CHAPTER 6
Learning Curves

Learning curves, also called experience curves, are closely related to accommodating design changes; however, the scope of learning curves is generally far broader. Learning curves take into account all aspects of the product, its operation, maintenance, processing, and essentially all cost elements that can be tied to the product. Some products experience learning curves on the order of 70%, whereas the learning curve for products associated with very mature industries can be far more modest at about 95%. The single biggest factor in accommodating learning curves in product development and project economics is developing an accurate model with clear boundaries, where a learning curve will start and stop with a given technology. For example, assuming that a 50% learning curve will be in place after five years may result in exemplary product and project economics, but are systems, processes and strategies in place to allow that learning curve to be captured? In our particular case, we wished to take a closer look at the following:

1. Was there an appropriate learning curve value that could be used in overall project economic analysis that would accommodate the migration from one specific technology to the next given the relative immature state of the starting technology?
2. Does each technology have its own learning curve or is a new learning curve generated for each technology improvement?
3. If a single learning curve can be developed, when should it start, and how would it best be accommodated in overall project economics?
4. Assuming technology changes occurred, how and when should these changes be incorporated, if sufficient time has not passed or the technology does not allow for root cause analysis to be performed for failures in the field?
5. If the organization chooses not to make the technology generally available to the marketplace, how should the "doubling concept" be considered if competitive market forces for the technology do not serve as incentives for cost reduction? (This one really hurt our heads!)

Background

Learning curves can be utilized, especially by materials-based manufacturers, to gain a view into how costs may be reduced over time. The learning curve has been in use by managers since the advent of modern management techniques. The idea behind the learning curve is simply that as the number of units produced increases, the associated unit costs decreases in an exponential and asymptotic fashion as shown in Exhibit 6-1. Some firms, for example, semiconductor and chemical firms, use learning curves to predict production cost of integrated circuits or batches of chemistries while utilizing the same production equipment. These same firms do not use their current learning curve to consider the impact of the insertion of new technologies, but rather, create new learning curves based on the realities of new production processes.

Usually it is a bit easier to view the learning curve as a straight line by using logarithmic functions as shown in Exhibit 6-2.

Important characteristics to note when assessing a product's learning curve are:

![Exhibit 6-1. Conventional Learning Curve](image-url)
Exhibit 6-2. Learning Curve Using a Log Scale

(a) service or physical products;
(b) emerging or established technology;
(c) complexity of the product and/or manufacturing processes;
(d) number of subsystems in the product.

Complex products are characterized by:

(a) manufacturing processes with numerous and expensive capital equipment or extremely expensive building costs;
(b) highly skilled labor with many labor-intensive steps and that possess relatively low physical limits;
(c) processes with many subsystems requiring many steps or one system with many steps.

Non-complex products are characterized by:

(a) production processes with relatively few manufacturing steps and few costly pieces of equipment;
(b) elimination of much of the labor requirements through the use of automated and semi-automated systems;
(c) relatively high physical limits to the base costs;
(d) either having few subsystems or few steps in one system.

Large learning curve gains typically occur in materials-based products, which are characterized by high complexity and a high amount of labor. As a
general rule, a product that has a cost basis of 75% machine operations and 25% direct labor offers much lower learning curve gains than a product that is characterized by 75% direct labor and 25% machine operations. Consider semi-conductor manufacturing. Ten to twenty separate and unique masking and metallization steps are used to manufacture most chips. The production process provides 100–400 unique opportunities to lower costs through learning curve capture. Most learning curve benefits are obtained through decreased labor costs, increased throughput, and increased yield.

The reasons that learning can occur as production experience accumulates, include:

(a) direct labor, indirect labor, and managers learn;
(b) specialization, standardization, and methods improve;
(c) small routine innovations drive incremental learning;
(d) capital learning – as production increases manufacturing equipment is more fully exploited, thereby lowering fully accounted unit costs;
(e) as a company acquires experience, it can alter its mix of inputs;
(f) as experience increases, minor design improvements are identified;
(g) suppliers and distributors also obtain learning curve benefits, thereby improving the supply chain;
(h) as product use increases, consumer use is more efficient and effective; spill-over effects suggest that efficiencies gained from one product can be applied to other similar products, between people and between organizations. The latter being especially true with information technology.

