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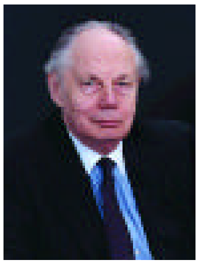

By ***Stephen G. Revay***

The article by Zey Emir in this issue describes the theoretical and the practical applications of learning curves for both managing construction projects and analyzing loss of productivity claims. The theory is well recognized in an assembly-line-type of environment, but its usefulness has, at times, been questioned in construction. After all, as the non-believers argue, tradesmen are already well experienced in their craft when they arrive on a project. Unfortunately, this argument is seldom sustainable, particularly during a buoyant economy. On any new project, workers always require time to learn to perform their specific tasks well. It has also been said that most construction activities are of a non-repetitive nature. It is true that any two projects are seldom identical; but within the same project many tasks are repetitive, at least to some degree. Anyone who has done the same or a similar task twice recognizes that, barring disruptions, it takes less time to perform it the second time. Nobody could disagree that forming the tenth slab in a high-rise building takes less time than the first one even though the slabs may not be identical. In 1965, the United Nations issued a report describing the results of extensive research on the beneficial effects of repetition in construction operations. The report clearly indicated that more complicated tasks (e.g. erecting formwork) displayed greater improvement in productivity as a result of repetition than simpler tasks (e.g. stripping formwork). These results were subsequently confirmed by a number of independent researchers whose findings were published in the journals of various learned societies as well as by our own experience, monitoring productivity on numerous construction projects. A word of warning, however, repetition will not automatically improve productivity. Such improvement requires a concerted effort by management.

LEARNING CURVE IN CONSTRUCTION

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PRODUCTIVITY

In its broadest sense, "productivity" is the measure of output (the work produced) per unit of input (various cost items that are incurred). Although productivity is often thought of as relating to labor only, in practice it relates to any resources used to produce a result.

Lost productivity is not necessarily measured based on the optimized utilization of resources to maximize output. Contractors frequently decide — for practical reasons — that maximizing output is not in their best interest, or they fail to maximize output due to their own shortcomings. However, no matter how inefficiently a contractor has performed the contract from the outset, it may still be exposed to reductions in the level of productivity it anticipated due to disruption of the work routine by others — and that loss of productivity may be compensable.

HOW DO WE MEASURE THE IMPACT OF THE DISRUPTION?

Clearly, one should not compare the productivity during the period of disruption to a theoretical value reflecting optimum or near optimum efficiency as the Contractor may not have been working at that level of efficiency prior to the disruption. Similarly, however, the Contractor should not be deprived of recovery because the tradesmen were not efficient prior to the disruption. The loss, therefore, should be the difference between the actual manhours expended to produce the output, and the would have been manhours required to produce the output but for the disrupting event.

MEASURED MILE

In recent years, techniques least favored by courts and arbitration boards for measuring damages have been the "total cost" method and the "modified total cost" method because these methods do not allocate the responsibility for the loss. In other words, the quantity of the loss is, in effect, offered as proof of the loss for which the Owner is responsible. Courts tend to hold contractors to more rigorous standards when damage claims are based on hypothetical baseline productivities. Such claims are viewed as self serving and simply subjective. Instead, courts seem to favor claims that are as closely linked to reality as possible.

The method of calculation most favored by courts uses some cause and effect analysis to prove damages. The most convincing evidence of loss of efficiency results from comparing the work done during an impacted period with work done during a period of unimpaired productivity. The best measure of the baseline against which the loss of productivity is established is that productivity which has been actually achieved performing the same task on the same project. For example, if a particular task is impacted by a change introduced after 30% of that task has been completed, the productivity realized prior to the occurrence of the change is the best possible baseline for proving and calculating the loss of productivity caused by the change.

This approach is known as the "measured mile" method. The "measured mile" method is used to calculate productivity losses by comparing productivity rates achieved in unimpacted work periods or "normal periods" to productivity rates experienced during periods of claimed or alleged impact.

