MODELING THE EFFECTS OF LEAN CAPACITY STRATEGIES ON PROJECT PERFORMANCE

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ABSTRACT

Common lean wisdom concerning efficient operations is to reduce variability in workflow throughput. Lean producers use various methods to dissipate production variability in a system that provides wide product variety in order to allow production to better match demand. Amongst these is the use of flexible capacity strategies to adapt to changeable conditions when this approach best suits. Yet, this is a part of lean thinking that is not yet well understood by the lean construction community. This paper models the effects of adaptable capacity strategies on project performance. Construction operators tend to match capacity to situations of minimal variability. Consequently, they do not always have sufficient capability to efficiently engage the changeable conditions commonly encountered in construction projects. The analysis in this paper focuses on the effects of additional capacity on project performance. A stochastic model was run over a number of projects, indicating in all cases improved performance when an optimal amount of capacity was added. The best results achieved were a 40% reduction in project delivery time and 10% reduction in project costs. It is concluded that further research is needed to develop more adaptable capacity management strategies, as there is strong evidence to suggest improved project performance as a result.

KEY WORDS

Capacity, resources, process dynamics, lean construction, simulation modeling.

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INTRODUCTION

Flexible capacity strategies can sometimes be the most efficient means of managing the conditions in which operations are carried out. Capacity provides the capability to complete tasks and usually refers to the volume of resources available for task realization. Flexible capacity strategies relax the usual aim of maximizing resource utilization to avoid excessive resource consumption. Instead, they provide sufficient capacity to cover a range of demands.

Lean production focuses on workflow throughput (the flow of work through a process) and flexible capacity strategies to manage the difficulties of production variability. Lean construction, so far, has emphasized reducing variability in workflow throughput. Ballard and Howell's (1998) *Last Planning Technique* focuses on improving planning reliability to reduce workflow variability. Yet, this is not the only way to manage production variability. Lean operators in other industries also use flexible capacity strategies to adapt to changeable environments when this approach best suits (Horman and Kenley 1998, Wild 1995). Resources in lean operations are provided in sufficient volume so that they can be distributed between tasks in much the same fashion as grocery store staff are distributed between the tasks of stocking shelves and checking out. When demand increases, staff stocking shelves move to the cash registers to more rapidly serve customers. Flexible capacity comes from having multiskilled resources and having them supplied in sufficient quantities to be able move between functions, absorbing demand fluctuations, while ensuring that system operation is sustained. In lean manufacturing, when the system is not operating at full capacity, personnel may operate the production line, assist other teams affected by absenteeism, perform machinery maintenance, analyze defect sources, or research and develop improvements (Horman and Kenley 1998).

Lean capacity strategies in construction are likely to involve increasing levels of resources supplied to projects to add capacity. Construction projects tend to be resourced in ways that do not always provide an effective method to accommodate the variable conditions typically present. That is, they tend to be staffed for minimal uncertainty. Project costs are a function of the cost of the resources allocated. Yet, it is often difficult to accurately determine the capacity required for a project due to its uniqueness. Companies will usually aim for the highest resource utilization in order to maximize their competitiveness and their returns. Accordingly, rarely will more than a modest excess of capacity be deliberately provided unless otherwise required. This approach to project resourcing, while common, leaves little room to accommodate difficulties when things become variable and levels of waste become quite substantial. An analysis by Horman and Kenley (forthcoming), which builds on work by others like Oglesby et al. (1989), indicates that on average nearly 50% of time is spent in wasteful activity.

Adding capacity provides a capability to absorb variability while allowing quick and economic project completion. Added capacity would be used to prevent problems before they arise, or to solve them quickly thereafter, thus minimizing delays. Additional capacity can enable, for instance, the readying of materials and equipment for upcoming tasks (the lack of which is a significant source of waste) as well as the more effective planning of work. Additional capacity can also engage problems close to their point of incidence minimizing the impact of the problem on normal operating resources and preventing propagation through the production system. Using added capacity in this way minimizes the distraction of normal operating resources from their primary function allowing them to rapidly finish their tasks.

Lean capacity strategies remain a relatively undeveloped part of lean construction. Ballard (1999) proposed that we underload resources to absorb variations in work content. He provided a hypothetical example to illustrate this proposal. Much more analysis is needed to explore how flexible capacity strategies influence project performance.

It is argued that using additional capacity, as outlined, to prepare work assignments and to respond to problems that arise can reduce levels of waste and improve project performance. Adding resources increases costs, but the reduced waste that results shortens delivery time and lowers costs. Best levels of resources can be determined by optimization.

The potential impact of flexible capacity strategies is demonstrated with a stochastic model that simulates levels of waste present in activities across a project and the effect that supplying extra resources has on overall performance. The analysis was based on a study of six commercial projects. The model shows that project delivery times could be improved by up to 40% and project costs by up to 10%. The model demonstrates that lean capacity strategies can be an effective means to manage construction variability and lead to improved project performance.

