CAPACITY UTILIZATION AND WAIT TIME: A PRIMER FOR CONSTRUCTION

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ABSTRACT

The relationship between capacity utilization, wait time and variation is well understood in traffic and industrial engineering where the relationships are stated as fundamental laws. This paper will explain this concept and its implications for construction, and will challenge the current view that time and cost must always be in tension. The paper will show that reducing variation in work flow will improve performance and that the resulting improvement can be applied to reducing duration and/or cost.

KEY WORDS
Capacity Utilization, Cycle Time, Last Planner, Little's law, Production Management, Productivity, Throughput, Variability, Wait Time

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INTRODUCTION

The belief that project cost and duration falls with increased resource utilization appears to be a matter of common sense. If workers spend more time working, how could that not reduce project cost, at least labor cost? If work is being completed faster, doesn't it follow necessarily that the project (doing all the work that has to be done) will be completed more quickly?

In this case, common sense is wrong. Efforts to improve capacity utilization or productivity reduce project cost and speed completion only if the project involves a single processing step supplied by a ready inventory. But projects are a complex web of activities fed by supply chains. If there is variation in the release of work from one internal or external supplier to the next, increasing capacity utilization will increase the length of the project (wait time or cycle time) and increase work-in-process. The idea that duration becomes longer as capacity utilization increases seems counterintuitive if not wrong, but can be mathematically demonstrated.

A full understanding of the relationship between capacity utilization and cycle time requires first understanding the relationship between throughput, cycle time and work-in-process, and then the impact of variation on production systems. This paper follows this order and draws examples from transportation engineering to show that project costs and duration will increase by pushing for higher levels of capacity utilization without first reducing variation in workflow. The paper concludes by revisiting the Time-Cost tradeoff dilemma.

FUNDAMENTALS

OPENING METAPHOR

Everyone who has ever driven on an urban road knows that delay time and work-in-process increase with capacity utilization. Traffic engineers define capacity as the maximum hourly rate at which vehicles can traverse a section of highway under prevailing roadway, traffic, and traffic control conditions (Transportation Research Board 2000). For this definition, roadway conditions include parameters such as alignment, lane width, and design speed; the primary traffic factor is the presence of large trucks. Highway capacity has been studied extensively over the past 50 years, and there is a significant body of knowledge that permits engineers and planners to estimate highway capacity for streets and highways. In the vernacular, urban- area traffic demand approaches capacity during the "rush hour," an incongruous term considering that peak-period traffic conditions often extend for several hours during which motorists aren't rushing. As the roadway's volume to capacity (v/c) ratio approaches 1.0, freeway traffic slows to 50± mph and traffic density (the number of vehicles per mile per lane) increases. Under these conditions, even a small perturbation (a motorist applying the brakes or a vehicle pulling onto the shoulder) can abruptly deteriorate the situation, causing speeds to drop to zero while traffic density increases. The net result is that throughput, which traffic engineers seek to maximize, decreases and motorists become frustrated not only with the stop-and-go driving but also with the delay in reaching their final destination.

Uniform speed is essential for a freeway segment to operate near capacity. Most prudent motorists have learned that accelerating to squeeze into a gap between two

vehicles in an adjacent lane and then braking to avoid impact with the lead vehicle won't get them to their destination much sooner; imprudent drivers may never learn this lesson. Even in the absence of erratic drivers, speeds are adversely affected at those points where on-ramps bring additional vehicles onto the freeway. The problem is due to both the additional traffic and the inherently lower capacity at a merging point. On many urban freeways, on- ramp traffic is metered in an effort to maintain the optimal volume, speed, and density relationships on the through highway. Of course, uniform speeds and ramp metering are less important during those off-peak hours of the day when the v/c ratio is low.

Even when the v/c ratio is a comfortable 0.85 and the freeway is flowing freely, traffic flow can deteriorate quickly in response to a lane-blocking incident. Studies on freeways with three lanes in one direction have documented that an incident blocking one lane will reduce capacity not by one-third but by one-half. On this freeway, the immediate consequence of such an incident is a demand greater than the roadway's revised capacity and a rapidly growing traffic backup. Although the physical removal of the lane-blocking incident returns the highway capacity at the blockage point to its original value, additional time is required to disperse the queue created by the incident. Under this scenario, a lane-blocking incident at time t = 0 that is removed 15 minutes later will result in continued stop-and-go driving for at least 50 minutes while the backup is dissipated.

