is only 1% less than ordinary two step expansion.

It can be concluded that expansion by replacement is likely to be appropriate only when the size of the first plants built were limited due to technical constraints to values less than the unconstrained optimum. Alternatively it may be appropriate if the growth rate has increased significantly since the time when the existing plant was installed.

4.42 Mixture of Processes

If a higher operating cost process has been used to defer the installation of new capacity then it may be appropriate to retire the higher operating cost plant at the time the new capacity is installed. During the period where there is surplus capacity of the lower operating cost process the higher operating cost process will not be needed. Of course, if possible the higher operating cost process could be shut down and held in reserve, however this option has not been considered.

However, it is possible to determine what the cost of plant retirements must be in order for it to be better to retire the higher operating cost plant when the new installation is made. It is found that for all growth rates the cost of plant retirements must be less than about -6.7 million DM for retirements to be preferable. This means that, if the cost of plant retirement is the saving in future labor costs only, it will be preferable to close down the higher operating cost plant. However, if the employees of the old plant cannot be transferred to the new plant or the old plant is relatively new so that the present worth of future savings in tax due to depreciation may be significant (this will be a positive cost) then immediate plant closure may not be appropriate.

Up to the present each Canadian steel company has only operated at one location so there has been no problem in their transferring employees from old steel making facilities to new facilities. However, when STELCO's Nanticoke plant is operational some difficulties could arise. However, the social and other costs of steel plant closures have become an important issue in the U.K. and the U.S. and have acted as a constraint on the closure of outdated and obsolete open hearth facilities.

5. THE INTRODUCTION OF A NEW PROCESS

The development of a new process will usually progress through successive stages of experimental plant, prototype, first commercial and so on with a progressive increase in plant size. In general most steel firms are aware of new process developments.

Suppose that at the time a firm becomes aware of a new process it uses only one process and has capacity gs' of the old technology. Suppose also that its actual production in the year in which it becomes aware of the new process is $gs(s \leqslant s')$. Then the questions are: Should the firm introduce the new technology or stay with old? If it decides for the new technology, how large should the plant be?

A crucial factor is whether there is any size limit on the new technology.

5.1 No Limit on Plant Size

If there is no limit on plant size then, if retirement costs are ignored, it is possible to determine the optimal plant size of the new process as a simple extension of the model of capacity expansion with imports.

Once again the old technology is treated as an "import" with cost $v_j - v_1$. Let s^*g be the level of "Imports" which minimizes $f(m,I,g)$ (cf. section 4.3).

Then the optimum policy with respect to the new technology will have the following form

(i) If $s \leqslant s' \leqslant s^*$ defer construction of the new plant until $s = s'$.
(ii) If $s \leqslant s^* \leqslant s'$ defer construction only until $s = s^*$.
(iii) If $s^* \leqslant s$ build the new plant immediately.

The optimum size of the new plant in case (i) is given, for 2/1 plants, by the results in table 8 and in case (ii) by the results in table 9.

If $g\tau^*$ is the optimal size if the plant is constructed when $s = s^*$ then it can be shown that in case (iii) the optimal size will at least be $g\tau = g(\tau^* + s - s^*)$. Figure 1 shows some optimum values for different levels of s. Note that for the firm with a substantial commitment to the old technology the size of the first plant built will be very large. The question of whether the firm might be better to keep to the old technology is discussed in the next section.

5.2 Effect of a Limit on Plant Size

The requirement that the first plant built of the new technology be very large could usually only be met if there has been some restriction on the use of the new technology (e.g., due to restrictive licensing agreements) and the restriction is then removed.

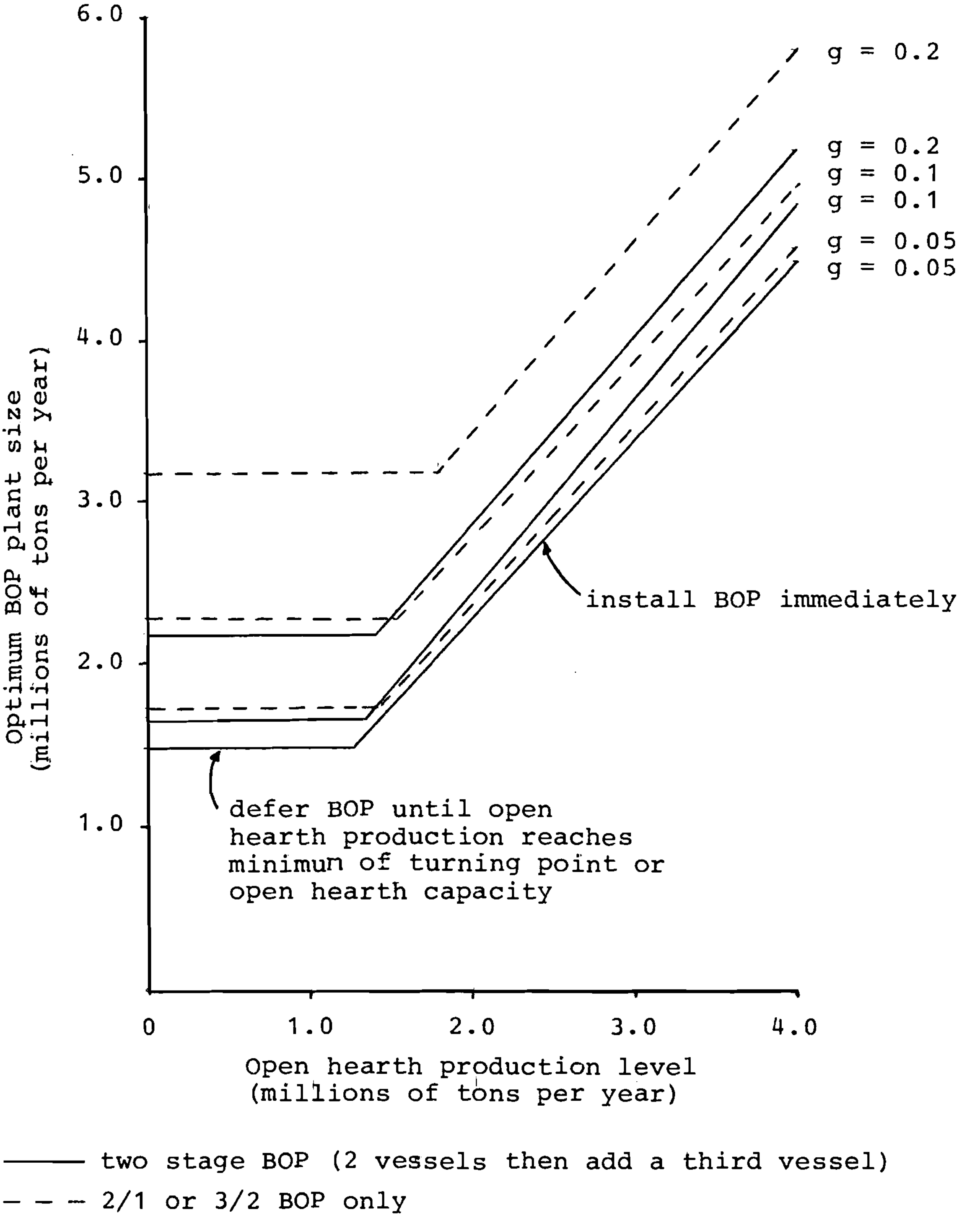

Figure 1. Advent of New Technology: Optimal BOP Plant Size as a Function of Open Hearth Production Level ($v_2 - v_1$ = 16 DM/ton)

Usually when a new technology is developed it would be considered highly risky to build a very large new plant when the experience in the implementation and use of the new technology is limited. As experience is acquired there will be a gradual increase in the size of the largest plant considered technically feasible.

