CHAPTER 6 SCALE, TECHNOLOGY, AND THE LEARNING CURVE

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The learning curve, which represents the relation between accumulated production and the cost per unit of production (or a similar index), was used in several papers at the workshop and stimulated lively discussions. On one side, the usefulness of the concept was questioned, and on the other side, the relation was treated as a natural law. Also, the implications and the nature of "learning" and their relations to the changes in scale and technology were discussed.

This chapter will summarize the important points of the discussions and attempt to clarify the usefulness and limits of the learning curve concept based on a literature survey and on a conceptual, hierarchical model. For a basic understanding of learning curves, the reader is referred to Yealle (1979 b).

6.1 DISCUSSION SUMMARY

The fuzziness of the learning curve concept and the learning itself is partly due to the word "learning," which can arbitrarily refer to individual, managerial, organizational, and societal learning; without a specification of the subjects and the objects, the meaning of the world becomes rather obscure. This was most clearly expressed by Gold, who asked, "who learns what."

In particular, Gold expressed his doubts about the usefulness of the learning curve for the blast furnaces (Figure 6.1) presented at the workshop by Derkx and Kamerman (Derkx *et al.* 1978).

Gold: I am very much troubled by the use of the term learning curve. Do we use the term learning curve to cover everything: improvements in technology, the learning of people how to do the same job better, changes in the nature of the product, changes in the nature of inputs, feedstocks and stuff of these sort? Is that what the learning curve is? In which case we don't have to use "technology" any more. We can simply say that everything represents the learning curve. A learning curve drawn for a blast furnance from 1896 up to now necessarily reflects the changes in furnance technology as well as in the qualitative characteristics of its inputs and outputs.

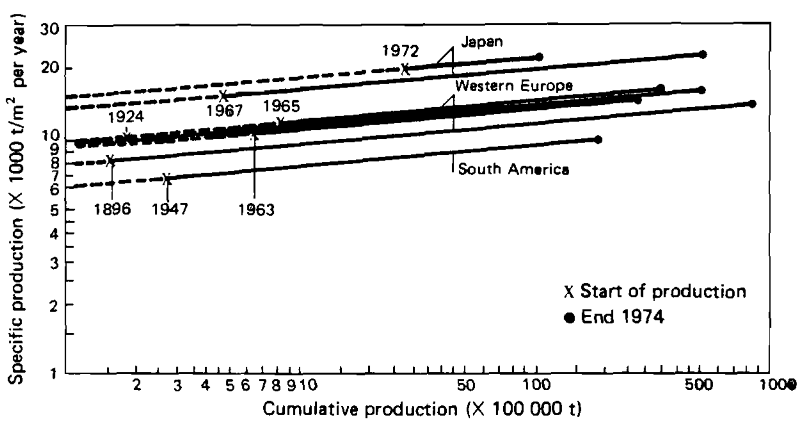

FIGURE 6.1 Graph of the effect of dynamic scale economies in steel plants, showing equal relative increases in productivity for all plants. Source: Derkx *et al.* (1978).

Derkx: Learning is the basic experience of labor inside a plant. They learn to do better. But this experience also results in overcoming bottlenecks in the facilities. Experience not only has the effect of doing the same job better, but results of experience can also be incorporated in investments to improve existing facilities or when constructing new facilities. A good example for me is the increasing hearth diameter of blast furnaces. In the 1960s the Japanese tried to increase the hearth area and then the next bottleneck was the cooling capacity. Thus technological development is going step by step from bottleneck to bottleneck based on the experience with the facility. In this respect our curve could be considered as the envelope of step-by-step technological development.

Gold: The increase of hearth diameter in Japanese blast furnances was due to a basic change in the theory. The Japanese developed a new theory. The original theory about the combustion being confined to the core of the blast furnace led to the decisions of the American industry that there would to be no gain from increasing the hearth area. With the change in basic theory, the Japanese were able to jump up from 1,000-ton to 10,000-ton-per-day blast furnaces (Boylan 1975, Gold 1974). Now this represents a change in technology and theory rather than merely eliminating bottlenecks; this involves developing some new ways of doing things. I do not think that the learning curve concept is quite discriminating enough to differentiate among the variety of factors associated with scale effects.