IMPACT OF VARIATION

Queuing theory shows that increasing variability in a system increases wait time. (Hopp and Spearman page 286). [1] This variability may be in processing times at each station, or in the arrival time of inputs from upstream. The impact of increasing variability is most pronounced if the processing unit, perhaps a crew installing fixtures, is running very near its maximum capacity. In these cases, the crew will have little slack time, and so will be unable to respond to early deliveries. Further, there will tend to be few work opportunities or 'unoccupied work stations', reducing the chance of finding alternative work when faced with late deliveries. This difficulty in matching capacity to load (work to workers) causes the time required to install any specific fixture to increase in a highly nonlinear fashion. The mathematical relationship between waiting time and capacity utilization is shown graphically in Figure 1.
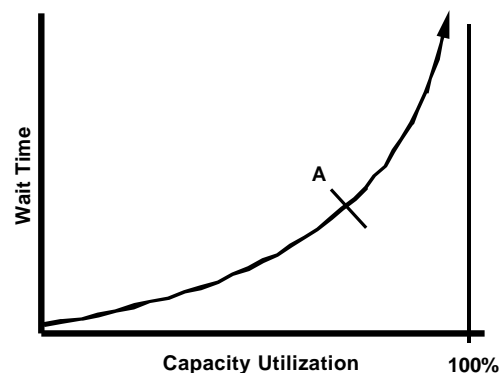

Figure 1: Capacity Utilization and Wait Time

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[1] Since cycle time, the time for any unit to transit the system, is the sum of time spent waiting and time being processed, we can infer that variability also increases cycle time.

Here we can see that delay times increase as capacity utilization increases.[2] Point "A" along the curve was chosen to relate this concept to the "Time-Cost Tradeoff" familiar in construction. Moving to the right increases capacity utilization (productivity) and will benefit the contractor working under fixed price but delay the completion for the owner. Moving left reduces productivity but speeds completion. Battles are fought over the cost of acceleration and claims result. In these cases, the owner typically pushes the contractor to add people in the belief that more people will increase rate of completion by increasing available work force capacity. This usually means that more work stations are occupied so crews are forced to wait for work to be released from others. Congestion on site increases the variation in arrival times and/or processing times, in effect moving from one curve to another as in Figure 2. In this case, capacity utilization drops and project duration increases.
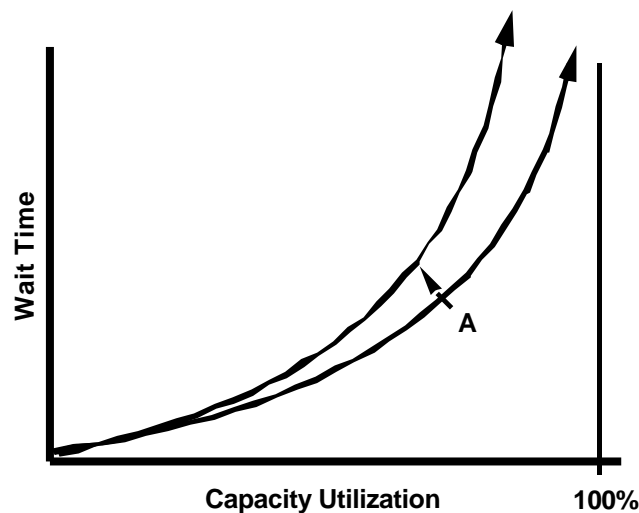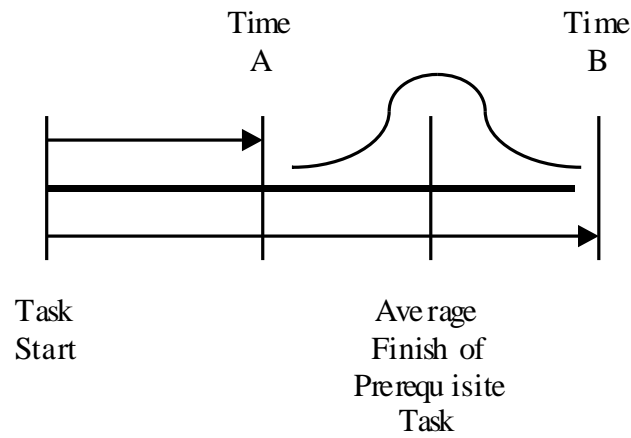