The development of the BOP process demonstrates this gradual increase in size. Figure 2 shows the increase in the size of the largest vessel installed in the U.S., FRG and Japan (based on figure 9 of Resch (1973)).

Obviously, in making decisions on the timing, choice and size of plant additions, managers take account of the available experience in the use of a process and the perceived limitations in the maximum size of plant. However, what is not clear is the extent to which they anticipate the process of gradual increase in maximum size and hence defer an addition of the new process because they anticipate that in a few years time it will be possible to build much larger plants than currently technically possible.

Although there have been studies of the growth of maximum plant size with time (Sahal 1979), any study based on actual data is limited by the fact that actual plant sizes are determined not only by technical considerations but also by economic and market considerations. Because the modelling approach used in this paper considers these economic and marketing factors explicitly, data is required on the growth of the maximum technically feasible plant size, not on the growth of the largest actual plant sizes. Furthermore, since any scaling up of plant size beyond present experience involves risk and the risk increases with the amount of scale up, a model assuming rational behavior by managers should allow explicitly for this risk.

The simplest approach is to assume that managers do not consider as feasible any plant size which exceeds the largest yet built elsewhere in the world. Furthermore, it will be assumed that managers do not anticipate larger plant sizes becoming feasible in the future.

Thus, it will be assumed that M is the largest feasible plant size of the new technology (M in millions of tons per year).

(a) Will the New Technology Be Introduced At All?

If M is sufficiently small then the new technology may not be appropriate for the firm. The conditions under which the firm will stay with the old technology can be found by assuming that the optimum policy of the firm is to stay with the old technology and then seeing under what circumstances the present worth of future costs would be reduced through building a plant of the new technology (see appendix 2).

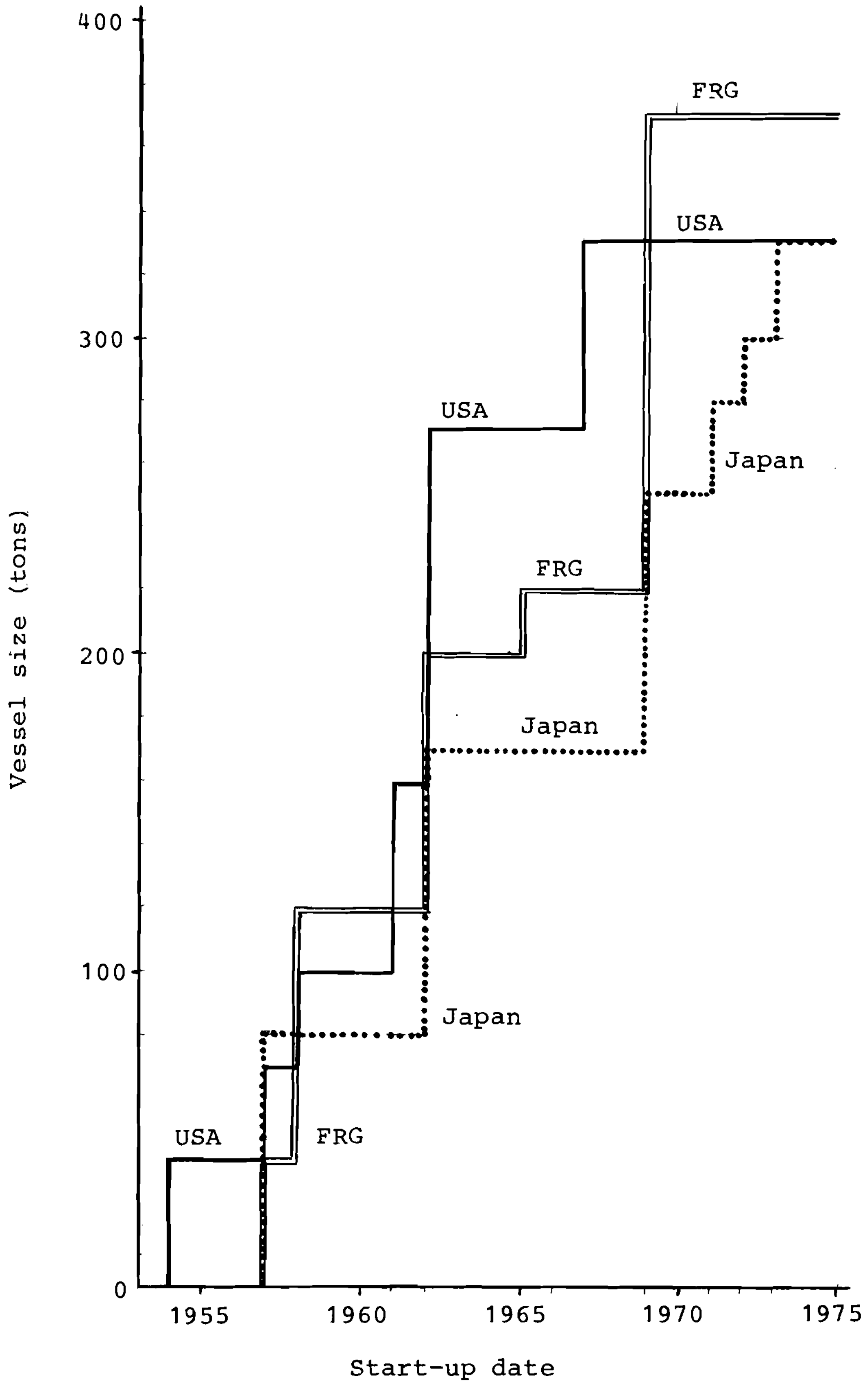

Figure 2. Growth of Largest Size of BOP Vessel for USA, Japan and FRG (Source: Resch 1973)

If f(m,g,2) is the minimum present worth of capital and fixed operating costs (see section 4.2) if only the old process is used and I(ng) the capital and present worth of fixed operating costs associated with building a plant of the new technology of size ng then the condition for the firm to stay with the old technology is

$$f(m,g,2) \leqslant \min_{n \leqslant M/g} \left\{ \frac{I(ng) - (v_2 - v_1)\, ng\alpha/(1 - \alpha)}{1 - \alpha^n} \right\} .$$

Assuming m = 2 and using the values of f(2,g,2) given for the two furnace open hearth plant in table 6 it is possible to determine the critical value of $v_2 - v_1$ as a function of M for different values of g. Figure 3 shows these values.

Note that the critical value of $v_2 - v_1$ increases with g for a given maximum plant size. That is, the firm with the higher growth rate can more readily justify staying with the old technology as long as the maximum plant size is limited.

This conclusion is, of course, related to the cost characteristics of the alternative processes. If the fixed operating cost of the open hearth were 3.6 million DM/year instead of 5.6 million DM/year and all other costs are unchanged then figure 4 shows the way in which the optimal policy is determined by $v_2 - v_1$ when M = 0.5 million tons per year. Note that the critical value of $v_2 - v_1$ below which the new open hearth plant is preferable is least at g = 0.05 million tons per year. As g either increases or decreases from this value the critical value of $v_2 - v_1$ increases.

Note that if $I(M) - (v_1 - v_2)\, M\alpha/(1 - \alpha) < 0$ then the BOP would be preferable to the open hearth no matter how low the capital and fixed operating costs of the open hearth. Figure 5 shows the critical value of $v_2 - v_1$ such that this would be true as a function of M for the BOP.

(b) When Will the New Technology Be Introduced?