Derkx: We are talking about specific production. We have compared the big Japanese furnance of 10,000 tons per day with the specific production of smaller blast furnances. This is a way to compare technological content of the facility, the specific production, and the way it goes, better or not. This is the reason why we compare specific production.

A reaction to this argument was:

Schenk: In summary learning means different kinds of changing technology, different kinds of changes in society, etc. Even with large jumps in technology, there is a stable pattern of learning in different industries.

Sahal: In fact, learning involves a multitude of activities (e.g., material handling procedures, plant layout, scheduling of labor, etc.) and, therefore, it is conditional upon the participation of a great many agents in the production process. The theoretical basis of the learning curve is straightforward: it is isomorphic to the Pareto distribution (see Sahal 1979b). The learning curve is far from a trivial regularity . . . it is one of the most important law-like relationships to have been observed in this area.

In his presentation later on, Sahal claimed that the accumulated experience will determine the maximum size of a plant and also the technological change (Sahal 1979a, c, d). In other words, it is not only that improvement in the efficiency of the existing production processes is conditional upon learning or accumulation of relevant experience. Learning also determines the scope for development of new techniques. He demonstrated this by the results from the analysis of historical data on advances in the efficiency of computational devices, farm tractors, turbogenerators, and transportation equipment. The strong emphasis on the role of learning brought up some counter-arguments.

Van Dalen: You've suggested that the general trend toward improved efficiency in certain sectors, or the "volume scale" (the more you produce, the more efficient you get), is largely due to a learning process within the industry. Couldn't this also demonstrate the drift of technological improvement in the world as a whole? The improved efficiency of tractors, for example, could depend on the development of the ball-bearing industry, or the development of lightweight metals or a new kind of synthetic rubber. These products were not designed specifically for tractors but were developments in general. The tractor manufacturer does not learn from his own business, but benefits from technological drift in the world.

Learning has too much of a passive connotation and doesn't take human ingenuity or inventiveness into account. I have observed that there are a host of ideas available for implementation, but they are considered by managers to be impractical or too risky for business. Things are not hampered by technological ingenuity, but by an apprehension of economic considerations. The idea of learning from operations should have less emphasis than has been brought out so far.

Rosegger: Mr Cantley started with a taxonomy that was more than ornamental, which I hoped would sort out size effects from experience or time effects. I am uncomfortable with measures of learning that suggest there are prolonged periods of "forgetting" with respect to a particular technology. I am not sure what one does statistically, but conceptually we can do better than to say those are periods when we learned from errors only, which is the implication of the measures when the rate of learning is negative. We must look for the underlying causes, not subsume them.

Rochlin: The fuel economy of automobiles shows no learning curve. It shows a correlation with the price of fuel relative to other goods, but not a correlation to the number of units produced.

External factors may in fact be the most important ones. One of the driving forces in tractor innovation was that people were killed because tractors turned over. Perhaps a better example is the three-point tractor hitch; this was largely a consequence of the shift toward urbanization, which made the size of the average farm increase greatly. Now, to say that the three-point hitch caused something is to turn the dependent and independent variable around.

As for the question if the learning curve is a law:

Price: There has been an assumption that learning curves automatically give you a lower production cost. This is not so. If you have cumulative experience, you have the potential for having lower production costs through learning: but there is nothing automatic or inevitable about the achievements of lower costs. There are some companies who don't learn; you can also have countries with industries such as the Japanese, that start with disadvantages, but adjust their industrial policies to get a high rate of diffusion in their country and hence to take a leap forward along and hence down the learning curve in cost terms.

Betts: I think there are two aspects of the learning process, strictly related to the problem of plant scale. One aspect, one area of the learning process is, let me call it, the rate and final level of utilization of fixed assets. Let me characterize it like this. Just supposing that we have built over there a half-a-million-ton-per-year ethylene plant. It is standing there. It is a fixed asset, it is inert, it won't bite us at all if we leave it alone. We have put into it an immense amount of investment and this has to be properly used, because investment is in fact the result of past successful efforts and therefore has to be carefully utilized. There is undoubtedly in real life an actual process which takes place in which human beings learn to face up to, control, and manage such fixed assets. It is the interface between inert things and the human mind. And there is a barrier somewhere in that interface. This demonstrates itself, in the rate at which this plant reaches its design or full capacity. This may be long and slow, and sometimes it may never reach it. The rate at which the human beings involved manage to achieve a greater output for that fixed asset in terms of tons an hour, preferably tons a day, much more preferably tons a year, much more preferably still tons a decade, that is what I describe as one aspect of the learning process.