The "measured mile" approach is also more readily accepted by Owners because it inherently adjusts baseline productivity to account for inefficiencies caused by the Contractor. It takes into consideration the productivity losses which are caused both externally and internally. For this reason, the "measured mile" method has been recognized as a superior method of measuring inefficiencies. This approach also represents the most objective method of claim presentation because, instead of using industry averages for comparison, control figures come from the project itself, such that the quantification of loss of productivity represents the particular project and the particular circumstances of delay actually experienced. This method also eliminates disputes over the validity of cost estimates, or factors which may have impacted productivity due to no fault of the Owner. As a result, the "measured mile" approach is valid even where the Contractor's bid estimates are unrealistic.

The underlying assumption in the "measured mile" method is that the productivity rate achieved during the unimpacted period would have continued in the impacted period (and even improved with the learning curve) but for the Owner caused events that impacted production. The claimed amount is then calculated based on the difference in the productivity rates.

LEARNING CURVE

As crews or individuals produce more of a product, the unit cost of production typically decreases at a decreasing rate. This effect is commonly called the "learning curve". The learning curve demonstrates that there is a steadily decreasing number of manhours required for a given operation when that operation is repeated. With a straight line learning curve, the rate of decrease is assumed to be constant each time the number of repetitions doubles. The effect is that the absolute amount of decrease is less with each successive unit produced. After a considerable number of repetitions, the learning curve approaches a plateau that reflects the minimum time required to perform a task.

The learning curve theory is often applied in the construction industry where the work is repetitive and continuous. For example, when the design calls for repeated utilization of the same concrete forms in high-rise or multiple building construction, the productivity may be susceptible to learning curve analysis. The same is true for rebar work, concrete placement, or the rough-in and finish work of the trades, as long as there is a relatively constant percentage reduction in the input required to produce an item as the production quantities double. For example, an 80% learning curve represents a 20% reduction in the time it takes to produce units one and two, an additional 20% reduction in the time it takes to produce units two and four, units four and eight, units eight and sixteen, etc. as shown in Table A.

The most obvious application of learning curves is forecasting manpower requirements. Specific examples in the construction industry include estimating overall average productivity in order to arrive at a competitive bid price or establishing a project schedule based on anticipated rates of progress. Costs as well as durations of the project can therefore be quantified with greater accuracy by applying learning curves.

Table A

Unit Cost-Quantity Relationships for the Learning Curve Factor of 80%

Cumulative Production	Unit Cost
1	100
2	80
4	64
8	51
16	41

Another application of learning curves is that of construction claims and disputes. Learning curves can be used in determining the cost of acceleration, where the Contractor is required to work overtime or alternatively use additional crews to perform the same work. An obvious result of this acceleration is the increase in labor costs if the crews work overtime for which they are paid a premium. An equally important but not immediately apparent result however, is the loss in the improvement in productivity which would be expected as the result of repetitive work. In other words, if the same amount of work is being done by two crews rather than one, then each crew will have half the number of repetitions. Simply stated, the crews will not achieve the same level of proficiency as originally anticipated — the routine-acquiring effect is cut short, thereby raising the average time required to produce a single unit of work.

When a Contractor is required to stop work temporarily on a certain operation, the crew may be assigned to other work or may be laid off (depending on the expected duration of the delay). When, the cause of the delay is removed and the Contractor is required to resume the interrupted operation, it may be necessary to restart the learning process.

When a Contractor is required to perform extra work, the cost of the work is usually reimbursed on either a cost-plus or a negotiated price basis. If the extra work assigned to the Contractor represents a large number of repetitive units, the result may be that the additional units are performed at a lower cost because the Contractor will move further down the learning curve in performing these units. In this situation, the average bid price may be too high. This would only apply if both the original and additional units are produced by the same crews. If the additional units are produced by a different crew, the learning curve may start over and the cost for the units would be higher than the original cost.

If the extra work assigned to the Contractor is of short duration and relatively non-repetitive, then the additional work is performed at a higher cost. Similarly, when a Contractor is working on a large number of repetitive units, the earlier units will have a higher average unit cost. If the later units are deleted from the scope of work and the lower cost units are not produced, then the Contractor will not be able to recover its tendered cost estimated using average rates.