METHOD

The method uses a computer model of a construction project network to calculate the impact of added capacity on activity waste and subsequently on project time and cost performance. The model is based on stochastic estimating using the Monte Carlo simulation method. The model is run by progressively increasing amounts of capacity added to the project and graphing the results to determine the optimum levels.

The simulation uses a stochastic mechanism to generate waste levels for each activity in a project. This mechanism operates independently for each of the scheduled activities. The simulation is executed over a set of six commercial projects from Melbourne and Sydney, Australia. These projects range in value from AUD$8.9 to $168.8 million. The simulation is constructed with *Crystal Ball Pro*. *Microsoft Project* is used to provide project data and to recalculate the duration of the project at each iteration. *Visual Basic for Applications* is used to control operation of the simulation.

The model operation may be summarized as follows.

1. For the project, the components automatically:
    - open the desired project in Microsoft Project and import activity data (duration, fixed costs (materials, etc.), and variable costs (labor, etc.)) into Microsoft Excel;
    - create a stochastic element (called assumption cells in CB Pro) for each activity for wasted time, time overrun, and cost overrun variables;
    - format cells (called forecast cells) for collecting and tallying the results from each iteration of the simulation model; and,
    - prompt the user to set the amount of capacity to be added to the project.

2. Then at each iteration, the components automatically:
    - calculate the adjusted duration and cost of each activity based on the waste modeled in the activity and the influence of the capacity added;
    - collect the adjusted activity time and cost data;
    - calculate adjusted project costs based on all of the adjusted activity data;
    - import adjusted activity duration data to Microsoft Project and recalculate the project duration;
    - collect adjusted project duration and export to CB Pro for tallying; and,
    - reset the spreadsheet for the next iteration.

The assumptions, the method of applying the stochastic estimates, and the method of calculating the impact of added capacity are summarized in Table 1 and are detailed in this section.

ACTIVITY CHARACTERISTICS

Wasted time, time overruns, and cost overruns are three important variables concerning how waste is manifested in building projects. These variables are calculated for each activity in the project network by stochastic estimation. Levels of waste vary markedly in building projects and to adequately replicate this feature a universal mechanism operates independently for each variable for each of the scheduled activities. Between 231 and 747 assumption cells (the number depends on the number of project activities) are created in the simulation. These are recalculated at each iteration. The universal mechanism is an efficient means of describing waste and its variability over so many calculations and is an effective use of existing available data.

A large empirical data source is used to describe the behavior of each of the variables. This data was sourced from meta-analyses of past research into time utilization levels and levels of project overruns (Horman 2000). Table 2 provides a summary of the statistics pooled from these studies.

Wasted time was replicated with a normal distribution while time and cost overruns were replicated with the lognormal distribution. The normal distribution suited the wasted time variable because the (effectively) zero skewness was best matched by a symmetrical distribution. The time and cost overrun data were positively skewed. The lognormal distribution best suited time overruns because the natural logarithms of the means of the studies of these variables were normally distributed (Decisioneering 1996). The lognormal distribution best suited cost overruns because this distribution is best for stochastic estimates of cost variables (Wall 1997).

Dependencies between variables are also very important in stochastic models (Wall 1997). Correlation was measured between the input variables and the only significant correlation found was between time and cost overruns (coefficient = 0.805). This was incorporated into the simulation.

Table 1: Overview of the model and associated main assumptions.

Model Description	Model Mechanism
Projects have min. capacity provided to them	Base assumption
Projects are highly variable, which leads to waste (mostly extended duration)	Stochastic apparatus is used to calculate (and recalculate at each iteration) waste for each activity. Stochastic behavior based on empirical data.
Capacity added to project is used to address waste-causing elements	Model postulate (assumption)
Capacity added provides capability to prepare work and rapid response to problems	Model postulate
Impact of added capacity is reduced activity waste levels leading to changes in duration and cost	Initial rule is that a 10% increase in capacity will reduce waste proportionally. Adjustments to this: (1.) added cap. is 31% more effective than normal capacity because it is using lean-based practices; (2.) impact is limited to overrun amount and allowances in duration; (3.) capacity impact is reduced for increasing congestion; (4.) exclusion of waste causes not impacted by changing resource levels; and, (5.) material costs reduce due to more efficient usage with lean-based practices
Reducing activity waste across the project will change project delivery time and cost	Project duration is determined by the critical path, which is recalculated for each iteration. Cost is calculate by summation of revised activity costs. Added capacity increases cost, while shorter duration reduces cost
Interaction between added capacity and float can achieve better improvements	Float is used before capacity to absorb waste. Capacity amount provided to non-critical activities is reduced by a calculated amount

Table 2: Statistical profiles of wasted time, time overruns, and cost overruns.