The other aspect is the process of making better, more reliable or more credible investment decisions. This is a management problem. For example, we may find that in increasing plant scale, we have introduced an innovation. I am not talking of change in the manufacturing process or about some fundamental technical innovation, I am simply talking about building something much bigger. We may find that in practice and in contrast to our original expectations, and the basis on which the original investment decision has been made, that for example, the plant cost half as much more to build and twice as long to build. That is learning. We may find that it takes say 3 years to reach its design output or it never reaches its design output or in fact we may find ways in which to get a more rapid build-up of output. That is learning.

Now, learning by whom? This experience will be learnt only by the people actually involved. In other words, if you look at that, their process of learning, and you say, suppose that we build a duplicate plant 5 years later, undoubtedly, in my view, the benefit of their process of learning – provided that they have analyzed the data to find out why it is that the plant has cost more and the output has been less, is repeatable at least within their particular organization and circumstances. To look at such experience in a macroscopic way, as things on graphs, plotting everything against everything as though the whole of human race naturally performed according to some God-given law, is not valid.

Also Gold talked more about the learning curve concept in relation to the scale problem. This is summarized in his paper (Chapter 2).

The problem here seems to be whether the term learning should be restricted only to the process of people getting to do the same job better and better, or be allowed much broader implications. As indicated earlier in this section, the arguments come from the fuzziness of the term *learning*. Thus, the nature of learning and the sources of learning must be looked into in detail in order to clarify the point raised in the discussion.

6.2 SOURCES OF THE LEARNING CURVE

The learning curve was first introduced as an observed relation between accumulated production and the cost of production per unit in terms of direct labor hours in the airframe production industry (Wright 1936). In this industry, the learning by the assembly workers from the repetition of a complex task was considered to be the cause of the relation, and thus the term "learning curve" was adopted. Since then, similar phenomena have been observed in a wide range of industries manufacturing everything from electronic instruments to chemical products; the possible causes of these phenomena are controversial and have been discussed in the literature rather extensively.

Andress (1954) made the distinction between "learning in the literal sense on the part of workers" and "a whole series of other factors among which management innovations appear most significant," and concluded that the former learning is the predominant factor. But his observation was restricted to the aircraft industry.

Conway and Schultz (1959), who demonstrated the phenomenon for electronic assembly products and electromachine products, argue that the learning from repetition of the same task is not very important but such factors as changes in tooling, production methods, design and volume, improvements in quality, and improvements in management have a more significant effect. Levy (1965) has divided various possible factors into three classes that he refers to as planned learning, autonomous learning, and random or exogenous learning. The first two correspond to the causes pointed out by Conway and Schultz above, and the last one implies the improvement based on information acquired unexpectedly from the environment.

Baloff (1966) suggested the possibility of the existence of similar phenomena in a wider range of manufacturing industries:

. . . the phenomenon usually results from an integrated adaption effort on the part of a variety of direct-labor, indirect-labor, and technical personnel, and it relies primarily on "cognitive" rather than manual "learning."

In terms of who learns what, engineers, supervisors, machine operators, maintenance men, quality-control personnel, and other indirect-labor employees can all make contributions through

. . . such cognitive activities as redesigning the product or process, altering raw-material and end-product quality specifications, evolving more effective maintenance procedures and finding the proper operating "balance" of a manufacturing process.