Examples of activities and associated learning curve rates are shown in Exhibit 6-3.

To accurately use learning curves for developing a better understanding of the cost of producing assembled goods, a company should make a significant effort to determine the learning curve effect on major product subsystems and the final assembled product. This information should then be used to create a cumulative learning curve. Finally, the insertion of new technology should be factored into the cumulative learning curve to produce an overall learning curve that not only combines incremental production-related improvements associated with the existing technology, but also accommodates insertion of new technologies. But where does
Exhibit 6-3. Examples of Industries and Associated Learning Curves

<table>
<thead>
<tr>
<th>Product/industry</th>
<th>Time frame</th>
<th>Learning curve rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steelmaking</td>
<td>1920s-1950s</td>
<td>79%</td>
</tr>
<tr>
<td>Nuclear/Wind Energy</td>
<td>1990s</td>
<td>64%-79%</td>
</tr>
<tr>
<td>Repetitive Machining</td>
<td>1950s-1990s</td>
<td>90%-95%</td>
</tr>
<tr>
<td>Repetitive Electronics</td>
<td>1960s-1990s</td>
<td>90%-95%</td>
</tr>
<tr>
<td>Manufacturing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Machine Tools</td>
<td>1960s-1990s</td>
<td>80%</td>
</tr>
<tr>
<td>Model T Automobile</td>
<td>1910-1926</td>
<td>85%</td>
</tr>
</tbody>
</table>

one start looking? Certainly Exhibit 6-3 can be used as a starting point, but it is also important to consider analogous situations and products in addition to analogous industries. Broadening the scope of learning curve capture into these three areas (analogous situations, products, and industries) will provide additional insight into opportunities to be considered for learning curve capture. The point is that it is probably fair to assume a 90-95% learning curve (meaning a five percent to ten percent reduction of costs associated with each doubling of production output) when preparing project economics, but determining if greater learning curve benefits can be captured will require significant time and management effort.

**Application to Our Business**

In our particular case, based on the production processes expected to be used for the starting technology, and equivalent (and also mature) production processes available in industry at the time that would be used to manufacture our technology, it became quite clear that we should expect no more than about a 5-10% reduction in costs over time due to learning curve contributions within the starting technology. The primary contributor to this situation was the fact that the bulk of material processes we would use were well established in industry and suppliers had little to offer for capturing learning curve benefits. Even when proposed design revisions were considered to the starting technology, it was quite clear that the project must accommodate significant technological changes to meet economic hurdles. In other words, we needed to leap from one technology to the next as soon as possible; however, the follow-on technologies were even more immature than the current technology.
The integration of major innovation is generally not considered a part of conventional learning curve theory. Typically, technology is integrated into an existing system if there is a belief that over time the product cost will decrease (and/or product value will increase). A diagram of two learning curves and one of the potential paths associated with the two learning curves is offered in Exhibit 6-4 for illustration. The top curve represents the initial learning curve believed to be in effect with the existing technology, and the bottom curve represents the new learning curve based on a significant change in product technology.

The danger here is that it is extremely easy to get trapped into thinking about what future costs are expected to be, accommodate these projections into present day project economics, and then taking a decision to move forward when the technology has not been adequately tested. So predicting cost reductions based on learning curve capture can be hazardous and the following health warning is hereby issued:

*Health warning: Line of sight prediction of cost reductions is not always possible (i.e., defeats purpose of learning curves), but "people smoke in spite of health warnings.")

*People also speed in spite of speed limit signs—we think you get the idea.*

In our particular case, if we assumed that all planned technology innovations were successful and that the most cost-favored technology

![Exhibit 6-4. "Jumping" Across Learning Curves](image-url)
and structure were used, our cost improvements had the potential to mimic an 85% learning curve.

