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Loss of Learning in Disruption Claims

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It is generally accepted that a worker learns as he works. There is also wide recognition that the more often the worker repeats an operation, the more efficient he or she becomes. The result of that efficiency is a decline in direct labor input required to continue performing the operation. It is then reasonable to assume that, as efficiency improves and the amount of direct labor input (hours) required to perform the operation decreases, the productivity of that worker increases at a corresponding rate during a given time period.

Productivity refers to the quantity of units produced per direct labor input, or hour of effort. Specifically, productivity is the ratio of output to input. Productivity loss, therefore, generally means that the planned rate of production is not being met and a worker is spending more per unit of production than originally planned [1].

There are many causes for lost productivity, most of which are either a result of a disruption to the planned workflow or result in a disruption to the planned workflow. An example of lost productivity that is the result of a disruption might be defective or late engineering releases that prevent a continuous flow of structural steel installation. On the contrary, a disruption may be the result of worker absenteeism. In both cases, worker efficiency is reduced, and productivity is less than planned.

The acknowledgement that a worker learns as he works resulting in improved efficiency has given rise to the basic theory of the learning curve. This theory simply states that the rate of improvement is predictable and this predictability can be expressed in the form of a curve. Likewise, if this learning process is disrupted, the result is a loss in productivity.

This paper will explore both the learning and loss-of-learning experienced during the workflow, relate those concepts to disruptions in the planned flow of work, and discuss how to quantify the impacts of those disruptions.

For purposes of this paper, the following definitions are presented:

- Productivity refers to quantities produced per employee hour of effort (work-hour). It can simply be expressed as Output ¸ Input. To improve productivity, the work-hours must be reduced [8].
- Efficiency is the degree by which productivity is yielding the desired results. Efficiency occurs when the output is either constant or increasing with continually fewer hours being expended. In this case, productivity is improving.
- Inefficiency is, therefore, the degree by which productivity is not yielding the desired results. Inefficiency occurs when the output is either constant or decreasing with continually more hours being expended. In this case, productivity is not improving.
- Lost productivity means that the planned rate of productivity is not being met.

LEARNING CURVE THEORY

The concept of the learning curve was introduced to the aircraft industry when T.P. Wright published an article in the February 1936 Journal of the Aeronautical Science. Wright described a basic theory for obtaining cost estimates based on repetitive production of airplane assemblies. The underlying hypothesis of the learning curve is that the direct labor work hours necessary to complete a unit of production will decrease by a constant percentage each time the production quantity is doubled.

The learning curve was originally derived from the phrase *learner's curve* and adopted the concept that individuals performing repetitive tasks exhibit a rate of improvement due to increased dexterity. It held the notion that the mental and muscular adjustments made by an individual from the time he or she performs a task for the first time to the time it is repeated result in a reduction in the time required for each repetition of a uniform unit of work.

Over the years as this concept was applied more broadly within the manufacturing industry, observation and analysis discovered that the causes of improvement are really more complex than that. Dexterity on the part of individual workers is only one reason for productivity improvement. Changes in the work environment, work flow, worker morale, management practices, and design are some other reasons for improvement. As this evolutionary thinking continued, the meaning of the word "learning" in learning curve held less significance as the understanding of improvement curves gained wider acceptance. Throughout this, the phrase learning curve has remained unchanged.

The rate of improvement is referred to as the learning rate and is expressed in terms of slope of a curve. There have been several mathematical models developed to show the effects of the

Table 1–Examples of Cumulative Average Time per Unit for Two Different Ratios

Number of Units in Sequence	Cumulative Average Time per Unit 90% Ratio	80% Ratio
1	100.0	100.0
2	90.0	80.0
4	81.0	64.0
8	72.9	51.2
16	65.6	40.9
32	59.1	32.8

learning rate but the straight-line unit learning curve is most widely used in construction [4,5]. The formula for this model is given by the following equation:

$Y = Cx^{-n}$

Where:
Y = cumulative average work-hours (cost) per unit of production
C = work-hours (cost) required for the first unit
x = the sequence number
n = the slope of the logarithmic transformation of the learning curve

(equation 1)

The slope is negative because the cost per unit decreases with production.