HOW IS THE IMPROVEMENT IN PRODUCTIVITY CALCULATED?

The learning curve is a mathematical, graphical or tabular representation of how resources such as manhours are reduced as the production of a product or a service is repeated. The learning curve can be expressed mathematically as:

$$y = ax^{-n}$$

where,

y = manhours to produce the xth unit

a = manhours to produce the first unit

x = number of the unit

n = exponent that relates the learning curve factors to the learning curve slopes.

This theory states that the unit cost decreases by a fixed percentage of the previous unit cost each time the number of units produced doubles. This fixed percentage is identified as the learning curve factor. On operations that are machine paced and for which there is no improvement in output, the learning curve factor would be 100 percent. For complicated tasks without external restraints, the rate of improvement might be as much as 70 percent. In other words, the second unit would take only 70 percent as long to produce as the first, and the 32nd only 70 percent as long as the 16th, and so on.

Typical learning curve factors for construction operations fall in the 70 to 90 percent ranges. Figure 1 shows units and the corresponding manhours for one particular learning curve factor, i.e., 85 percent.

The effect of variable learning curve factors on the manhours per unit is demonstrated in Figure 2. As seen, a higher learning curve factor (i.e., 90%) amounts to less improvement than an 80% learning curve factor as the cumulative production quantity increases. It follows, then, that the learning curve effect is more evident when operations and even entire projects are of a unique nature.

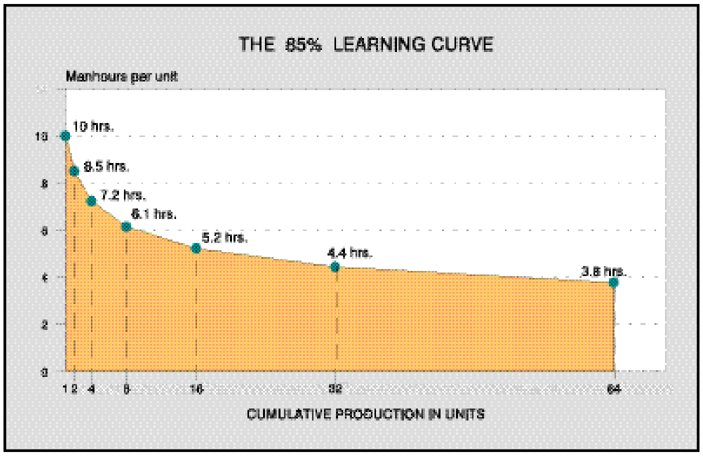

Figure 1

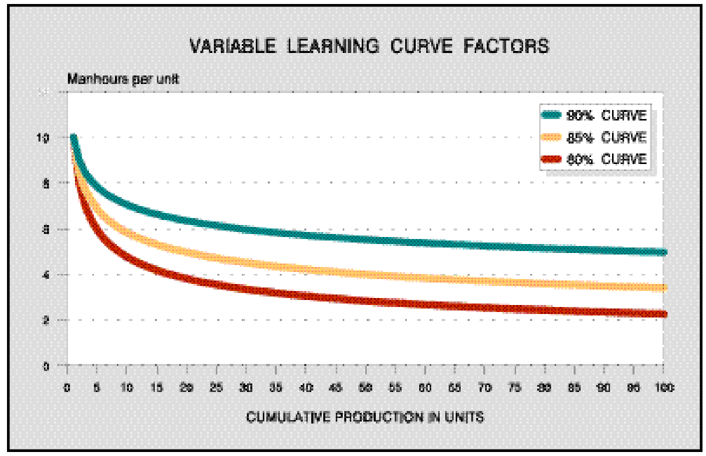

Figure 2

LEARNING CURVES IN CLAIMS ANALYSIS

Learning curve analysis can be very useful in measuring loss of efficiency, especially when detailed productivity records are maintained throughout the duration of the project. The learning curve effect should be used when preparing a "measured mile" analysis. The damage quantification will yield inadequate results if the unimpacted productivity rate achieved while performing the earlier units is compared with the production during the impacted later period. Instead the unimpacted rate of productivity or the "normal period" should be adjusted for what productivity would have been without the impact — i.e., incorporating the learning curve effects before comparing it with the productivity during the impacted period.