Even though it can be shown that the firm will not always use the old technology in spite of the limit on the maximum plant size of the new technology, this does not of course mean that it is appropriate for the firm to switch to the new technology immediately. First of all, it may be appropriate to wait until its existing plant capacity is fully utilized before switching; secondly, even if its existing capacity is fully utilized it may be preferable to expand capacity of the old technology if this can be done relatively cheaply:--for example, the firm may have previously made provision for addition of extra furnaces to an open hearth shop.

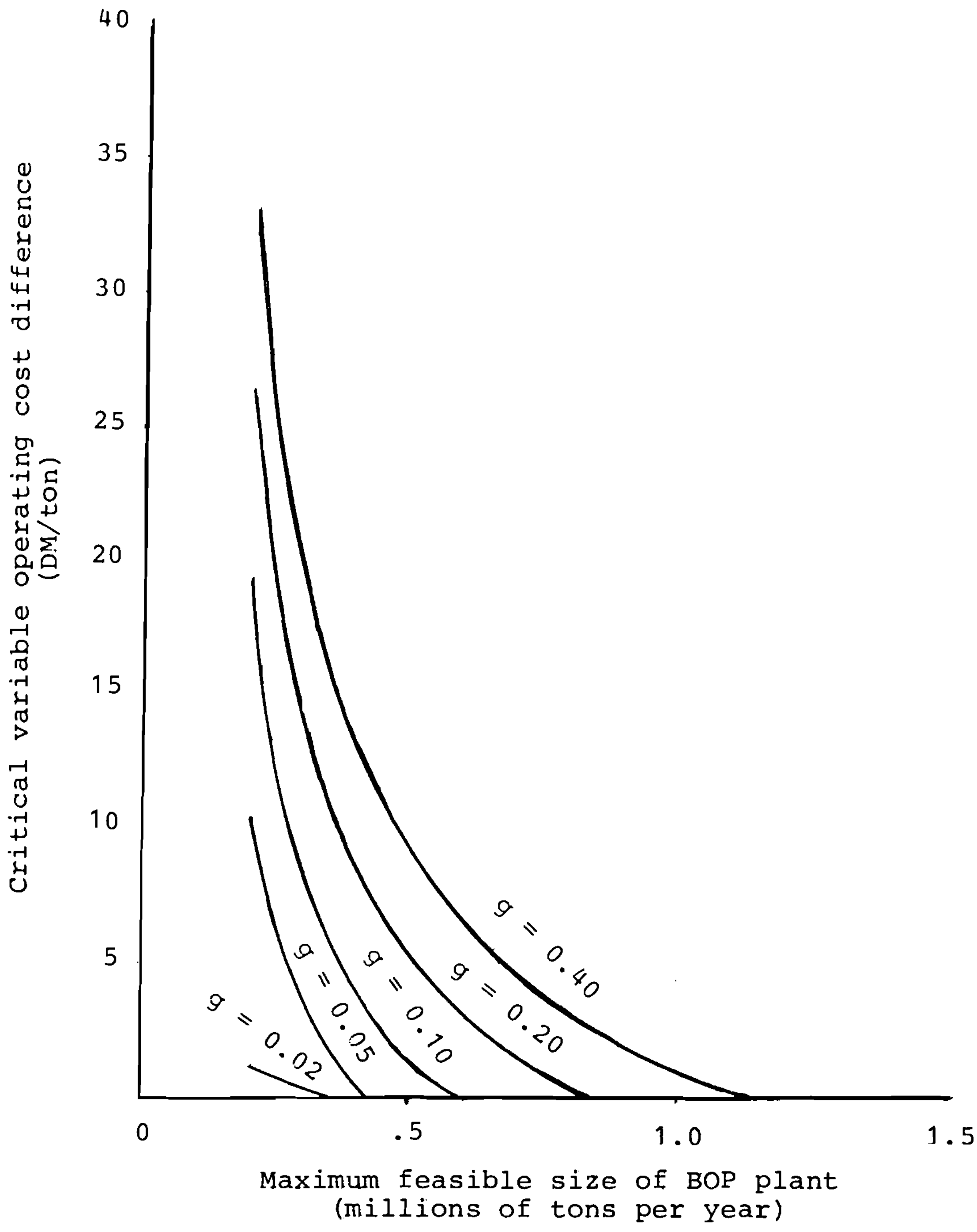

Figure 3. Critical Variable Operating Cost Difference Above Which Restricted Size BOP Plant Preferable to New Open Hearth Shop for Different Values of Growth per Year g (in millions of tons per year)

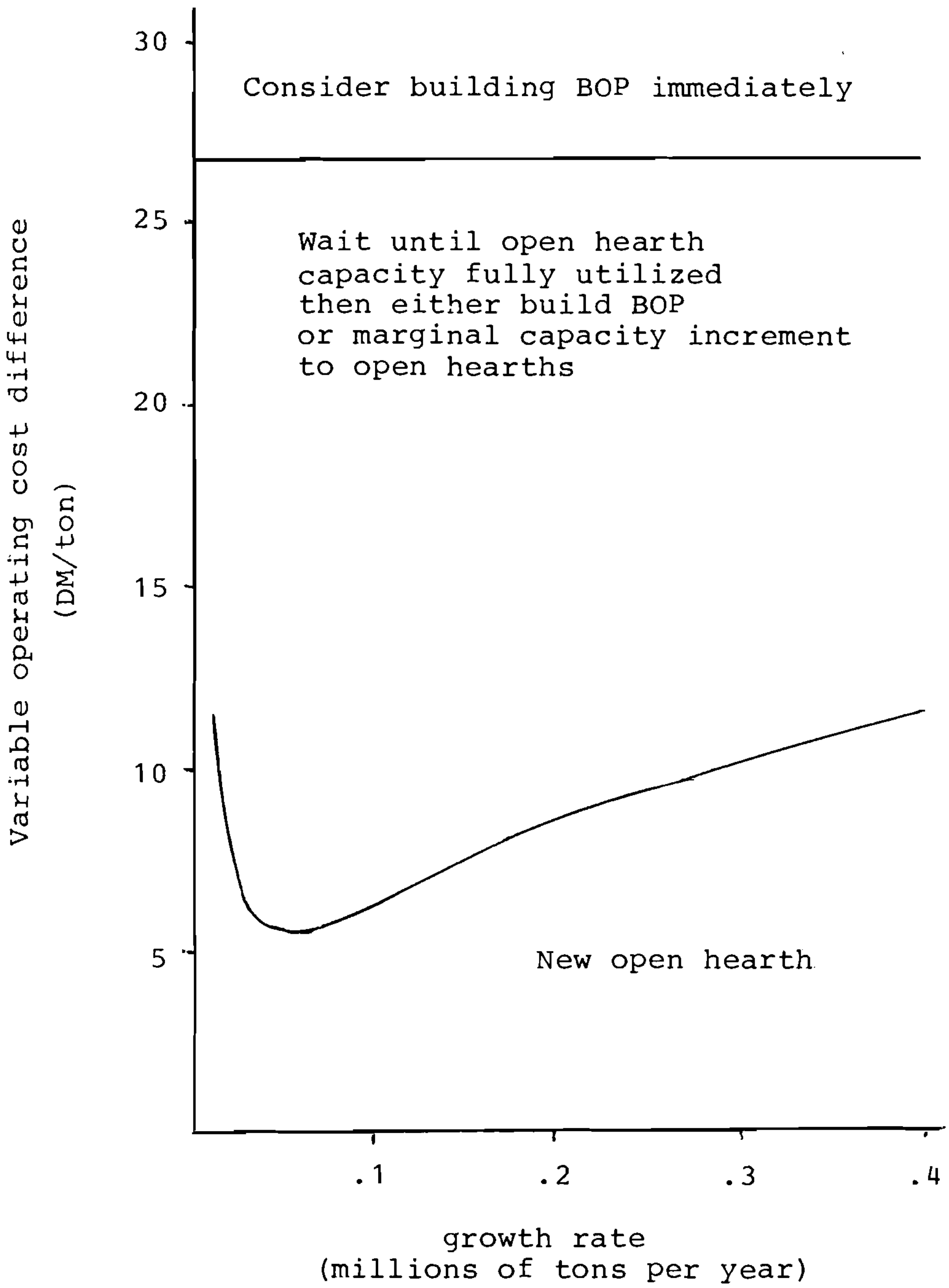

Figure 4. Optimum Policy When Maximum BOP Size Equals 0.5 million tons per Year and Open Hearth Labor Cost 3.6 million DM per Year