Statistical Property	Wasted Time	Time Overruns	Cost Overruns
Range	1.6 – 93.1	-27.0 – 293.0	-13.3 – 244.0
Mean	49.6	27.3	6.5
Standard Deviation	11.9	32.1	17.0
Skewness	0.03	1.34	1.18

The benefits of reducing waste are limited by the amount of waste present in an activity. However, the full magnitude of waste in an activity is "typically obscured…by the use of allowances…to accommodate the impact of unexpected influences" and other difficulties encountered in the project (Horman and Kenley 1998, 231). As wasted time levels provide a measure of the volume of waste in an activity and time overruns a measure of the obvious delay impact, the process of deduction provides the allowance amount. This is shown in Figure 1. Wasteful activity as a proportion of total available time is measured over the actual duration. Actual duration is the aggregate of planned duration and any overrun amount. The minimum duration is the difference between the actual duration and the waste amount. Consequently, the allowance amount is the difference between the planned duration and the minimum duration. Any further expansion of waste reducing practices would yield no improvement in performance once waste has been eliminated from the activity.

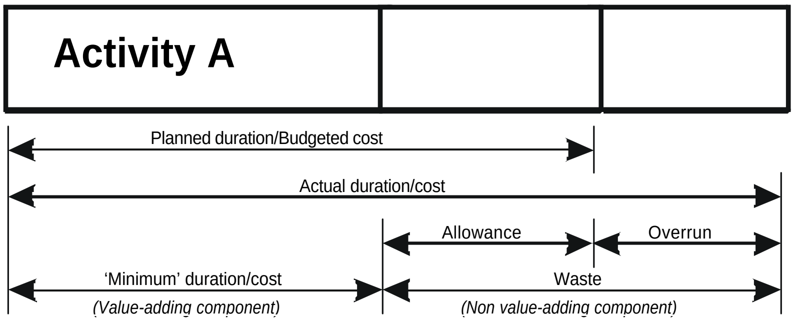

Figure 1: Connecting planned duration, time overrun, and wasted time to calculate 'minimum' duration

The planned duration and budgeted cost for each activity is provided the project network data obtained from Microsoft Project. These values are used in the calculation of actual duration, waste, minimum duration, and the impact of the added capacity.

ADDING CAPACITY

Capacity is added to engage the causes that induce wasteful activity. Consequently, increases in capacity generate proportional decreases in waste. Hence, if an activity is modeled with 45% waste and 10% capacity is added, then waste is reduced by 4.5% (10% of 45%). This amount of capacity is added to all activities (subject to it being integrated with other buffers as discussed below) regardless of whether waste is expected or not. In some instances, this addition of capacity will generate waste rather than reduce it. There will be situations where there is no waste for the added capacity to address and others where the waste present exceeds the capabilities of added capacity. Because waste is variable, the amount of capacity needed for each activity will be different and therefore is difficult to predict on an individual basis. The model focuses on the level of capacity to add across the project. It accounts for the fact that the waste in each activity will differ and therefore so will the impact of the added capacity. The model is run with different levels of capacity added to the project to determine the optimal level.

The performance of resources utilized to address wasteful activity is typically superior to that of resources engaged in normal operations. Additional resources are used to prepare work assignments (plan) and to respond to problems that arise, i.e. they engage the very issues that impede performance (Horman 2000). However, there is no ready indicator of performance change with additional resources. An indication must be extrapolated from other work. A measure of performance improvement under an initiative aimed at addressing wasteful practice is provided by Ballard and Howell's (1998) percent of planned complete (PPC) measurement. The interest in PPC lies in the change in performance that results from the implementation of the last planning technique given that this technique is directly founded on lean principles. In their PARC case study, Ballard et al. (1996) reported that the percentage of tasks planned being completed rose from 65% to 85% with the implementation of the last planning technique. This represents a 31% improvement. Given the overlap between the preparatory function of additional capacity and the last planning technique, additional capacity is incorporated in the simulation as having a performance level 31% higher than that of ordinary operating capacity. Thus, rather than the 10% capacity generating a 10% reduction in waste, it now produces a 13.1% reduction (10% + 31% of 10%).

The addition of capacity involves labor, equipment and management resources but excludes materials. Adding material would form an excess of inventory and consequently an inventory buffer (Horman and Kenley 1998). Organizations participating in a project would provide resources (other than material) in addition to their anticipated needs. These costs would be incorporated in the project. In some instances, proportionately more management resources than production resources would be better suited to the problems engaged. Management possesses the necessary decision making capability to rapidly resolve problems encountered and to organize upcoming production. For modeling purposes, these costs are equivalent to production resources.

ADJUSTMENTS TO THE IMPACT OF ADDED CAPACITY

The influence of adding increasing amounts of capacity to a project is adjusted for congestion inefficiencies and is confined to appropriate waste causing factors. As noted in the introduction, projects are typically supplied with capacity sufficient for instances of minimal variability. Adding capacity to these amounts can help to address variability and improve overall performance, but inefficiencies are also introduced that limit the capabilities of this mechanism. Thomas and Arnold (1996) conducted an empirical investigation of the effect of overmanning on labor productivity. They found that overmanning diminished the efficiency of labor at an average linear rate of 19.9%. The simulation incorporates this effect by discounting this amount from available capacity to determine an effective amount of added capacity.