The learning rate (decimal ratio expressed as a percentage) is given by the following equation:

$S = 2^{-n}$

(equation 2)

In Table 1, the time taken for the first unit is 100%. At a 90% ratio, the average time taken for the first and second unit is 90%, i.e., the actual time taken for the second unit is 80%. By the time the fourth unit is reached the average time taken for all four units is 90% x 90% = 81% and so on.

These values can be plotted as curves as shown in Figure 1. However, if the same data is plotted on log-log paper as shown in Figure 2, the result is a straight line, which is more useful for manual analysis or mathematical illustration.

For a given job the slope is constant, meaning that the learning rate is constant as well. This should not be confused with a constant productivity rate which is typically used in estimating and tracking construction projects.

A constant productivity rate is used because it is assumed that the productivity rate (e.g., Output/Input) never changes throughout the project. Based on the definitions provided herein, this is generally not true in practice. As workers continue on the assigned task, they develop, for a number of reasons, the skill to perform that task with increasing efficiency and therefore productivity increases. This is called the "learning effect."

APPLYING LEARNING CURVE THEORY TO CONSTRUCTION

It is clear that the use of the learning curve has been most conspicuous in airframe production where conditions were most favorable for its use. Historically this was true because of the nature of the work involved in that type of production where assembly operations were predominate, non-mechanized, and repetitive. Given the evolution of conventional wisdom that improvement comes in many forms and seeing that the very nature of airframe assembly has transformed in recent years, the use of learning curves has managed to adapt to various applications. One of those adaptations can be seen within the construction industry.

Although not as widespread, learning curve theory has been used successfully to explain improvements in productivity within