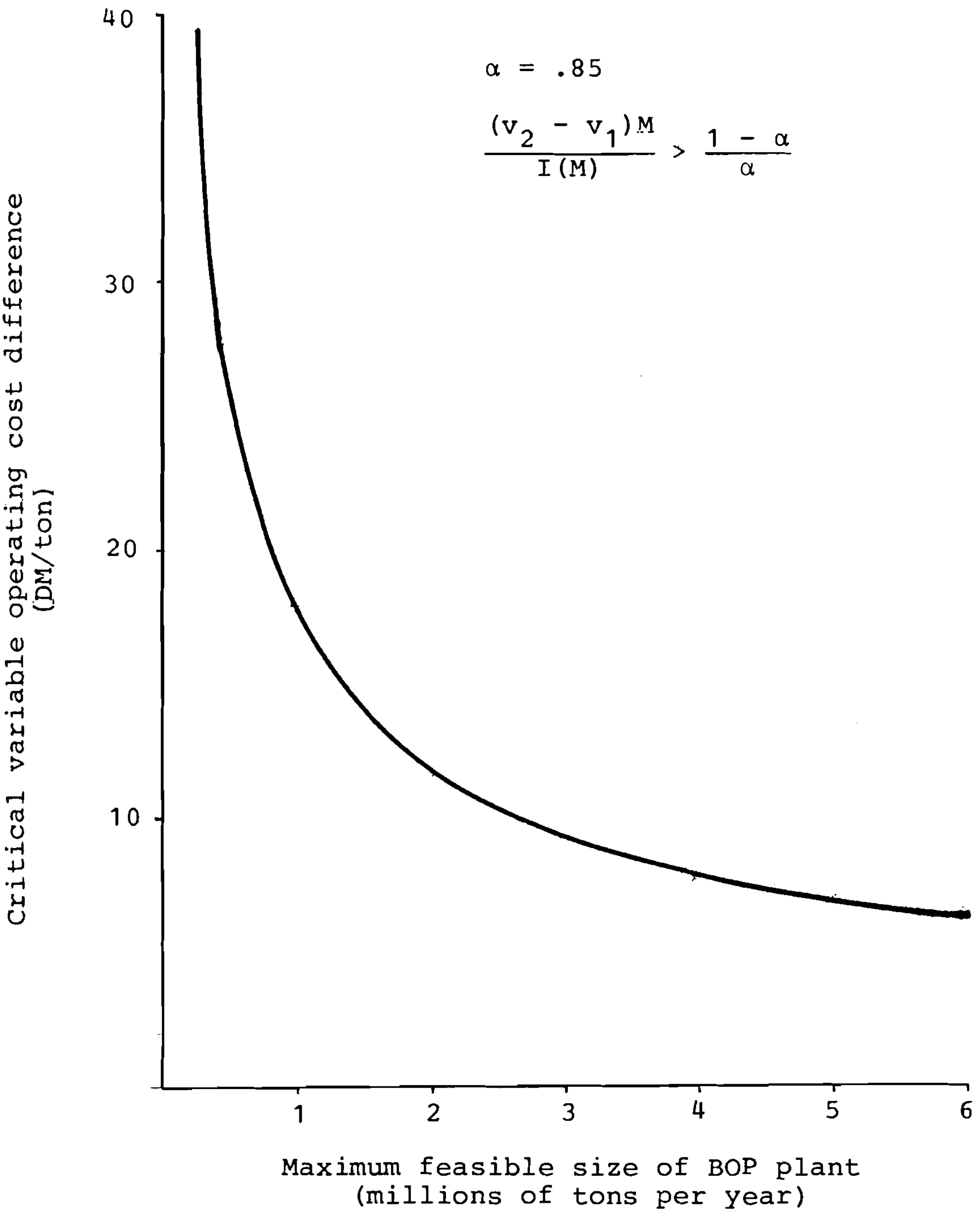

Figure 5. Critical Variable Operating Cost Difference above which Expansion of Open Hearth Capacity Should Not Be Considered Regardless of Its Expansion Costs

(1) Should the Firm Instal the New Technology Before the Existing Capacity is Fully Utilized?

Assuming that the optimum policy is to wait until the existing capacity is fully utilized and then the firm will build a plant of the new technology, it can be shown, using dynamic programming, that this assumed policy of waiting until capacity is fully utilized is optimum provided

$$I(M) - (v_2 - v_1)\ M\alpha/(1 - \alpha) > 0$$

and $M \leqslant s'g$ where $s'g$ is the existing capacity of the old technology.

If $M > s'g$ then the condition is more complex and depends on the relationship between M, s' and s* (the production level at which a new plant will be built when there is no limit on M).

(2) Should the Firm Expand Using the Old Technology Before Introducing the New Technology?

Again, using dynamic programming, it can be shown that for $M \leqslant s'g$ the firm should expand using the old technology rather than introducing the new when the present capacity is fully utilized if

$$\frac{I(M) - (v_2 - v_1)\ M\alpha/(1 - \alpha)}{1 - \alpha^{M/g}} \geqslant \min_{p} \frac{I'(M/g)}{1 - \alpha^{p}}$$

where $I'(M/g)$ is the capital cost and present worth of fixed operating costs associated with expanding the old technology by an amount M/g.

For example, if $M = .6$ and $v_2 - v_1 = 16$ DM per ton then it would be preferable to expand open hearth capacity if, for example, the only capital costs associated with the expansion were the cost of one new oven of say G = 300 tons and no further expense were required (i.e., foundations were already installed and crane capacity was adequate). [From Schenck (1970:214) the capital cost of the new oven would be $.326 \times G^{.47}$ or 4.75 million tons. Also, the fixed operating costs of one extra oven can be estimated at 1.8 million DM per year (half the difference between the fixed operating costs of four ovens and 2 ovens)].

Since the firm could readily have such means of increasing the capacity of the old technology quite inexpensively, it is not surprising that firms often increase the capacity of the old technology even though there is a new and better technology available.

6. APPLICATION TO DECISIONS OF CANADIAN STEEL FIRMS

Each decision listed in table 1 will be analyzed to see whether it can be explained by the model. Also a number of non-decisions, i.e., occasions where the firms did not decide on additions and retirements will also be analyzed.

It is evident from section 5 that a key assumption is the maximum feasible plant size. Based on the data in figure 2 it will be assumed that the following are the maximum vessel sizes that could be used with the BOP process:

1954-57	40 tons
1958-61	80 tons
1962-67	240 tons
1970 on	380 tons

That is, the maximum production capacity of 2/1 BOP plants would be 0.5 million tons in 1954-57, 1.0 million tons in 1958-61, 3 million tons in 1962-69 and 5 million tons after 1970.

The firms will be considered in the order in which they first introduced the BOP process, i.e., DOFASCO, ALGOMA, STELCO.