Not all aspects of wasted time are affected by changes in the levels of resources allocated to a project. In particular, time spent resting, on personal matters, used for non-work communication, or wasted due to late starts, early finishes or extended breaks is not affected by changing resource levels. Consequently, this proportional amount (5.3% of total available time (Horman 2000)) is added to the 'minimal' duration of an activity. This limits the extent of possible improvement through increasing capacity levels.

COMBINING ADDED CAPACITY WITH PROJECT SLACK

The integrated use of added capacity and project slack is analyzed. Rather than adding the full amount of capacity to all activities across a project, a reduced amount is added to non-critical activities. The slack available to non-critical activities is used to accommodate the impact of waste causing factors before capacity is added.

The focus of capacity on critical activities is a similar focus to Goldratt's critical chain (Goldratt 1997). Applying the theory of constraints to projects, Goldratt argues that the chain of critical activities is the bottleneck in project environments. His technique jointly schedules activities in a chain and inserts a time buffer at the end of the chain rather than using separate allowances in individual project activities (Newbold 1999). While there is a similar focus on critical activities between flexible capacity strategies and the critical chain, flexible capacity strategies allow capacity rather than time (or inventory) to buffer variability. In some cases, this is likely to generate better performance. Best performance is likely to be achieved when we learn to better integrate different buffers.

The interaction between added capacity and project slack is determined by systematically reducing the amount of capacity added to non-critical activities while continuing to apply the full amount to the critical activities. This enables determination of the optimal reduction amount to be applied to non-critical activities. The simulation is then executed with the added capacity applied to non-critical activities reduced by the optimal amount. These results are compared to the results where the full amount of added capacity is applied to all network activities.

CHANGES IN PROJECT TIME AND COST PERFORMANCE

For each activity, the revised duration and cost is computed. Added capacity reduces the amount of waste present in an activity and thereby shortens the duration of the activity. In line with Figure 1, the 'minimum' duration component of an activity is first calculated. The duration component associated with the reduced amount of waste (due to the addition of capacity) is then calculated. The revised activity duration is the sum of these two components.

Activity costs increase with the addition of capacity and decrease due to the shortening of duration. Activity costs were segmented in the original schedules into time-constant (materials) and time-variable components (labor and equipment). Savings in materials costs are generated because of the better control of material consumption provided by the added capacity under a lean regime. This better control leads to reduced waste of physical materials. This builds on the research of Agapiou et al. (1998) who showed that a materials control system saved 5% of project costs. A significant part of the system was the addition of a devoted materials manager, who prepared materials requisitions and bundled materials that were delivered to site on a just-in-time basis. This reduced damage to materials as well as over-ordering and over-supplying materials to site. Time-variable costs vary proportionately with the reduced duration. Thus, a simulated duration of 7 days for an activity of 10 days actual duration would have its time-variable costs reduced to 70%. Cost overruns vary in the same manner as time-variable costs until they are depleted. Added capacity costs to an activity involve labor, equipment, and management resources. This cost is calculated by multiplying the added capacity by the time-variable costs. Thus, the provision of 45% added capacity to an activity costing $638,731 with labor and equipment involving $350,340 would cost $157,653 (45% of $350,340). Regardless of whether an activity uses the added capacity, this cost is applied. When added capacity is integrated with project slack, non-critical activities that have a reduced amount of capacity applied are costed according to the reduced amount.

The revised duration of all project activities are imported into Microsoft Project to enable recalculation of the project duration. Revised activity costs are totaled in Excel for project cost. Project overheads are treated at this level by adjusting them in proportion to the change in project duration.

Modeled performance at the project level is gauged against scheduled and actual project performance. Scheduled performance describes the expected levels of time and cost performance (i.e. the contract amounts). Actual performance describes the performance at the end of the project and includes the overruns that occur during the course of the project. The result charts indicate performance as the ratio of modeled performance to either scheduled or actual performance. The performance measures blend the time and cost ratios by simple averaging to provide a combined performance coefficient. A coefficient of 1.0 indicates no change in performance and lower coefficients indicate better performance.

RESULTS

The results of the simulation indicate that the addition of capacity to address waste is able to generate improved project performance in most instances. The best improvement obtained was a 40% reduction in project time with a 10% reduction in project cost.

The simulation systematically varied the amounts of capacity added to a project and observed the effect that this has on levels of project performance. A series of data points for project time and cost performance are produced and these are plotted on a set of axes. Typical displays of the simulation results are provided in Figures 2 and 3. The time and cost performance results form their own series. These results are also integrated to form a *combined* series. This combined series is an average of the time and cost performance results. A trendline is fitted to each data series to provide an equation that describes the series profile. To assist in interpreting the precision of the trendline, an R^2 *goodness-of-fit* measure is calculated. An R^2 value of one indicates that the trendline is a perfect representation of the data series, whereas a value of zero indicates that the trendline is unrepresentative of the data.