More recently Bodde (1976) discusses in detail the forces that make the learning curve operational. In addition to the efficiency increase in labor in which he included not only direct labor but also maintenance personnel, supervisors and staff members, he points out other factors such as the introduction of new technological processes and improved methods, effects of substitution in the products, technical conservatism that results in product redesign, standardization of the product, and economies of scale and development of a common experience base; Badde points out that the last factor is important especially in multiproduct companies. Hedley (1976), from his association with the Boston Consulting Group, summarizes the variety of factors as:

- productivity improvement due to technological change and/or "learning" effects leading to adoption of new production methods
- economies of scale and of specialization
- displacement of less efficient factors of production, especially investment for cost reduction and capital-for-labor substitution
- modifications and redesign of products for lower costs

Certainly the range of potential factors that cause the learning curve phenomenon has increased as the areas of observation have increased from the restricted area of the airframe industry to more integrated areas such as the electricity, steel, and chemical industries. Beyond this point, it is more appropriate that one recognize the learning curve phenomenon as a description of the evolution of an industry rather than just enumerating every possible cause. In this macroscopic viewpoint, the causes of the learning curve phenomenon can be related of the major events that have taken place during the evolution of the industry. The Department of Prices and Consumer Protection (1978) describes this clearly:

In the course of their evolution, most industries expand their scale of plant to achieve real-terms reduction in unit costs. This process is reinforced by two other factors; technological advances, which are usually embodied in newer, larger plants; and a process whereby managers and operators learn from experience how to operate particular technologies and facilities more effectively.

Thus, in addition to the various factors mentioned before that can be attributed to "learning", change in scale and technological advance must be considered as the major sources of the learning curve phenomenon.

6.3 EVOLUTION OF MANUFACTURING SYSTEMS

Before proceeding to the discussion of the implications, usefulness, and limits of the learning curve concept, it is perhaps wise to find a structural basis on which the relations between the general learning effect, scale increase, and technological advance can be discussed.

We will structure this on the basis of hierarchical decomposition and time dichotomy of the various causes raised in the previous section. First, let us consider the hierarchical level of an industrial organization. Here we follow the level classification by Cantley and Glagolev (1978); the unit level, plant level, organization (firm) level, and industry level. Each level in this classification is not very strictly defined; however, the classical observations in the airframe industry or the electronic or electromechanical assembly products in Conway and Shultz (1959) are examples, on the unit level. Cameras, time recorders, basic paper products, and glass containers are examples on the plant level or the firm level, and electricity and petroleum production are examples on the industry level.

Casual observation on the different levels suggests that in the higher levels, more factors would enter as the source of learning phenomenon. To look at the unit or the plant level implies that there is a given fixed plant (asset) and the learning implies the general effort toward increasing the efficiency of the given asset. Let us use the term "learning by doing" in order to express this subclass of learning. Stated differently, this learning by doing would correspond to the description by Joskow and Rozonski (1979): reduced labor requirements as tasks become routinized through repetition, more efficient production and labor scheduling and improved production control by management, improved routing and handling of material thanks to the engineering department of a firm which redesigns the capital equipment utilized by workers and makes changes in the operation of the plant.

This class of learning is the one associated with the learning curve in the traditional sense, i.e., for airframes, electronic products, electromechanical products, or more recently power plant construction (Kennedy and Allen 1979). The essential feature of this class is that the production process being looked at (or which will be looked at) is fixed and all sources of learning come from the minor improvements in an effort to utilize the given production facilities. In this case, it is assumed that the production process under consideration can be isolated from the surrounding environment and no major technical changes or scale changes occur over the time period of ibservation. In this situation workers learn in the sense that they do better and better as they work on the same (or a similar) job. Also workers and managers will get better in utilizing the given production facilities. Minor improvements may be achieved by design changes or changes in methods. That is, this class of learning is the result of a continuous effort towards better utilization by everyone who is related to the particular (isolated) production facilities.

In the higher levels, the learning becomes more sophisticated in nature and perhaps it is rather difficult to describe exactly who learns what. The people in research and development in a company learn about new theory or new technological know-how. The people in top management acquire information concerning the operation of the company. Here we refer to this class of learning as the "accumulation of knowledge." These possible sources of learning at different levels are also discussed in Cantley and Sahal (1979) from whom Figure 6.2 is taken. In this figure, the arrows represent information transfer, or "learning." They are of three kinds:

1. The circular arrows represent learning occurring cumulatively over time within a particular entity on its own level.
2. The vertical arrows represent transfer of information or know-how between levels.
3. The horizontal arrows represent transfer between an entity and other entities on the same level – whether or not within the same higher level

Thus, in addition to the possible learning inside each level, they stress the importance of information exchange across the boundaries of these levels.