6.1 DOFASCO

1953

Installation of first BOP plant. When $M = .5$ million tons and $v_2 - v_1$ equals 16 DM/ton then $I(M) - (v_2 - v_1) M\alpha/(1 - \alpha) > 0$. Hence the BOP process should not be considered unless the open hearth coapacity is fully utilized. DOFASCO's situation in 1953 was that its open hearth capacity was fully utilized and it had surplus capacity from its blast furnace built in 1950. Its growth rate of demand was at this time 0.05 million tons per year. Because of the age of its existing open hearth shop adding more open hearth capacity would have meant building a new open hearth shop (Dilley and McBride 1967). From table 6 the optimum size of open hearth would have had a capacity of 0.5 million tons per year and a present worth of 97.

For the BOP at $M = 0.5$, $(I(M) - (v_2 - v_1) M\alpha/(1 - \alpha))/(1 - \alpha^{M/g})$ would be less than 97 as long as $v_2 - v_1 > 0$, thus the economic justification for installing the BOP was clear, although the newness of the process means that the firm showed boldness in adopting it.

Once experience with the process had been obtained the addition of the third vessel in 1955-56 was obviously justifiable.

1959

Replacing 50 ton furnaces by 105 ton furnaces and closure of the open hearth plant. The capacity of the 3/2 plant with vessels taking 50 tons per heat would have been about 1.2 million tons per year using Schenck's results (1970:80), however it is likely that in 1959 it would have been less. The growth rate of demand was now about 0.1 million tons per year.

Thus, although the capacity was more than the critical capacity determined in section 4.4, rebuilding would have been worth while provided the cost of rebuilding was less than 90% of the cost of building a new plant of the same capacity and it is quite likely that this would have been the case. Table 6 suggests that the appropriate capacity increment should have been about 1 million tons per year thus the size of plant seems appropriate.

Closure of the old open hearth facilities would have been justifiable at this time.

1965

Rebuilding the BOP plant to 3 x 160 ton vessels. Although staggered over a number of years in order to maintain full production, it can be estimated that the cost of rebuilding the BOP plant would have had to be less than 50% of the capital cost of building a completely new plant of the same size for this decision to be correct. Given that the converter vessels themselves only cost about 20% of the total cost of a new plant and the experience DOFASCO had gained in rebuilding the plant in 1959-61 it is possible that they were able to keep the cost within this limit.

Alternatively, the decision could be justified if a lower discount rate, 12%, was used. It is likely that the size of vessel was determined by technical constraints associated with the rebuilding, however the capacity increment of about 1.3 million tons is consistent with table 6 at the 1966-71 growth rate of 0.12 million tons per year.

1974

Building No. 2 BOP of 2 x 280 ton vessels. Over 1971-76 production increased by 0.17 million tons per year. By table 6 the 2/1 plant should have had a capacity of about 1.5 million tons, i.e., a vessel size of 140 tons. Thus this plant seems larger than appropriate although the present worth of the costs would only be about 10% higher. However, if it is assumed that DOFASCO use a lower discount rate (10-12%), then the 2 x 280 ton plant can be justified.

Conclusions

DOFASCO's decisions seem to be consistent with the model if it is assumed that they use a lower discount rate (12%) instead of the 15% assumed in sections 4 and 5. There is some evidence (Schell 1979) that DOFASCO use two different discount rates: a lower one (10-12%) for major expansion projects and a higher one for minor projects, so that the overall return of the mixture of projects is acceptable. Since there would appear to be more market risk associated with major expansions it would appear that the firm is relatively aggressive in its attitude to the future.

6.2 ALGOMA

Start up dates of new facilities are given in brackets.

1953-55

No investment in BOP facilities. Over the period 1950-53 ALGOMA had enlarged their No. 2 open hearth shop so that they had surplus capacity during the period 1953-57. From figure 3 the critical value of $v_2 - v_1$ was about 25 DM/ton when M = 0.5 million tons per year thus, as long as they had surplus capacity there was no reason for them to invest in BOP facilities.

1956(1958)

No. 1 BOP plant with 2 x 80 ton vessels. These BOP facilities were installed within an existing Bessemer building (Ess 1964), thus the cost of the facilities would have been less than the cost of a new plant. At M = 1 million tons per year the critical value of $v_2 - v_1$ is 17 DM per ton by figure 3, however because of the lower cost of this particular plant the critical value of $v_2 - v_1$ would have been less. Thus, it was appropriate to build a BOP plant of the largest size then feasible given their large open hearth capacity and growth rate in 1956-61 of about 0.1 million tons per year. Closure of No. 1 open hearth shop occurred when the BOP plant was completed.

1959-61

Rebuilding open hearth furnaces. This rebuilding would have increased capacity by 10%. Since its cost was probably low it was likely to have been marginally justifiable.

1961(1964)

Addition of a third furnace to No. 1 BOP plant. Since provision for this furnace was made when the first two furnaces were installed this decision seems appropriate.

1962-1964

No replacement of open hearth facilities. Once the technical limit on BOP vessel size was removed ALGOMA could have considered replacement of its open hearth facilities. However, with open hearth capacity of 1.3 million tons per year and a growth rate of 0.14 million tons per year in 1961-66 figure 1 suggests that it was not necessary until they were fully utilized.

1965(1973)

Construction of No. BOP plant of 2 x 260 ton vessels. From figure 1 the appropriate plant size, once expansion occurred, should have a capacity of about 2.5 million tons or 2 x 200 ton vessels. Although initially authorized in 1965 the drop in growth of demand which occurred during 1967-70 resulted in construction of the plant being delayed. In 1975 an ALGOMA official stated

> We learned a lesson then. We learned that to stay competitive you have to expand. That period of inactivity did us no good at all. (Financial Post 1975)

However, the lack of growth suggests that, at least in the short run it was a rational decision to delay.

In 1971-76 the growth rate of demand was 0.1 million tons per year. This tends to reinforce the conclusion that the No. 2 BOP plant may have been somewhat larger than appropriate.

Conclusion

ALGOMA's decisions seem to fit the model quite well. However, as compared to the other two companies its growth rate since the mid 1960's has been much less and it has lost market share. This is probably due to the cost penalties it suffers due to its location and a product mix which made it vulnerable to competition from the non integrated mini mills located near markets in Western Canada and Southern Ontario.

6.3 STELCO

1953-57

No investment in BOP facilities. STELCO had added about 1 million tons per year of open hearth capacity in 1952. Thus over the period 1953-57, with a growth rate of 0.2 million tons per year it had surplus open hearth capacity. The size limit on BOP plants would not have justified building any new capacity until existing capacity was fully utilized.

1959(1961)

Add 1 x 400 ton furnace to No. 3 open hearth. Improvements to open hearths (adding volume oxygen). The addition of oxygen to the open hearths would have increased their capacity by about 40% because of the reduction in time per batch. Thus this capacity addition was probably justifiable. However, the addition of the 1 x 400 ton open hearth to No. 3 open hearth shop requires more careful analysis.

The capacity would have increased by 0.5 million tons per year. Assuming that the cost of installation was just the cost of the furnace itself and there were no other facilities, such as cranes, required then it is possible to estimate the maximum value of $v_2 - v_1$ such that this open hearth would have been preferable to a BOP plant with capacity 1 million tons per year. It is found that this critical value is 12 DM/ton.

There are a number of factors that suggest that this might have been the case. First of all, in Schenck's analysis of open hearth operating costs fuel was estimated at 10 DM/ton. The construction of the trans Canada oil and gas pipe lines in the mid 1950's probably meant that the relative cost of oil and gas in Canada was less than the FRG. Second, DOFASCO's decision to close down its open hearth shop may have created a surplus of scrap and a lowering in scrap prices, making the cost of input materials to the open hearth less than the BOP.