The optimum amount of added capacity is determined by solving the differential of the trendline equation. This is because the interest in the results is in the trends rather than individual results because of the stochastic nature of the model.

ADDED CAPACITY APPLIED IN FULL ACROSS ALL ACTIVITIES

The results of executing the simulation with additional capacity applied in full across all activities are reported in Table 3. While every project generated different results, the performance coefficients indicate that performance improved in all projects. Noticeably, simulation generated superior levels of time performance in all instances simulated.

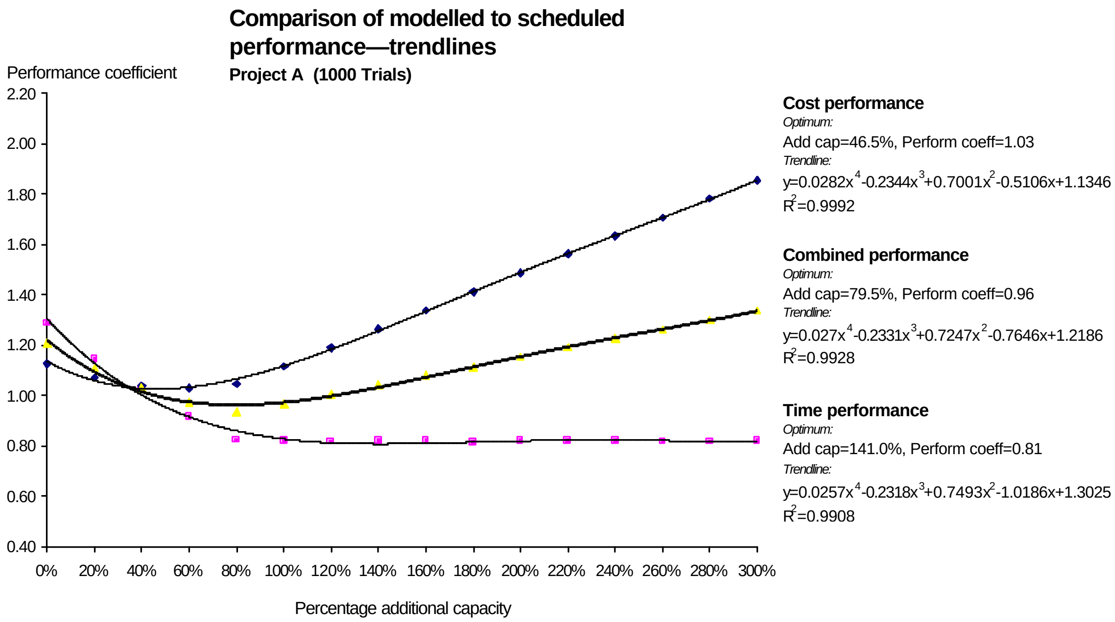

Figure 2: Simulation output – modeled to scheduled performance

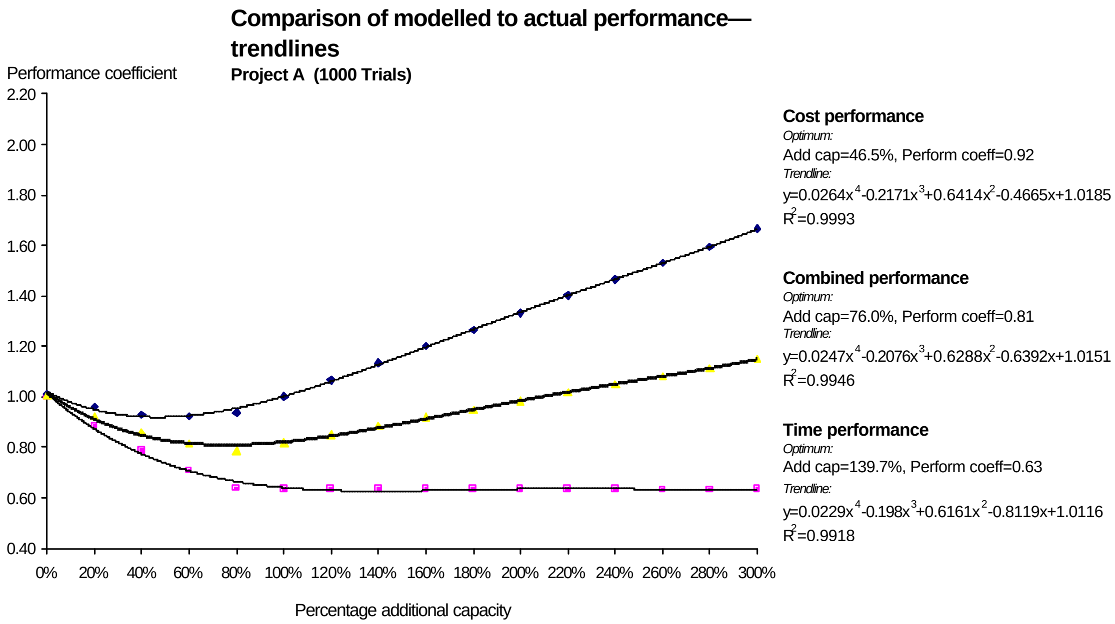

Figure 3: Simulation output – modeled to actual performance

However, cost performance exceeded the amount against which it was gauged in five of twelve instances and never when it was gauged against scheduled performance. Nonetheless, improved time performance outweighed cost performance deterioration as was reflected in the favorable performance coefficient values, which are a combination of time and cost performance results.

Table 3: Summary of results where capacity is applied in full across all project activities

	Modeled Performance as Measured Against	Optimal Added Capacity	Yielded Performance Coefficient[a]	Constituent Time Performance	Constituent Cost Performance
A	(Scheduled) (Actual)	79.6% 76.0%	0.962 0.810	86.0% 67.1%	106.5% 94.5%
B	(Scheduled) (Actual)	73.7% 69.0%	0.976 0.850	85.7% 69.7%	109.5% 100.3%
C	(Scheduled) (Actual)	82.0% 77.8%	0.982 0.804	87.6% 64.4%	108.8% 96.4%
D	(Scheduled) (Actual)	80.2% 76.4%	0.965 0.808	84.6% 64.4%	108.4% 97.3%
E	(Scheduled) (Actual)	81.2% 77.9%	0.956 0.798	83.1% 62.9%	108.2% 96.6%
F	(Scheduled) (Actual)	86.0% 83.7%	0.930 0.773	80.5% 62.0%	105.5% 92.5%