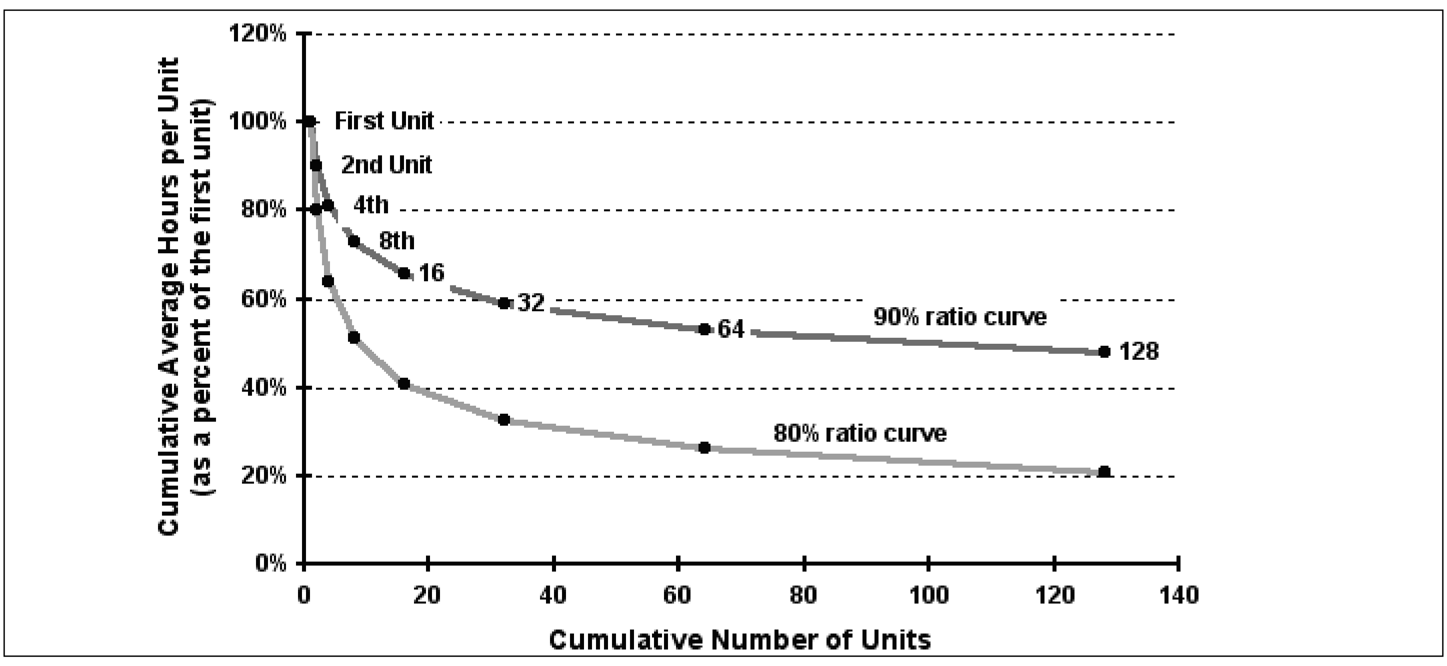

Figure 1—Illustration of Learning Curves

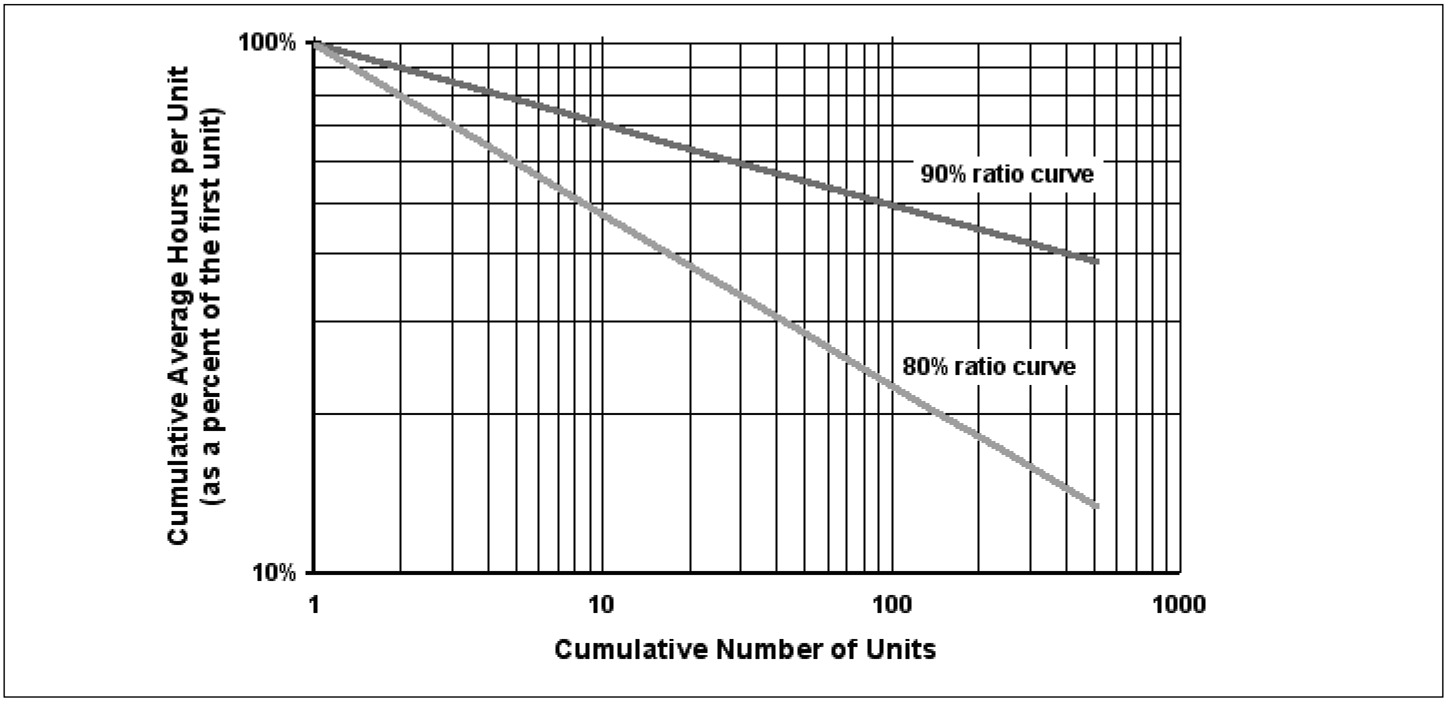

Figure 2—Learning Curves Plotted on Log-Log Scale

certain construction crafts. The Continuous Improvement Is Normal (CIIN) model uses the learning curve as its basic tenant, but with modifications to allow for mobilization and demobilization as well as the portion of work that does not improve [9]. Many papers have been written on methods for applying construction data to the learning curve model. One such paper strongly recommends the use of either the Cumulative or Unit Learning Curve Models for all contractors as an estimating tool [12]. A study was conducted within the Hensel Phelps Construction Company that applied a straight-line learning curve model to quantify formwork productivity for spandrel beams installed on a high-rise building in 1985 [14].