1963-67

No construction of BOP facilities. With the increase of maximum plant size of the BOP then the attractiveness of BOP increased. STELCO had approximately 4 million tons per year of open hearth capacity and a growth rate of 0.25 million tons per year in production over 1961-66. Figure 1 suggests that it should have built BOP facilities. Only if $v_2 - v_1$ was less than about 9 DM/ton was it appropriate to wait until open hearth capacity was fully utilized.

However, during this period STELCO was short of hot metal capacity. Its No. 5 blast furnace was authorized in 1964 but not completed until 1968 and without this capacity there was no reason to authorize BOP facilities. STELCO had devoted a substantial amount of research to alternative iron ore reduction methods (leading to the development of the SL/RN process) and the delay in authorizing and completing this blast furnace may have been due to a hope that these other methods might be competitive to the blast furnace.

1968(1971)

Construction of No. 1 BOP shop of 3 x 140 ton vessels. The lower growth rates over 1966-71, about 0.17 million tons per year and the figure 1 suggest that the appropriate plant size would have had a capacity of around 5 million tons per year or 3 x 190 tons at $v_2 - v_1$ equal to 16 DM/ton. Since it would appear that $v_2 - v_1$ was less in STELCO's case the appropriate plant size would have been somewhat smaller. It must be noted that STELCO opted for a three vessel plant rather than a two vessel plant. A 3 x 140 plant has a capital cost of 5% less than a 2 x 280 plant however its fixed operating costs are higher so the two vessel plant is preferable. STELCO probably chose the three vessel plant because of its lack of experience with BOP and the easier material handling with smaller vessels.

Closure of No. 2 open hearth seems appropriate.

1973(1980)

Construction of Nanticoke BOP plant of 2 x 250 tons. With a 1971-76 growth rate of 0.2 million tons per year and a remaining open hearth capacity of about 2 million tons construction of new facilities would have become appropriate about 1976. By figure 1 its capacity should have been 2.5 million tons to 3 million tons, i.e., about 2 x 230 tons.

However, the model indicates that on completion of the Nanticoke plant the remaining open hearth facilities should be closed.

Conclusions

The model predicts STELCO's behavior reasonably well, although the justification for its decisions in 1959 and its lack of decision in 1963-67 requires that the difference in operating cost between the BOP and the open hearth be less than Schenck's value of 16 DM/ton. There is reason to believe, because of lower energy prices in Canada, that this was the case.

It must also be noted that it is relative costs which are important, i.e., the ratio $(v_2 - v_1)M \div I(M)$ determines the policy recommendations of the model, not absolute costs. So, even if energy costs were the same in Canada and FRG, higher construction costs in Canada would change the critical value of $v_2 - v_1$.

Even though STELCO's behavior is consistent with the model this does not mean that STELCO behaved optimally. It is interesting to speculate whether STELCO would have opted for further open hearth capacity in 1959 had its research concentrated on steel making instead of iron making in the late 1950's. It would then have had a better understanding of the potential capability of the BOP process. It is likely that the correct decision in 1959 was to add volume oxygen to its open hearth but to wait and see whether the limitations of the BOP could be overcome before installing further capacity.

7. THE INNOVATION PROCESS

The application of the model to the decisions of Canadian steel firms suggests that each of the firms behaved rationally in the light of their particular situation. The differences in the behavior of the firms can be accounted for by the size of their capacity of the old technology, the rate of growth of demand and the particular characteristics of the new technology. Of crucial importance is the rate at which the maximum feasible size of plant of the new technology increased.

It does not appear that any firm behaved irrationally or showed excessive caution in adopting the innovation. While STELCO's construction of further open hearth capacity in 1959-61 may, in hindsight, have been unwise, on the basis of their situation at the time and the perceived limitations of the new technology it appears that it was a rational decision in the light of a reasonable appraisal of their situation. On the whole our results are such that Dilley and McBride's (1967) justification for the slowness of adoption of the BOP can be supported.

Yet, on the other hand, viewed from a more macroscopic perspective the behavior of the firms is also consistent with Utterback's (1978) description of the innovation process.

> Small new ventures, or larger firms entering a new business introduce a disproportionate share of innovations...the new technology enters a special market niche.

When DOFASCO introduced the BOP in 1953 it was in a rather special situation. In contrast to almost all other North American steel companies it had not expanded its steel making facilities at the beginning of the Korean war rearmament boom (1950-51). In fact, the Korean war boom and the associated scrap shortage had resulted in it building a blast furnace so that it became an integrated producer and had surplus hot metal capacity in 1953. Thus, when the innovation occurred it was in the unique situation of requiring more steel making capacity and having a particular size, rate of growth and product mix for which the new process was ideal (cf. Dilley and McBride 1967:149)

> during periods of technological substitution the defensive efforts of established firms may cause the old technology to reach much higher levels of performance and sophistication than those previously obtained...the old technology improves dramatically when threatened.

The addition of oxygen lancing to its open hearths and other modifications enabled STELCO to significantly increase the capacity of its plant using the old technology at low cost. Furthermore, the new technology was initially not suited to its situation as market leader with a high absolute growth rate, thus it is not surprising that it devoted considerable effort to improving open hearth performance. It may also have felt that the plateau which blast furnace development appeared to have reached around 1960 (cf. Gold 1974) (limiting what was considered to be the maximum size of blast furnaces) was a significant constraint on investing in a process which would require high investment in blast furnace capacity

technological innovation leads to changes in market structure.

DOFASCO's early adoption of the innovation and its accumulated experience with it enabled its share of Canadian steel production to increase from 10% to 23% over 1951-1976, enabling it to replace ALGOMA as the second largest producer. However, because steel making is just one stage in the process of the manufacture and distribution of steel products the cost advantages of its early adoption of the BOP were not sufficient to seriously challenge the position of STELCO as market leader. These cost advantages may have been compensated for by disadvantages in the cost of acquiring raw materials, coal and iron ore.

It is unlikely that ALGOMA's relatively poor profitability after 1965 was due to its decisions with respect to the BOP process. It was probably due to penalties associated with its location which could not have been overcome by a high level of processing and manufacturing efficiency. The location penalties changed in the 1960's due to other innovations--such as the improvements in bulk raw material transportation which lowered the costs of raw materials in relation to the costs of delivery of finished products (Manners 1971).

However, not until STELCO's Nanticoke development is fully operational will the overall effect on market structure be apparent. If STELCO should have problems in the coordination of steel making at two locations then one would start to conjecture what would have happened if it had adopted the BOP earlier when the costs were lower (the expected cost of the first phase of the Nanticoke expanison doubled between 1973 and 1976).

The other significant change in the structure of the Canadian steel market has been the increasing share of steel production from scrap fed electric furnaces (mini mills). Our results suggest that this is the appropriate process option when the market growth is low in absolute terms. High transport costs give mini mills an advantage in those parts of Canada remote from Southern Ontario. There is a link between this development and the advent of the BOP. The BOP reduced scrap requirements and thus helped to keep scrap prices low most of the time. On the other hand the scale characteristics of the BOP provided the market niche for the mini mills. The survival and growth of mini mills in Southern Ontario, where there is no advantage in transport costs with respect to the integrated producers, is due to the small producers being able to offer faster delivery and better service on products with a low demand. The large scale integrated producers have problems in scheduling their large mills to fit in the production of low demand products and this large scale is a result of the characteristics of the BOP.

Implications

Since on the one hand the Canadian steel firms behaved rationally, yet, on the other hand, their response to the innovation demonstrates most of the typical macroscopic features of the innovation process, there seem to be some general conclusions about the industry structure which supports innovation that can be made.