Figure 2: Capacity Utilization with Increased Variation

Despite the mathematical theorem, some readers may still be wondering how in fact increasing work flow variability can increase cycle time as labor utilization approaches 100% capacity utilization. Surely a crew running at capacity must do their job quickly, that is, release work to the next crew with no delay. Consider Figure 3 below, in which the start time of a task is related to the variable finish time of the prerequisite work. In this case there is a distribution of completion times of the prerequisite work around an average. To assure the crew is running at capacity, we would not want them to arrive at the location until we were certain that the grid to hold the fixture was set in place and the fixture itself was on hand. To assure capacity is not lost, we could either wait until the leading crew reports back they are complete, or we could set a time for the crew to arrive well after the most likely time for the advance work to be complete. This would mean the crew would arrive at about "Time B." Of course if we wanted to achieve the quickest progress (shortest cycle time) we could sacrifice the installation crew's productivity by instructing them to be standing by at "Time A"; this is the first moment when there is any chance that the work might be available.

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[2] See Hopp and Spearman (1996) Chapters 7 through 9 for a full treatment and page 285 for the formula that relates variations in arrival time and processing time to congestion, capacity utilization and cycle time.

Time
A

Time
B

Task
Start

Average
Finish of
Prerequisite
Task

Figure 3: Arrival time for following crew

The "Time-Cost Tradeoff" is real. But the extent of the trade depends on the extent of capacity utilization when the change is made. At low levels of utilization, the increase in productivity has little effect on wait time. At high levels of utilization, the impact can be dramatic. Further the effect of changes in utilization depends on the extent of variation in the system. This is good news. If we can change the variation in the flow of work between stations, we can elevate the level at which we must trade off time and cost—have our cake and eat it, too.

Under lean construction, variations in the flow of work are reduced by the application of the last planner system of production control (Ballard and Howell 1996). Figure 4 illustrates the effect of increasing planning system reliability on the production system. Increasing Percent Plan Complete (PPC) indicates that a higher proportion of the assigned work is completed in the week assigned. PPC provides a good measure of work flow reliability.
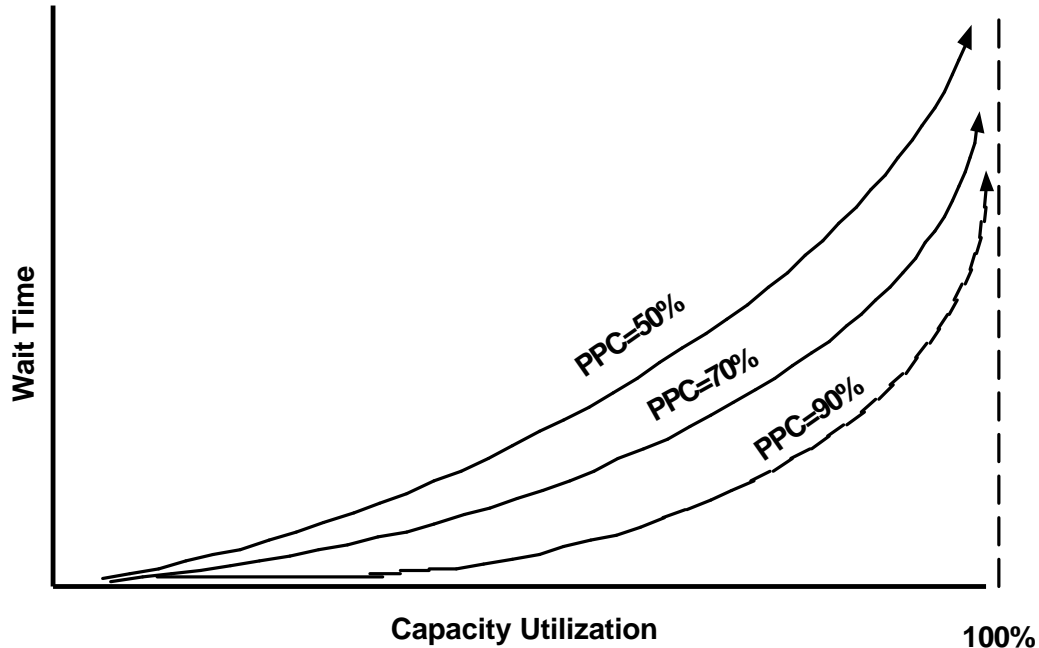
Figure 4: Effect of increasing planning reliability

Wait time does not increase as quickly with capacity utilization when planning reliability is higher but it still increases as full capacity utilization is approached. Near the upper limit, the effect is more pronounced but always lower than in systems with lower reliability in planning. When these curves are loaded with data relating levels of productivity and PPC drawn from practice[3], the importance of improving reliability becomes more apparent.