a A performance coefficient of 1.0 indicates that the modeled performance is the same as that against which it is being gauged – either scheduled or actual performance. A smaller coefficient reflects better performance.

The best performance simulated was that of Project F as gauged against actual performance. The addition of 83.7% capacity, which is nearing double the project's resources, yielded an average performance coefficient of 0.77. Composing this coefficient was an average time performance of 62.0% and cost performance of 92.5%. This represents a time performance improvement of 38.0% and a cost performance improvement of 7.5% when the results are compared to actual performance. Results of a similar pattern were generated for other projects.

ADDED CAPACITY INTEGRATED WITH PROJECT SLACK

The simulation was executed with additional capacity functioning in an integrated manner with project slack. This required determination of the optimal reduction amount to be applied to non-critical activities. Capacity added to non-critical activities was systematically reduced to provide a set of curves indicating performance at various levels of reduced added capacity (Figure 4). The optima of these curves provide a series of data points that indicate the best performances achieved at each level of reduced capacity. These optimal points are then plotted on another set of axes to describe the range of best performance outcomes over the various reduction amounts (Figure 5). Finally, the optimal amount for this curve is calculated to describe the amount by which capacity applied to non-critical activities should be reduced to achieve optimum levels of performance. Table 4 summarizes these results.

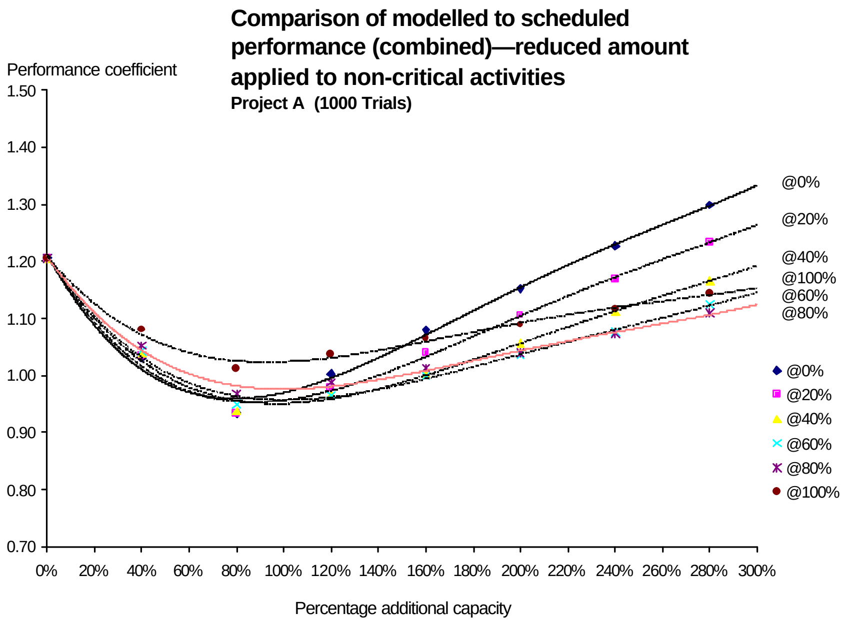

Figure 4: Output for the systematic reduction of added capacity to non-critical activities