First of all, the advantages of diversity, in terms of size of plant, age of plant and market growth. It is quite likely that there should also be diversity of firm sizes--had DOFASCO and STELCO been controlled by the same management the appropriate decision in 1953 would have been to expand STELCO's open hearth capacity. Diversity of sizes, age and growth rates means that it is more likely that the particular niche for a new innovation will exist.

Second, there would also seem to be an advantage in diversity of economic climate and environment. It was "bad luck" for the US steel industry that it expanded during the Korean war boom and hence had sufficient surplus capacity afterwards for major expansion of capacity not to be required. Other countries, less affected or less able to respond to the increased steel demand in the early 1950's were in a better position to adopt the innovation. On the other hand, the US and Canada appear to be in a very favorable position to exploit the development of the scrap-fed electric furnace and the mini mill (or the market mill) (Iverson 1975; Morris 1979) because of the availability of scrap and relatively low electricity prices (even though this may impair the survival of the integrated producers).

8. DIRECTIONS FOR FURTHER RESEARCH

It would be of great value to rework some of the analysis with more accurate cost data, in particular to look at STELCO's decisions in the period 1958 to 1968 with better information on operating costs and taking account of the costs of plant closures and tax and depreciation effects.

The model could also be applied to the steel industry in other countries. Analysis of US firms would give insight into the effect of a firm owning more than one plant and how this modifies the decision on adoption of the innovation. By contrast, analysis of the Soviet steel industry would give further insights. The persistence and further development of the open hearth by the Soviet steel industry may have been due to their having large steel plants with high absolute growth rates. There may have been a long delay until the niche for the introduction and wide spread adoption of the BOP occurred.

Next, it is apparent that a more comprehensive model is desirable, in particular one which would give a better understanding of the role of scrap fed mini mills. Such a model would be more complex because it would be essential to allow for location as well as scale effects and, probably also, the specialization of mini mills to a restricted range of products.

At a more general level the model could be applied to a hypothetical population of firms with some appropriate distributions of firm sizes and growth rates. This would enable a model of the overall rate at which innovation occurs within an industry to be developed. However, the correlation between the surplus capacity of firms, introduced by such extraneous factors as the effect of the Korean war on US plant expansions and the consequent surplus capacity at the time the BOP innovation occurred, would make such an analysis somewhat academic.

Finally, since the perceived maximum size of plant of the new technology has such an effect on the appropriateness of adoption, it would be desirable to develop a better understanding of the process of scale-up of plant and the way in which the maximum plant size increases with time.

APPENDIX 1

THE BASIC MODEL

Symbols

T = time horizon

P_s = required total production in period s $(0 \leqslant s \leqslant T)$

X_{jt} = original capacity of plant built in period t and using process j $(-\infty \leqslant t \leqslant T)$

U_{jts} = capacity in period s of plant built in period t and using process j

δ_{jtp} = 1 if plant built in period t and using process j is retired in period p

= 0 otherwise

Note that $\sum_{p=t+1}^{T} \delta_{jtp} \leqslant 1$

P_{jts} = production in period s from plant built in period t and using process j

$k(X_{jt})$ = capital cost of plant with capacity X_{jt}

$s_p(U_{jtp-1})$ = retirement cost in period p of a plant with capacity U_{jtp-1} prior to retirement

$O(U_{jts})$ = capacity related operating cost in period s of plant with capacity U_{jts}

$v(P_{jts})$ = production level related operating cost in period s of plant when its production is P_{jts}

α = discount factor

ASSUMPTIONS

In order to simplify the presentation of the model and take account of the characteristics of the cost data the following assumptions will be made:

(1) No more than one plant of a given process is added in any year.
(2) The capital and capacity related operating costs of a plant are independent of plants constructed in earlier years. The cost of retirement of a plant are independent of other plants retired or constructed.
(3) Plant capacity remains unchanged until the plant is retired and the plant is retired as a whole.

i.e., $U_{jts} = U_{jts-1}\ (1 - \delta_{jts}) \qquad s > t$

$$U_{jtt} = X_{jt}$$

(4) All operating costs are independent of the age of the plant and all costs are independent of time
(3) and (4) together mean that the capacity related operating cost of a plant is given by (until the plant is retired)

$$O(U_{jts}) = O(X_{jt})$$

independent of s
(5) Schenck's data indicates that $O(X_{jt})$ depends only on m the number of vessels and j so

$$O(X_{jt}) = L_{mj}$$

(6) Production related operating costs are linear. Combined with (3) and (4) this means that

$$v(P_{jts}) = v_j \cdot P_{jts}$$

where v_j is the variable operating cost per ton of process j

(7) repair costs and depreciation will be ignored.

Assumption (2) can be relaxed to allow for two step expansions.

Note that the present worth of all capacity related costs of a plant of process j constructed in year t and scrapped in year p can be written

$$q(S_{jt},p) = I(X_{jt}) + \alpha^{p-t} F_p(X_{jt})$$

where

$$I(X_{jt}) = k(X_{jt}) + L_{mj}/(1 - \alpha) \qquad 0 \leqslant t \leqslant T$$

$$= L_{mj}/(1 - \alpha) \qquad -\infty < t < 0$$

$$F_p(X_{jt}) = s_p(X_{jt}) - L_{mj}/(1 - \alpha) \qquad T \geqslant p \geqslant \max(0,T)$$

OVERALL PLANNING PROBLEM

Determine for all j, the X_{jt} $(0 \leqslant t \leqslant T)$, δ_{jtp} $(T \geqslant p \geqslant \max(o,t))$ and P_{jts} $(T \geqslant s \geqslant \max(O,t))$

$$\begin{aligned}\min \sum_j & \sum_{t=-\infty}^{-1} (I(X_{jt}) + \sum_{p=0}^{T} \delta_{jtP}\alpha^{p} F_p(X_{jt})) \\ & + \sum_{t=0}^{T} (\alpha^{t} I(X_{jt}) + \sum_{p=t+1}^{T} \delta_{jtP}\alpha^{p} F_p(X_{jt})) \\ & + v_j \sum_{s=0}^{T} \alpha^{s} \sum_{t=-\infty}^{s} P_{jts}\end{aligned}$$

subject to

$$\sum_j \sum_{t=-\infty}^{s} P_{jts} = P_s$$

$$P_{jts} \leqslant X_{jt} (1 - \sum_{u=t+1}^{s} \delta_{jtu})$$

The problem of allocating production to the different plants can be solved separately.

Let U_{js} = the total capacity of process j in period s

$$= \sum_{t=-\infty}^{s} X_{jt}(1 - \sum_{u=t+1}^{s} \delta_{jtu})$$

Identify the alternative processes so that $v_1 < v_2 < v_3 < \dots < v_n$.