The Hensel Phelps study analyzed both unit cost data and cumulative average cost data from the formwork crew. The cumulative average approach tends to smooth out the data and generally makes the data appear better by reducing the amount of variation as compared to the unit data. Based on this, it has been suggested that the unit data curve is best for monitoring and controlling current work activities and in detecting short-term variations. The cumulative average curve, on the other hand, is best suited for estimating purposes [14].

As with every analytical tool, there will be cases where the learning curve theory is not entirely appropriate based on specific circumstances of a project. As explained, certain conditions are better than others for capturing the maximum benefits of the theory, such as a constant work force, unchanged work conditions, and a consistent design. These conditions are generally assumed to exist during the bidding phase of a project and, as such, the learning curve offers significant value at that point as an estimating tool.

This is particularly true when establishing a productivity baseline that reflects the conditions assumed at the start of a project, i.e., while the work is unimpacted by changed conditions. This process is commonly referred to as establishing the "measured mile."

"The measured mile process requires that a definitive estimate be prepared. A definitive estimate is the most common estimating approach used for construction projects. The most widely-used method for preparing a definitive estimate is the unit or line-item cost method [10]." This is yet another example of how the learning curve is of value to a construction project. It can provide an accurate and detailed accounting of the planned workflow at the unit level that can be used for tracking and monitoring progress.

The use of learning curves for determining planned productivity and lost productivity is rather simple once there is a basic understanding of the theory. There must also be general agreement of the following assumptions:

- Learning curves provide a valid method for estimating the costs of work that continues in a somewhat repetitive manner.
- Improvement occurs with this repetition at a predictable rate.
- Learning curve theory is applicable to construction in the same manner as manufacturing.
- Disruptions in the planned workflow result in a loss of productivity.

LOST PRODUCTIVITY AND THE LEARNING CURVE

"The most widely accepted method of calculating lost labor productivity is known throughout the industry as the "measured mile" calculation. This calculation compares identical activities on impacted and nonimpacted sections of the project in order to ascertain the loss of productivity resulting from the impact [11]." Not only does the measured mile process calculate the initial project (unimpacted) baseline, but it also identifies the same activities (impacted) after a change has occurred.

Changes that impact the planned workflow include such events as design changes, changes in working conditions, and changes in the workforce. These events were introduced earlier as being assumed conditions necessary for proper learning curve application. The hypothesis emphasized in this paper is that in the same manner that the learning curve theory identifies productivity in the assumed, unchanged baseline, it can likewise be used to identify productivity losses after a change has occurred.

Lost productivity was earlier defined as occurring when the planned rate of productivity is not being met. There are many causes for lost productivity, most of which are related somehow to a disruption in the planned flow of work. Twelve commercial sites in the United Kingdom were studied showing documentation that disruptions caused an average daily efficiency loss of 35 percent [13]. Another review of eleven masonry projects in Pennsylvania showed that disruptions accounted for more than 50 percent of the variability in the data [13].

Several things may happen when a disruption occurs and work is stopped. Work crews and supervisors may be reassigned to other activities or dismissed altogether if the disruption is long enough. The flow of work may become disorganized and get out of sequence. In either case, productivity is not the same after the disruption as before. When work is resumed there is a certain amount of "re-learning" that must take place and, during that time, the worker is less efficient, meaning there is a corresponding loss in productivity.

This assertion is supported by analysis of the concrete structural frame of a hotel building constructed in Worchester, Massachusetts, that experienced a disruption in the form of a labor strike [7]. By looking at only the portion of the study dealing with stair wall panels, the following data is provided in Table 2.

This data shows a definite shift in both the individual unit cost and in the cumulative average cost as work resumed from the disruption. The research conducted during this study noted no significant change in personnel or working conditions before and after the disruption.