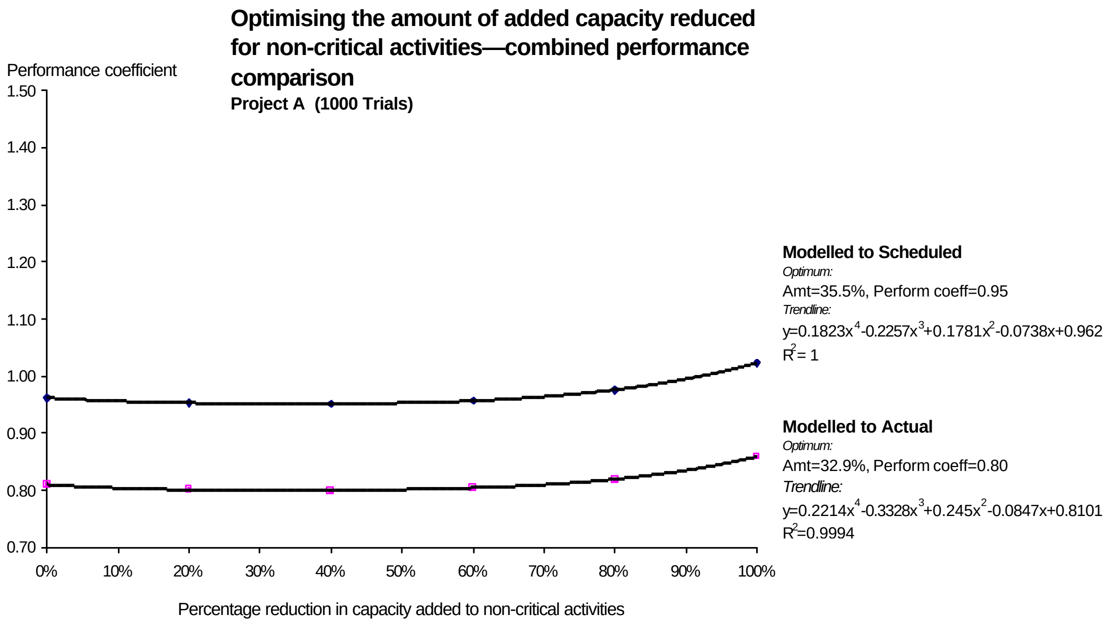

Figure 5: Display of the optimal capacity reduction amounts for non-critical activities

The model was executed with additional capacity applied to non-critical activities at the optimally reduced amount. These results are detailed in Table 5. When performance in this arrangement is compared with the results where capacity is added in full to all activities, then a small improvement is observed. This improvement is due to changes in both time

Table 4: Capacity optimization for non-critical activities.

	Modeled Performance as Measured Against	Optimal Reduction Amount
A	(Scheduled) (Actual)	35.5% 32.9%
B	(Scheduled) (Actual)	26.0% 23.1%
C	(Scheduled) (Actual)	13.8% 13.9%
D	(Scheduled) (Actual)	11.9% 15.3%
E	(Scheduled) (Actual)	10.7% 11.8%
F	(Scheduled) (Actual)	24.9% 24.7%

performance (average improvement of 1.44%) and cost performance (average improvement of 1.33%). The integrated use of capacity and slack also affects the amount of capacity added to the project. An average of 12% more capacity is applied to projects in the integrated environment than is applied to projects with only capacity added.

The best performance simulated was again that of Project F as gauged against actual performance. The addition of 99.4% capacity, which was reduced by 24.7% for non-critical activities, yielded an average performance coefficient of 0.75. Composing this coefficient was an average time performance of 60.1% and cost performance of 90.3%. This reflects a time performance improvement of 39.9% and a cost performance improvement of 9.7% when the results are compared to actual performance. Results of a similar pattern were generated for other projects.

DISCUSSION & CONCLUSIONS

The simulation demonstrates that lean capacity strategies can be an effective means to manage construction variability and lead to improved project performance. If added capacity is used to reduce waste as modeled, the results indicate that adding capacity to projects is capable of yielding significant improvements to project time and cost performance. The results also indicate that even better performance is possible when added capacity is integrated with the use of project slack.

Differences in added capacity amounts and performance coefficients were expected between projects, but it is notable that the patterns of change induced were similar. In each of the projects, the capacity added to generate optimal performance is approximately 80% of that originally provided to the project. When added capacity is integrated with project slack, the optimal amount by which capacity is applied to non-critical activities is reduced by approximately 20%. This reduction amount increases the optimal volume of capacity added

Table 5: Performance with added capacity optimized over non-critical activities.