Then the solution to the production allocation problem is

$$P_{ks} = \min (P_s - \sum_{j=1}^{k-1} P_{js}, U_{ks})$$

and the value of the cost function

$$\sum_j v_j \sum_{t=-\infty}^{s} P_{jts} = v_1 P_s + \sum_{k=2}^{n} (v_k - v_{k-1}) \max (o, P_s - \sum_{j=1}^{k-1} U_{js})$$

provided $\sum_j U_{js} \geqslant P_s$

The overall planning problem can be simplified by dropping terms which do not relate to the decision variables X_{jt} $(0 \leqslant t \leqslant T)$ and δ_{jtp} and it becomes

$$\begin{aligned} \min \sum_{j=1}^{n} & \Big(\sum_{t=-\infty}^{-1} \sum_{p=0}^{T} \delta_{jtp} \alpha^p F_p(X_{jt})) \\ & + \sum_{t=0}^{T} (\alpha^t I(X_{jt}) + \sum_{p=t+1}^{T} \delta_{jtp} \alpha^p F_p(X_{jt}))) \\ & + \sum_{s=0}^{T} \alpha^s \sum_{k=2}^{n} (v_k - v_{k-1}) \max (0, P_s - \sum_{i=1}^{k-1} U_{is}) \end{aligned}$$

subject to the constraints

$$\sum_j U_{js} \geqslant P_s \qquad 0 \leqslant s \leqslant T$$

$$U_{js} = \sum_{t=-\infty}^{s} X_{jt}(1 - \sum_{u=t+1}^{s} \delta_{jtu}) \qquad 0 \leqslant s \leqslant T$$

or $$U_{js} = U_{js-1} + X_{js} - \sum_{t=-\infty}^{s-1} X_{jt} \cdot \delta_{jts} \qquad 0 \leqslant s \leqslant T$$

$$U_{js} = \sum_{t=-\infty}^{-1} X_{jt} (1 - \sum_{u=t+1}^{-1} \delta_{jtu}) \qquad s = -1$$

DYNAMIC PROGRAMMING FORMULATION

This problem can be solved using dynamic programming.

Stage variable s

State vector $\{U_{jts}\}$

Decision variables X_{js}, δ_{jts}

Economic function $f_s(\{U_{jts}\})$ = present worth of optimum policy over period (s,T)

$$f_s(\{U_{jts}\}) = \min \Big[\sum_{j=1}^{n} \big(I(X_{js}) + \sum_{t=-\infty}^{s-1} \delta_{jts} F_s(X_{jt})\big)$$
$$+ \sum_{k=2}^{n} (v_k - v_{k-1}) \max (0, P_s - \sum_{j=1}^{k-1} U_{js})$$
$$+ \alpha f_{s+1}(\{U_{jts}(1 - \delta_{jts})\} \cup \{X_{js}\})\Big]$$

$$f_{T+1}(\cdot) = 0$$

where the minimum is with respect to the above decision variables and it is required that $\sum_{j=1}^{n} U_{is} \geqslant P_s$.

If no retirements are permitted then the state vector reduces to $\{U_{js}\}$.

In the special case of arithmetic growth in demand, i.e.,

$$P_{s+1} = P_s + g$$

it is convenient for numerical work to use as state variables

$$g_{ks} = (\sum_{j=1}^{k} U_{js} - P_s)/g \qquad k = 1, 2, \ldots, n$$

and set $n_{js} = X_{js}/g$.

When no retirements are permitted the dynamic programming recursion becomes

$$f_s(\{g_{js}\}) = \min \Big[\sum_{j=1}^{n} I(n_{js}g) + \sum_{k=2}^{n} (v_k - v_{k-1}) g \max(0, -g_{k-1s}) + \alpha f_{s+1}(\{g_{js} + \sum_{k=1}^{j} n_{ks} - 1\}) \Big]$$

with the requirement that $g_{ns} \geqslant 0$.

In particular cases further simplification is possible using the results of Manne (1967), Erlenkotter (1967) and Shapiro and Wagner (1967).

APPENDIX 2

TECHNOLOGICAL CHANGE

With only two processes the above DP recursion becomes

$$f_s(z_{1s}, z_{2s}) = \min_{n_{1s}, n_{2s} \geq 0} [I(n_{1s}g) + I(n_{2s}g)$$

$$+ (v_2 - v_1)g \max(0, -z_{1s})$$

$$+ \alpha f_{s+1}(z_{1s} + n_{1s} - 1, z_{2s} + n_{1s} + n_{2s} - 1)]$$

with the requirement that $z_{2s} \geq 0$.

With the new technology (process 1) appears at time s then up till then only the old technology would have been used.

Thus $z_{1s} = -P_s/g = -s$

$$z_{2s} = (U_{2s} - P_s)/g = s' - s \quad .$$

The approach is to assume a particular policy and then derive the conditions under which this policy would be optimum.

(1) Keep the Old Technology, Do Not Introduce the New Technology

It can then be shown that

$$f_s(-s,s' - s) = \frac{(v_2 - v_1)g}{1 - \alpha} (s + \alpha/(1 - \alpha)) + \alpha^{s'-s} f(g,2)$$

$$(s \geqslant 0)$$

where $f(g,2) = \min\limits_{n_2} \frac{I(n_2g)}{1 - \alpha^{n_2}}$ is the present worth of the capital and capacity related operating costs using the optimal expansion policy of the old technology and

$$f_s(s,s' + s) = \alpha^s f(o,s') \qquad s > 0.$$

Now suppose instead that a plant of the new technology of size n_1 were built at time s.

Then the assumed policy, using only the old technology, will be optimum if

$$f_s(-s,s' - s) < (v_2 - v_1)gs + I(n_1g)$$

$$+ \alpha f_{s+1} (-s - 1 + n_1, s' - s + n_1 - 1)$$

This reduces to

$$\alpha^{s'-s} f(g,2) < \frac{I(n_1g) - n_1\alpha(v_2 - v_1)g/(1 - \alpha)}{1 - \alpha^{n_1}}$$

for $n_1 \leqslant s + 1$.

The left hand side is greatest at s' = s. If there is a size limit on the new technology, i.e., $n_1 \leqslant M/g$ the condition for the old technology only to be used becomes

$$f(g,2) < \min_{0<n_1\leqslant M/g} \frac{I(n_1g) - n_1\alpha(v_2 - v_1)g/(1 - \alpha)}{1 - \alpha^{n_1}}$$

It can be shown that this condition is sufficient even if $n_1 > s$. In the specific case considered the right hand side takes on its minimum at $n_1 = M/g$ in almost all cases.

(2) Wait Until the Old Technology Capacity is Fully Utilized Before Introducing the New Technology

Suppose $n_1{}^*g$ is the plant size which is such that at at $n_1 = n_1{}^*$

$$f(M,g) = \min_{0<n_1\leqslant M/g} \frac{I(n_1 g - (v_2 - v_1)\alpha n_1 g/(1 - \alpha)}{1 - \alpha^{n_1}}$$

For the specific case considered the minimum almost always occurs at $n_1 = M/g$.

Then it can be shown that if the new technology is introduced once the old technology capacity is fully utilized and plants of size $n_1{}^*g$ are built from then on that

$$f_s(-s,s' - s) = \frac{(v_2 - v_1)g}{1 - \alpha}(s + \alpha/(1 - \alpha))$$

$$+ \alpha^{s'-s} f(M,g)$$

if $n_1{}^* \leqslant s' + 1$.

Now suppose a plant of the new technology is built immediately. Then it can be shown that the present worth of costs of this policy will be higher if

$$\alpha^{s'-s} f(M,g) \leqslant f(M,g)$$

which is true if

$$I(n_1{}^*g) - (v_2 - v_1)\alpha n_1{}^*g/(1 - \alpha) > 0.$$

Similarly, it can be shown that, having waited until the old capacity is fully utilized, it is better to build a plant of the new technology rather than expand the old if

$$f(M,g) < \min_{n_2} \frac{I(n_2 g)}{1 - \alpha^{n_2}} .$$

When $n_1{}^* > s' + 1$ the conditions become more complex and details will not be given here.

Note. There is some similarity between the above conditions and the results of Jaskold-Gabszewicz and Vial (1972). They considered capacity expansion with growing demand and technological progress. They assume that the time of occurrence of technological change is either known precisely or has an exponential distribution. In the latter case this means that the size of the plants of the old technology will be smaller than if no technological change is foreseen, as in our case. They derive certain properties of the optimal policy after technological change has occurred under assumptions which guarantee that the change over to the new technology will occur only when the capacity of the old technology is fully utilized. They require that the size of the new technology plant should not be greater than the demand when the technological change occurs.

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