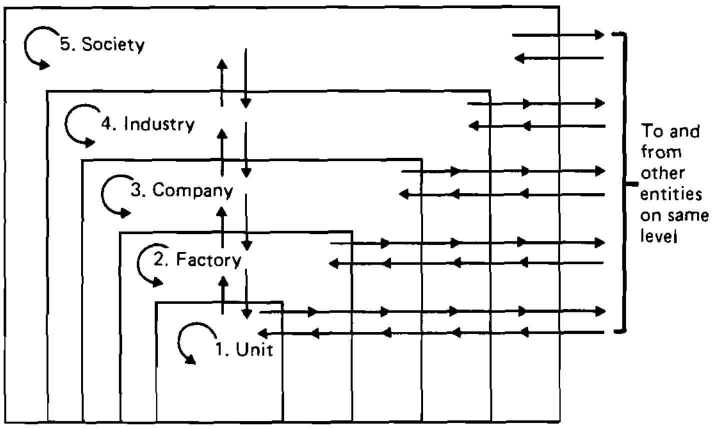

FIGURE 6.2 Levels and directions of learning or information transfer. Source: Cantley and Sahal (1979).

The second basis of structuring is related to the time horizon. Roughly speaking, the learning from repetition occurs in everyday work in a somewhat continuous manner, while design changes and other supervisory changes occur less frequently. Further, scale changes and major technological advance or changes occur much less frequently. These horizons were indicated in Lofthouse (1974), in which he used the terms "short run," "long run," and "very long run." He noted that such a treatment is always under criticism; how long is short or long or very long. But the horizons often serve adequately for structuring purposes. Learning by doing, defined above, tends to occur during the short run where no scale changes and technological advance would occur. In the long run, scale changes are allowed and in the very long run, technological changes are allowed. This implies also that the learning by doing is conditioned by scale and technology, and scale is conditioned by technology.

The discussion so far can be summarized into the hierarchical structure shown in Figure 6.3. Note that not all of the information flow is indicated; for example, there may be direct information acquisition in every box, which is not shown. Figure 6.2 would effectively supplement Figure 6.3. It is interesting to note that the structure is similar to one of the well-known hierarchical structures, i.e., the multilayer structure in which any action in the upper layer specifies the condition for the lower layer and activates actions in the lower layer; thus the actions in the upper layer take place less frequently than the lower-layer actions (Lefkowitz 1966, Mesarovic et al. 1970).

The broader class of learning, i.e., accumulated knowledge, resides perhaps in every box and it is rather difficult to show in the diagram. The role of this type of learning is conditioning; a certain level of accumulated knowledge enables a technological change or a scale change to happen.

6.4 USEFULNESS AND LIMITS

In the previous section, we sorted out various causes of the learning curve phenomenon