	Modeled Performance as Measured Against	Optimal Added Capacity	Yielded Performance Coefficient[a]	Constituent Time Performance	Constituent Cost Performance
A	(Scheduled) (Actual)	94.4% 91.2%	0.945 0.795	84.3% 65.7%	104.7% 93.3%
B	(Scheduled) (Actual)	86.9% 83.8%	0.963 0.836	84.4% 68.0%	108.2% 99.1%
C	(Scheduled) (Actual)	91.8% 86.6%	0.971 0.796	86.1% 63.5%	108.0% 95.7%
D	(Scheduled) (Actual)	89.5% 85.7%	0.953 0.800	83.1% 63.5%	107.5% 96.5%
E	(Scheduled) (Actual)	89.4% 85.9%	0.947 0.787	82.1% 61.7%	107.2% 95.7%
F	(Scheduled) (Actual)	101.5% 99.4%	0.906 0.752	78.3% 60.1%	102.9% 90.3%

a Note that a smaller coefficient reflects better performance.

to projects by 10-15%. This improves the performance coefficient by an average 0.013 points that results from an average 1.4% change in time performance and an average 1.3% improvement in cost performance.

The utilization of additional capacity to eliminate waste has important implications for management, especially concerning the level to which projects are resourced. It is clear from the simulation results that increasing project resources beyond that of the presently supplied levels generates (up to a point) superior performance. The notion of applying little more than the necessary resources to meet expected demand seems flawed. The application of extra resources is able to generate superior project performance, if they are utilized to prevent and respond rapidly to waste causing problems.

The results show that when a moderate volume of capacity is applied to a project, best results are generated. The precise amount of this moderate volume will vary from project to project, as it depends on individual characteristics. However, its volume needs to be sufficient to exceed the cost performance optimum but not so much as to exceed the time optimum. When this occurs, superior performance is enabled.

There are limits to the performance improvement that comes from the addition of capacity. Once the volume of capacity added to a project exceeds the amount for optimum time performance, there is no further impact in time but cost performance continues to deteriorate. For management, this means that there is no need to add further volumes of capacity to the project beyond the amount to achieve the time optimum.

The simulation results indicate promise in developing lean capacity strategies for construction projects. This analysis explored one flexible capacity strategy based on a single set of assumptions. The results present a challenge to practitioners and academics to realize the potential benefits of additional resources to remove waste. It is now necessary refine the model and learn how to develop, test, and implement tools to achieve and substantiate performance improvement under a lean capacity strategy. Further research should develop resource management techniques by looking at how best to use the added capacity (e.g. management vs. workers, a roving 'crack' team vs. auxiliary workers, etc.) as well as how to ensure that capacity added to projects is properly used to reduce waste. Effort should also be devoted to making better use of the capacity added to a project in order to reduce the capacity amount without reducing performance. It is clear that lean capacity strategies can be an effective means to manage construction variability and lead to improved project performance.

REFERENCES

Agapiou, A., Flanagan, R., Norman, G. & Notman, D. (1998) The changing role of builders merchants in the construction supply chain, *Construction Management and Economics*, 16, pp. 351-361.

Ballard, G. (1999) Improving work flow reliability, in: *Proceedings of the Seventh Annual Conference of the International Group for Lean Construction: IGLC-7*, The University of California, Berkeley, USA, pp. 275-286.

Ballard, G., Casten, M. and Howell, G. (1996) PARC: a case study, in: *Proceedings of the Fourth Annual Conference of the International Group for Lean Construction*, The University of Birmingham, UK.

Ballard, G. and Howell, G. (1998) Shielding production: an essential step in production control, *Journal of Construction Engineering and Management*, 124, (1), pp. 11-17.

Decisioneering (1996) *Crystal Ball® Version 4.0 User Manual* (Aurora, CO: Decisioneering).

Goldratt, E.M. (1997) *Critical Chain* (Great Barrington, MA: North River Press).

Horman, M. and Kenley, R. (1998) Process dynamics: identifying a strategy for the deployment of buffers in building projects, *International Journal of Logistics: Research and Applications*, 1, (3), p. 221-237.

Horman, M.J. and Kenley, R. (forthcoming) Quantifying levels of wasted time in construction with meta-analysis, *Journal of Construction Engineering and Management*.

Horman, M.J. (2000) *Process dynamics: buffer management in building project operations*, Ph.D. Thesis, The University of Melbourne, Australia.

Newbold, R.C. (1999) *Introduction to Critical Chain Project Management*, at: http://www.prochain.com/article_01.asp (Lake Ridge, VA: Prochain).

Oglesby, C.H., Parker, H.W. & Howell, G.A. (1989) *Productivity improvement in construction* (New York, McGraw-Hill).

Wall, D.M. (1997) Distributions and correlations in Monte Carlo simulation, *Construction Management and Economics*, 15, pp. 241-258.

Thomas, H.R. and Arnold, T.M. (1996) Overmanning and the effects on labour efficiency, in: *Proceedings of the CIB W65 International Symposium for the Organization and Management of Construction*, University of Strathclyde, pp. 39-48.

Wild, R. (1995) *Production and Operations Management: Text and Cases*, 5th Edition (London: Cassell).