This is particularly true when one considers that given an 85% learning curve, the time required to produce the 8th unit will be only 61.5% of the time it took to produce the 1st unit. Thus, if one were to use data taken from the first or second time a repetitive task was performed, and use that data to prove how long it should have taken the 8th time the same task was performed (without taking into account the learning curve), one would significantly overstate the amount that task should have cost. As a result, the loss of productivity measure would fall short.

It is important to note that a learning curve is simply a representation of the expected decrease in input per unit as the cumulative production increases. In order for the calculation to be useful and accurate, one must have reliable recording of the actually achieved productivity. If the data is sufficient in quality and quantity, then it can be used to predict the manhours required during the impacted period.

LEARNING CURVE APPLICATIONS IN CLAIMS ANALYSIS

Case 1

One case where the learning curve analysis was used involved the construction of a precast segmental bridge. Individual precast units or segments were manufactured in a precast yard located close to the site, which were then erected and secured together by longitudinal post-tensioning to form each span. The two lanes of the bridge were composed of 50 spans each; furthermore, each span consisted of two pier segments placed on the piers and ten typical segments.

The precast segments were fabricated in a special mold or "casting bed" where a new segment was cast against its older neighbor to achieve a perfectly aligned or "match cast" joint. There were three casting beds for the typical segments and one casting bed to produce the pier segments. Each segment was marked by a specific identification number which represented its proper place on the bridge.

The obvious profit potential in such a construction is in the repetition of segments in the casting yard. A long, straight bridge or elevated highway is a precaster's dream as the Contractor can achieve a level of expertise relatively quickly. The Contractor on this project, however, encountered considerable delays in the casting yard. One of the reasons for the workers' slowness in mastering the casting of the bridge segments was the complexity of the units. The construction drawings revealed that these segments had significantly more internal tendons than segments in most span-by-span construction. This resulted in an increase in manhours required to produce each segment in addition to increased overtime in order to accommodate the milestones on the span erection schedule. The claim analysis focused on determining the additional unit costs incurred in the casting yard.

The Contractor maintained very sophisticated cost records, such that the timesheets clearly differentiated between tradesmen placing rebar, pouring concrete or working on the formwork. Overtime hours and regular hours were also identified for each different trade. A different crew was assigned to each casting bed and the Contractor had detailed records showing which segment was fabricated in which casting bed.

The first step was to determine the weekly typical segment production based on the as-built information available. The typical segment productivity was plotted per each group of 15 units cast as shown in Figure 3. The reason for sorting the units fabricated in groups of 15 was based on having three casting beds operational five days a week.

The second step was to establish a "normal period". A detailed analysis of the typical segment productivity chart demonstrates that the average unit cost started to even out and reach a plateau at segment number 285, which represents approximately 30 percent completion. Once the "normal period" is identified on the productivity chart, the analyst must verify that a sufficient amount of work was performed to demonstrate the Contractor's ability to perform at that observed rate over an extended period of time. Another criterion to be met is to ascertain that the work performed during the "normal period" is representative and similar in all aspects to work performed during the impacted period. As a final test, to avoid mistakes due to biased sampling, asserted production during the "normal period" should be checked against the bid estimate and manloaded schedule to see whether production is unrealistically high.