Figure 5 shows that for the same wait time, capacity utilization increases with planning reliability. The extent of improvement shown between PPC levels of 50% and 70% are about what has been recorded in the field. Productivity increases about 30%, i.e., from 50% to 65% as planning reliability goes from 50% to 70%.[4] The first key point here is that management can choose how to invest the savings of improved reliability. Wait time can be reduced for the same level of capacity utilization, or capacity utilization can be increased for the same wait time – or a combination of both improvements. (Also see Ballard 1999). Here we see the tradeoff in a very different light, which leads to the second key point: Productivity and duration can be improved at the same time by improving reliability work flow within the system. (Koskela 2000).
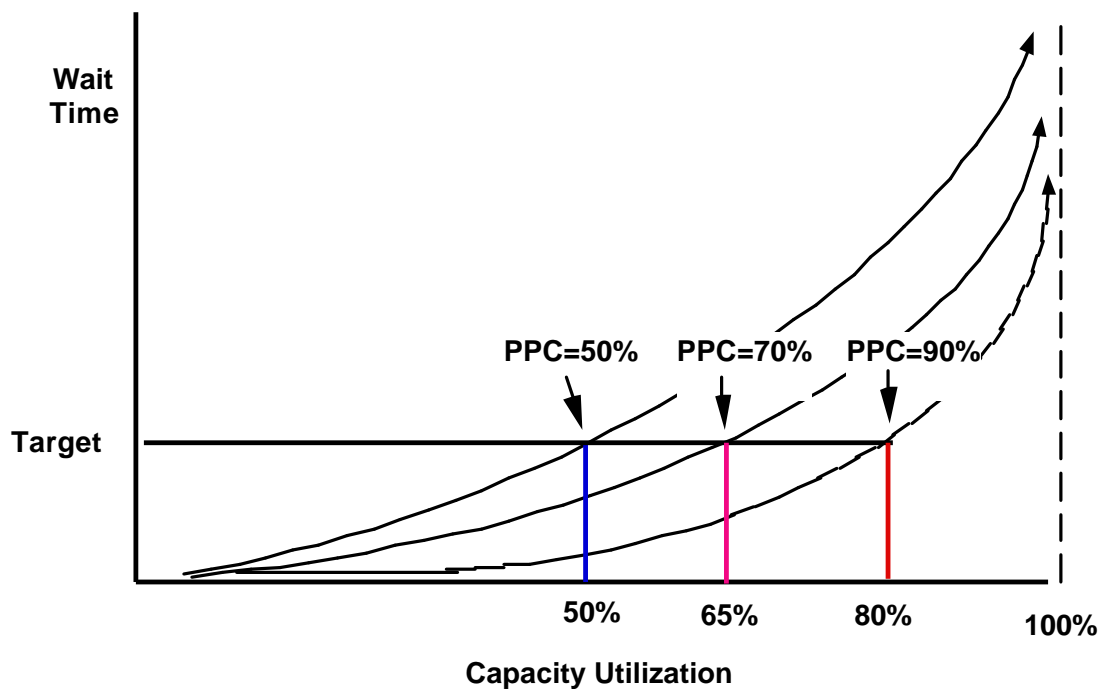

Figure 5: PPC and Capacity Utilization

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[3] From "Introduction To Lean Construction" A seminar by the Lean Construction Institute.

[4] Productivity is a function of resource utilization (percentage of time spent productively) and resource fruitfulness (output per productive unit of time). In this case, the increase in productivity from more reliable work flow appears to be a result of increased utilization. See Ballard (1999).

CONCLUSIONS

This paper has shown the relationship between capacity utilization, wait time and work flow variability within a production system and the "Time-Cost Tradeoff" experienced in construction. The impact of reducing variation on this tradeoff has been discussed.]Empirical, quantitative analysis is needed and will offer academics and researchers a rich vein of ore to mine. On the industry side, owners and contractors should question their common sense assumptions and stop pushing for maximum labor utilization or for doing every bit of work as soon as possible. Instead they should work to reduce work flow variation in order to improve project performance.

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