Why then couldn't our particular technology obtain a more aggressive learning curve (e.g., 75%) in terms of per unit manufacturing cost? The short answer was lack of market forces. Simply because a particular technology is an innovative product, it does not follow that a high learning rate and associated learning curve capture will occur based on cumulative production. Once again, if we think back to the semiconductor industry, the first 25–30 years of semiconductor manufacture was dominated by captive users of semiconductors that integrated these products into other products that were then sold. Semiconductors were innovative and creative; production involved a number of highly skilled and labor-intensive operations, and an order of magnitude higher number of steps for completion compared to many other technologies. The market was also small. Over that 25- to 30-year period, market barriers to entry began to lower slowly, but it was not until the advent of the personal computer that significant market barriers dropped and demand skyrocketed. Since demand outstripped supply, learning curve capture tended to not be a high priority within manufacturing and production until the memory chip crash. In the late 1980s, there was a major oversupply of memory chips, plants were closed, jobs were lost, and competition became stiff because of market forces in play at the time. As a result, the cost of memory chips reached an order of magnitude lower than what it was 20 years before. In our case, the technology only offered 40 to 50 manufacturing steps to capture learning, not 400. We also had no intention of marketing the technology, which thereby significantly decreased the opportunities to reduce costs through production doublings.

Another issue to come to grips with respect to learning curves is that firms learn differentially over time and with respect to the physical limits associated to specific design, process, or technology. Some studies suggest that organizational learning, captured through savings in labor requirements, is greatest in the first three years after initial start-up. In contrast, capital learning extends over a much longer time period and appears to increase over time. This suggests that new entrants to the market are at a relative disadvantage on the basis of physical capital productivity. However, new entrants also appear to have a relative advantage in terms of organizational and labor learning, which occurs very rapidly. Some
suggest that good entrepreneurs working with labor-intensive production techniques are able to learn faster and are therefore able to "out-compete" bureaucratic and formally managed incumbent firms as the learning effects attributable to the labor function are captured quickly.

Many consultants and practitioners also focus on predicting the "doubling" effect that can be obtained through the application of learning curves. However, this does not consider the asymptotic nature of learning curves over time. An easier way to consider the shape of the learning curve is to break a single nonlinear learning curve into two separate linear sections. The slopes of these two lines differ greatly and are determined by the forces that drive and retard learning curve benefits. The slope of the first line represents the early portion of a learning curve and is governed by the managerial capabilities, technological competency of a firm, and gains in the production of systems directly related to insights associated with initial movement from little knowledge of manufacture to great comfort with production requirements and opportunities. The slope of the second line is significantly smaller and is governed by the physical limits of the technology of choice. The first portion (or aggressive portion) of the curve is the portion of the curve associated with bringing the immature technology to a level mature enough to be deployed in the field. The second, or asymptotic portion of the curve, is defined by the technological limits of the system, processes, procedures and raw material costs.