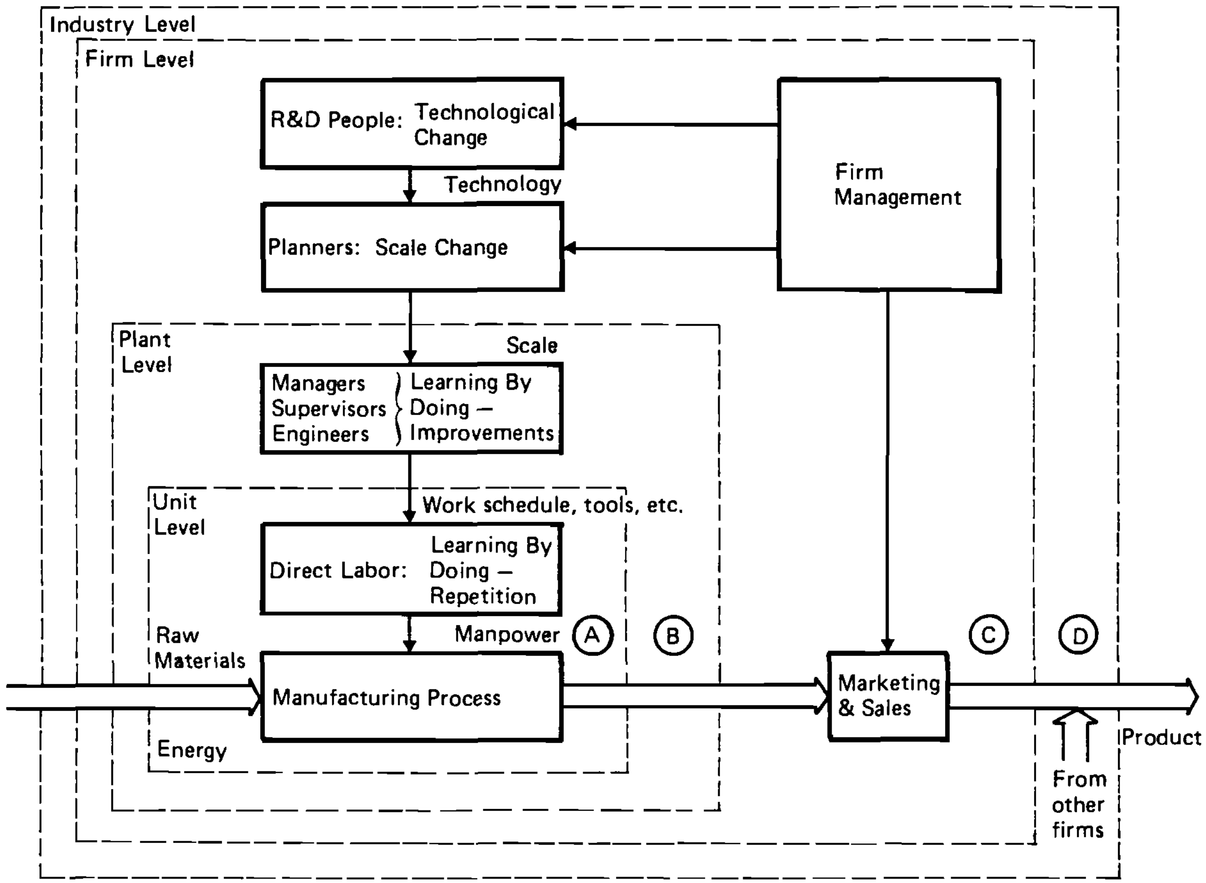

FIGURE 6.3 Conceptual hierarchical structure of manufacturing process: technology, scale, and learning.

based on a literature survey. It is clear from Figure 6.3 that the usefulness and limits depend very much on the purpose of using the learning curve and the level on which it is to be observed (this specifies the range of possible causes of the phenomenon).

In the early days, the learning curve was observed in the unit or plant level. Andress (1954), from his experience in the aircraft industry, finds the learning curve useful for estimating the direct labor cost, which then becomes a basis for price negotiation, make or buy decisions, and others. Since he essentially limits the major cause of the learning curve to the learning of workers from repetition (see the unit level in Figure 6.3), he suggests that every other possible cause must be removed from the raw data in order to get an accurate forecast. In fact, he did not observe similar phenomena in less labor-intensive manufacturing such as basic chemicals and petroleum production. Conway and Schultz (1959) also see the main purpose to be a means of estimating labor costs for pricing, major design changes, make or buy decisions, purchasing, and labor and facility needs for planning. Although they see the necessity for the aggregation of raw data in order to get more accurate forecasts, and hence consider various causes other than the literal sense of learning from repetition (and they do not believe that the learning curve represents a natural law), they conclude that progress can be predicted within some firms by the use of the learning curve, with tolerable amounts of error.

Young (1966) argues that even in the aerospace industry, the learning curve is not always meaningful because of the pessimistic estimate of labor needs, manufacturing methods, and tool changes, and so on, and concludes that there is a distinct possibility that the reduced labor trend may be caused solely by budgetary action.

More recently, as it has been observed in a wider variety of industries, the learning curve has been treated as an index that expresses the combined effect of various factors, including scale changes and technological changes. Abernathy and Wayne (1974) claim that the learning curve is a useful tool for strategic planning in marketing, financial planning, and production. Also, they imply that through exploiting the learning curve,

> . . . a strategy that seeks the largest market share at the earliest possible date can gain not only market penetration but also advantages over competitors who have failed to reach equal volume.