Theories abound with respect to why this loss of productivity occurs but most converge on a learn-forget-learn theory that impacts worker efficiency after a disruption [2, 3]. There are also various approaches offered on how to quantify the value of the loss, some more subjective than others. Again, most of those approaches have evolved through manufacturing channels and have varying degrees of applicability to construction projects.

CALCULATION OF LOST PRODUCTIVITY FOLLOWING DISRUPTION

It has already been explained how learning curves are valuable in the initial estimating of project baselines and in tracking actual cost data during construction. Both unit cost and cumulative cost data can be plotted to observe productivity, thereby providing a measured mile baseline.

Learning curves are also effective in determining changes in productivity. By plotting the changed cost data during the impacted period, a comparison to the measured mile baseline is now available. This process involves the following steps:

- Determine the cost of the first unit completed after the disruption is over.
- Find the cost of that unit on the learning curve already established for the unimpacted work.
- Find the units of retrogression (setback)
- Renumber all subsequent units

By using the Table 2 and Table 3 data, the following is determined:

Table 2—Stair Wall Panel Data

Period	Quantity this Period	Number of Units		Cost (hours/10m^2)		Productivity
		Individual	Cumulative	Individual	Cumulative Average	(m^2/hours)
1	129	1.77	1.77	16.40	16.40	0.61
2	361	4.95	6.72	11.10	12.49	0.90
3	308	4.22	10.94	8.50	10.95	1.17
4	178	2.44	13.38	9.80	10.74	1.02
5	229	3.14	16.52	8.00	10.22	1.25
6	84	1.15	17.67	8.20	10.09	1.22
Disruption-Labor Strike						
7	129	1.77	19.44	12.50	10.31	0.80
8	46	0.64	20.08	8.60	10.25	1.16
9	183	2.50	22.58	5.80	9.76	1.72

Table 3—Learning Curve Representation of Table 2 Data

Cumulative # of Units Produced	Average Unit Cost-No Disruption	Avg. Unit Cost-with Disruption	Cumulative # of Units Produced	Retrogression/ Setback
(a)	(b)	(c)	(d)	(e)
1	16.40	16.40		
2	13.93	13.93		
3	**12.66**	**12.66**	**18**	**12.50**
4	11.83	11.83	19	10.62
5	11.22	11.22	20	9.65
6	10.75	10.75	21	9.02
7	10.37	10.37	22	8.56
8	10.05	10.05	23	8.20
9	9.77	9.77		
10	9.53	9.53		
11	9.32	9.32		
12	9.13	9.13		
13	8.96	8.96		
14	8.81	8.81		
15	8.66	8.66		
16	8.53	8.53		
17	8.41	8.41		
		Disruption		
18	8.30	12.50		
19	8.20	10.62		
20	8.10	9.65		
21	8.00	9.02		
22	7.92	8.56		
23	7.83	8.20		

- Step 1. The cost of the first unit after disruption is $12.50
- Step 2. The cost of that unit correlates closely with the cost of unit #3 on the learning curve data shown in Table 3.
- Step 3. What would have been unit #18 on the unimpacted learning curve plot is now repositioned to unit #3 by retrogression. This represents a setback of 15 units.
- Step 4. The costs of the remaining units (18 through 23) are now calculated as units 3 through 8.

The data in Table 2 was determined by the analysis to represent a slope of –0.2356 and a learning rate of 84.93% [13].

This method provides accurate unit costs for work completed before and after the disruption with sufficient data to compare the two baselines. This is an improvement over the typical methods used in calculating the measured mile. "The measured mile method typically compares an average productivity rate for an unimpacted time period to an average productivity rate for the allegedly impacted time period. Unfortunately, while such average productivity rates may be easy to calculate and use, they hide the fact that a contractor typically does not achieve a single rate of productivity throughout a time period [6]."

Using the learning curve overcomes this reported deficiency in the measured mile process. By doing so, it becomes invaluable for both monitoring and tracking productivity during the construction process and for calculating damages to support disruption claims. The learning curve has a proven record with a long history of success. It has acceptance in the courts, is simple to use and explain, and should be used more in the construction industry, especially when cost data is available.

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