In our particular case, a handful of possible technology changes were identified and subsequently integrated into project economies resulting in potential for savings through technology integration of approximately 50% of product cost. It was also anticipated that there would be additional savings associated with more effective and efficient manufacturing. That is, workers would require less time to complete tasks, scrap would be reduced, better organization of work areas, and other manufacturing improvements would occur. Ultimately, the savings associated with these costs would become limited solely by the base costs of the materials. To achieve lower costs for completed units, it became necessary to change the product technology, which required less raw material and raw materials that were less expensive. The change between product technology improvements would result in moving from a higher cost learning curve to a lower cost learning curve, would provide additional immediate savings, and would create a lower physical limit to the
minimum possible cost. In Exhibit 6-5, learning curves for several of the new, yet extremely immature, technologies for the production of the same product are shown. As in Exhibit 6-4, each curve in Exhibit 6-5 represents what we believed to be the learning curve associated with that particular technology. The difficulty noted here is that the physical limit of the current technology's learning curve would never be reached, since a new technology would be introduced that would induce a new and lower learning curve. This situation would repeat itself as each new technology was introduced. In Exhibit 6-5 we illustrate the introduction of five new technologies and their corresponding learning curves, starting from the initial and current technology. While it is a “mistake” to view movement across the individual learning curves as a single learning curve, our view of this “mistake” was that it was an “academic splitting of hairs.” We did not care about the source of the learning, we just wanted our costs reduced to the lowest practical level as quickly as possible. Our overarching strategy was to get the biggest bang for the buck out of each learning curve, by producing as few units as possible, thereby generating an overall learning curve that mimics the one shown in Exhibit 6-5. Keep in mind that Exhibit 6-5 represents a fairly idealistic approach. The reality was that we were constrained by funding, manpower, and the duration of field trials which would cause these learning curves to be more staggered in their starting points with respect to time.

Exhibit 6-5. Combining Learning and Technology Integration and Generating a Single Learning Curve
Another question posed was when to start including or counting learning curve effects. For mass produced products, counting typically starts at the time that volume manufacturing is launched. In our case, we were extremely interested in the learning curve cost reductions that would occur prior to any significant capital equipment being purchased. We chose to use the actual costs of the first prototype that passed all field trials as the start of the learning curve for that particular technology.

One last idea to consider regarding learning curve capture is to approach learning curves from a systems perspective. It must be realized that systems learning occurs over a longer period of time and that this learning usually starts at a later time compared to the curve for the initial technology. To make a cookie baking analogy, just because you have Grandma’s cookie recipe does not mean that the cookies you make taste like Grandma’s the first time out of the oven. The equipment and ingredients may be the same, but Grandma simply has more learning in her “cookie making system” than what the recipe identifies.

It is also necessary to gain operational experience to establish the start of the learning curve for the entire system. Learning curves are governed by the opportunity to learn, individually at first, and then as a whole, and are a function of the mechanisms chosen to accomplish the work processes. Given the maturity of the starting technology and its follow-on technologies, the lack of market forces, and the high-cost of raw materials, it was wrong, and naive, to arrive at the conclusion that after a given number of production units (256 in our case), the production cost would be about 10% of the original, if one believed that a 75% curve was truly achievable. Remember the health warning? Line of sight prediction on cost reduction can be hazardous to your health.

Realizations

Given the above discussion, one should realize the following before expending a tremendous amount of effort in accommodating learning curves in project economics:

1. While learning curves have been highly successful at estimating changes in labor productivity that occur after the onset of production
operations, the technique is less suitable for considering overall cost—unless cost and labor productivity are highly correlated.

2. If substantial effort is devoted to preproduction engineering and planning resulting in higher than normal labor productivity, the rate of learning will be lower.

3. Learning rates vary substantially among industries, products, and types of work. Past learning rates are guides, not rules or laws. Consequently, an overreliance on publicly stated learning rates is risky.

4. The rate of learning is time dependent and progress does not continue indefinitely. Asymptotes will be reached as the physical limits of material, processes, and equipment are reached.

In our case, and unlike semiconductors that start with low-yield/high-defect rates, it was anticipated that scrap and defect rates for our products and associated components would be very low, therefore learning curve benefits would be limited most likely to reduction of scrap, time, labor, inventory, set-up costs, energy, and other process-related events involved strictly in production. Unlike aircraft, ships, and vehicles, there was a relatively small number of parts, so there were fewer opportunities for learning curve gains. As much of the cost associated with the technology was directly related to base material costs, the physical limits to cost reductions through learning were limited to be somewhere between 70% and 90% of the cost of the product.