But they emphasize that cost reduction along the learning curve does not happen automatically, and a strict cost minimization strategy is necessary to pursue the benefits of the learning curve. Hedley (1976) points out similar implications of the learning curve phenomenon. However, by using the Ford Model T as an extreme example, they discuss some unfavorable consequences of pursuing the learning curve.

This creates a dilemma: "management must realize that the risk of misjudging the limit rises directly with the successful continuation of the strategy" and "production innovation is the enemy of cost efficiency." Similar arguments can be found in Bodde (1976). He finds the learning curve more useful in long-range strategic planning, especially in the formulation of competitive strategy, and denies its usefulness in operating controls or short-term decision making. And he concludes that

> . . . to apply the learning curve successfully the manager will need an awareness of the multi-dimensional forces behind it and how these forces can be integrated into the total strategy of the organization.

These arguments in the literature can be clarified from Figure 6.3. That is, the usefulness and limits depend on the point at which the learning curve is to be observed. In

Figure 6.3 four possible points (A through D) are shown. If we are observing the learning curve at point A, then curve would represent the literal sense of learning where all other factors that come from the level above the unit level are fixed. If the literal sense of learning can be isolated in the raw data, then the learning curve at this level will be useful to estimate labor requirements in the future for existing products or even for a new product. (Yelle (1979a) has proposed a disaggregation – aggregation approach for estimating the parameters for the learning curve for a new product.) By the nature of the learning curve, its applicability will be restricted to those products that can be produced more efficiently by learning from repetition.

If the learning curve is observed at point B, then it can show the effects of various factors. This is the situation where there is a given plant and the learning curve may be observed as an overall cost reduction effort. If the precise relation between each potential cause and the amount of cost reduction is known, then the curve may be useful for control purposes. However, in practice these relations do not seem to be easy to determine and the learning curve may be useful at the most for monitoring. As long as the danger associated with pursuing the learning curve too far is recognized by the manager, it can be a useful guide or index for his cost reduction effort at his plant.

The learning curve observed at point C may be useful for strategic planning at a company, as was shown in the Boston Consulting Group's study and in other studies (Hedley 1976, Abernathy and Wayne 1974, Bodde 1976). It provides an explanatory tool for the implications of holding a large market share. Again the limits of riding down on the curve must be well understood and care is needed to apply the learning curve in, for example, as Taylor puts it,

> defining the product, the market segment, and the stage in life-cycle, and in ensuring that management have the capacity to realize the potential cost savings, and at the same time maintain a high rate of product innovation.

The main sources of the learning curve on this level are categorized as technology, scaling up, and a broad sense of learning. How much would each category contribute to cost reduction? In some industries scale may be the dominating factor, whereas in others it may not. The recent study by Snow (1975) tried to separate the effects of economies of scale and technical advance in satellite communication. Derkx *et al.* (1978), in their study of the steel industry, which was referred to in the Discussion section of this chapter, were successful in seeing the economies of scale in a dynamic sense; the dynamic economies of scale in turn were used by Cantley (1979) to illustrate the case for protectionism.

Another possibility of using the learning curve on this level is to incorporate it into the model of technical substitution. Recent attempts by Robinson (1979a, b) may expand the usefulness of the learning curve concept.

At the highest level, we can still find a learning curve (at point D). Examples are electricity generation and petroleum (see Marchetti 1975). On this level the relation should be treated as a hypothesis backed up with some evidence. This hypothesized relation may be used in strategic planning in a wider sense, for example, in energy planning (Aronofsky and Blum 1978) or in global modeling (Roberts 1978), or in national strategic planing.

6.5 CONCLUDING REMARKS

The issues raised in the workshop discussion have been identified. These issues have been controversial and have been the subject of much literature in the past. I have tried to put the various points together by using a conceptual hierarchical structure that represents the evolution of an industry in the simplest way.

A general conclusion obtained in this directed literature survey is that the learning curve concept is useful at various levels of industry in somewhat different ways (serving different purposes), but at the same time one must be careful in applying this concept to a particular case.

What is lacking is a concrete model that describes the evolution of an industry and results in a learning curve. One such attempt can be found in the paper by Sahal (1979b), but there must be various types of models that result in a learning curve. Such a theoretical development and a demonstration in a particular industry would help to establish the learning phenomena better and to clarify its usefulness in a production application.

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