The productivity during the "normal period" is then designated as the upper limit of proficiency. This upper limit or normal productivity serves as the basis of a scale to determine the level of input (i.e. unit cost), for the earlier units based

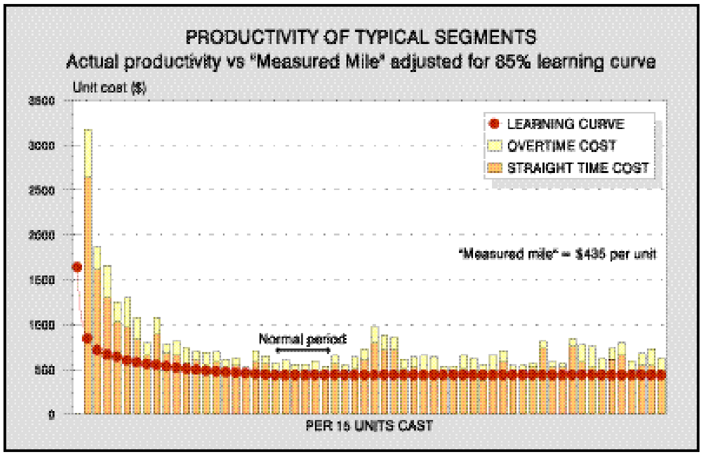

Figure 3

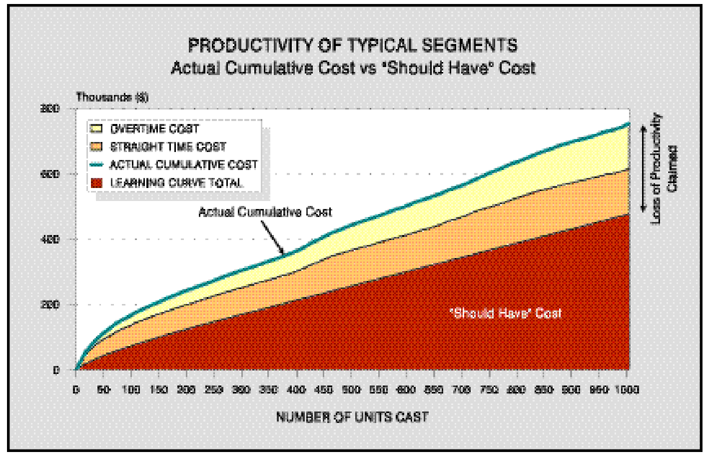

Figure 4

on learning curve. In other words, the project learning curve is calculated using the normal period and is extrapolated over the entire project time line, which then represents the baseline productivity. The learning curve is plotted against the actual productivity as seen in Figure 3. Any actual hours above the baseline are deemed to represent loss of productivity over and above those inefficiencies which are inherent to or the responsibility of the Contractor.

The cumulative loss of productivity for the project represents the difference between the actual total cost and the "should have" cost as illustrated in Figure 4.

Case 2

Another example of the application of the learning curve involved a drywall subcontractor, who incurred delays and additional costs due to interferences and difficulties encountered in relation to the mechanical and electrical design.

The first step was to establish the subcontractor's actual productivity for studding and drywall installation for the entire duration of the project. For this measurement, productivity was expressed as the ratio of actual input of labor (i.e. manhours), to the ratio of progress (i.e., labor content of percentage complete) of contract.

The next step was to determine the unimpacted or the least impacted period. The project history revealed that during the first six months (first quarter) of the project, the work force was constantly relocated due to lack of access to available areas. The re-design of mechanical and electrical systems was done during this time. Once the re-design of the systems was completed, the manufacturing of additional or modified components had a further delay on the installations and extended well into the second quarter of the contract. The third quarter represented the "normal period" with the least interference impacting the drywall system installation. The normal productivity or the "measured mile" was considered to be the level of productivity which the subcontractor, under normal circumstances, could have maintained for the duration of the project.

The baseline hours to complete the entire project were calculated based on the "measured mile" adjusted for the learning curve effect where the upper limit of proficiency was set at 33 percent progress. This percentage complete was selected to represent a point at which the subcontractor had performed a sufficient amount of work to reach a plateau on the learning curve.

The total loss of productivity was then calculated as the difference between actual manhours and cumulative baseline hours.

CONCLUSION

The use of learning curves as a tool to determining equitable adjustments has been recognized by courts and arbitration boards. The general theory of learning curves is that with repetitive tasks involving a considerable amount of labor, the speed or efficiency with which the task is performed increases as the number of units of work increases. In general, there is leveling off in any increase of productivity when the normal productivity is said to reach the upper limit of proficiency.

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