So where are we at? Cost reduction through the "learning by doing" approach is comprised primarily of reducing cost through labor productivity, minor innovations, lower capital costs, organizational learning, energy efficiency, and other incremental volume-related savings. Cost reduction accomplished by technological advancements is equivalent to jumping across individual product learning curves. This approach focuses on improvement by adopting new learning curves with strategically directed organizational learning and technology development and then by integrating volume-based learning in the more traditional fashion of learning by doing. Strategically directed learning can be accomplished within a given technology and structure through technology innovation and integration only if mechanisms are in place to force the jumps across the learning curves. The central difference between movement among...
design revisions within a technology and movement among different technology improvements is that movement among different technology improvements can result in a substantial reduction in the physical limits of the learning curve.

So here are a few guidelines in taking on the learning curve question. Greater opportunities for learning curve capture occur when:

1. There is high complexity of products and processes
2. There are high labor requirements
3. Firms are interested in learning and in taking a strategic approach that forces learning.

Returning to the R&D Discussion

You may be wondering at this point how all this discussion relates back to supply chains and research and development. First, it is important to understand that decreases in supplier costs are not automatically given to the buyer. As a matter of fact most suppliers seek to retain as much of the cost benefit as they possibly can. One's knowledge of learning curves, and where a particular supplier is at with respect to capturing learning curve gains is necessary to develop effective supplier engagement strategies.

Second, the application of the learning curve concept, and potentially using it to reduce costs, does not seem to be a realistic approach when dealing with commodity suppliers, but may work well with those suppliers that would be considered as “captive” to your requirements. If a captive supplier’s books are open to the customer as a whole, then the customer can identify and hopefully extract learning curve benefits. The difficulty with this approach is that firms that operate on a cost-plus basis are not motivated to find learning curve benefits. In fact, if profits are negotiated as a certain percentage of costs, it is advantageous for the supplier to try and inflate costs to ensure the highest possible profit.

Third, inducing internal and external competition through consideration of make versus buy decisions may change the entire thought process on supplier relationships. In the research and development phase, significant emphasis must be placed on the make versus buy analysis.
If potential suppliers are almost as disadvantaged as you are with respect to your product requirements, there is significant opportunity for the firm to capture the learning curve all to themselves by taking a “make” decision as opposed to a “buy” decision for the particular product. Of course, one should also expect some upper management arguments along the lines of “manufacturing this widget is not our core competency” and/or “why can’t we just pay someone else to do it?” In our case, we were simply unable to present a business case to different suppliers that provided sufficient motivation in terms of project timing, product costs, change orders, risk management, and so on, to effectively engage suppliers to share learning curve benefits as part of our research and development program. We paid top dollar on non-commodity items mostly because we were an interruption to our suppliers’ production processes. Additionally, when our suppliers considered the future potential of their participation in our technology development and project scopes, their more pressing needs of today far outweighed the opportunities of the future. As one supplier said, “hope is a great breakfast but a lousy dinner.”

Final Thoughts

Hopefully by now, a few ideas regarding learning curves and their impact to the supplier engagement strategy are beginning to form. Of equal importance is that one must also understand the reluctance on the part of suppliers to participate in learning curve benefits as part of the overall supplier engagement strategy. Additionally, there should be a couple of ideas regarding how to fend off management intent on using learning curves to make project economics look better and why doubling does not automatically reduce costs. Oh, by the way, in case you were wondering what we ended up doing, we used an overall 85% learning curve in our economics. This was based on an 82% learning curve with the starting technology which then moved to a much cheaper alternative that was 3–4 years behind in development but which only had the potential for a 95% learning curve. Since we were not planning on marketing the technology, we eliminated the opportunity for market forces to drive down costs through competition. Ultimately, we abandoned the effort to try and establish a “system” learning curve. Our 85% curve was strategically...
directed and jumped from one technology to the next. It also assumed that any field failures associated with each of the new technologies under development would quickly resolve themselves to meet commercial project requirements. Perhaps it was a bit conservative, but we must remind you of the previously stated health warning:

"Line of sight prediction of cost reductions is not always possible (i.e., defeats purpose of learning curves), but "people smoke in spite of health warnings."