A STUDY OF THE RELATIONSHIP BETWEENBUFFERS AND PERFORMANCE IN CONSTRUCTION

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ABSTRACT

Lean proponents argue that we should eliminate buffers because they are wasteful, impede workflow, and hinder performance. Yet, there is some work in (lean) construction that calls this into question. Buffers have been commonly used to shield production by absorbing the impact of uncertainties and variability that would normally disrupt production. Buffers can take many forms including materials (inventory), W.I.P. (work-in-procress, subassemblies, stock, safety stock), deliberate and unintentional delays (time buffers, lags, pacing mechanisms), and excesses of labor and equipment capacity (capacity buffers). To lean producers, these items slow production, obscure and worsen quality problems, and burden management with unnecessary activity. However, in construction, where conditions are often uncertain and variable, lean constructors have suggested that buffers be sized and located according to the conditions.

This paper analyzes the relationship between buffers and performance in construction with data collected from three commercial projects to see how buffers influence performance. The size of the buffer between rebar fabrication and installation in the construction of a structural system is compared to the labor performance of the crew. The results show that some buffer is needed between steps in order to achieve best performance in the construction operations studied.

KEY WORDS

Buffers, lean construction.

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INTRODUCTION

There is something of a tension in the lean literature about the role of buffers in the performance of operations. According to leading lean authors like Ohno 1988 and Womack and Jones 1996, lean production aims to eliminate buffers because they do not directly add value and are a waste. The lean focus for performance is to produce only what is needed in a rapid timeframe. Minimizing inventory, aligning machinery in close proximity to the physical flow of production, fixing quality problems at their cause, synchronizing production rates, and pulling products through the supply chain allows a system to be quickly reconfigured to respond to specific demands. The ideal for lean production is single piece flow pulled directly by a customer order. Buffers impede this by slowing detection of problems, impeding fast reconfiguration, and harboring waste. There have been many performance advancements with the adoption of lean practices (including the reduction of buffers). Certainly, very few manufacturing operations now carry the volume of inventory that they carried in the past.

Yet, recent work in lean construction suggests buffers have a role to play, especially in highly uncertain and variable conditions. Buffers absorb perturbations and problems, and allow varying rates of production. Howell et al. (1993) advocated the use of buffers to decouple interrelated activities. Ballard and Howell (1995), in looking to apply just-in-time to construction, called for research into the sizing and location of buffers. Tommelein et al. (1998) used a simulation game to illustrate the impact of variability on construction workflow and the role buffers might play. Tommelein and Li (1999) looked at just-in-time concrete delivery and found a frequent use of buffers in the operation. Tommelein and Weissenberger (1999) then looked at buffers in structural steel supply and erection finding that buffers were extensively used but not very effectively. Horman and Kenley (1998) showed that labor and machinery resources are used in lean systems to form capacity buffers which operate like inventory buffers in conventional systems. It is apparent that a tension exists in the use of buffers as advocated by work in lean construction and the core principles of lean production.

To explore the role of buffers further, this paper investigates a set of construction case studies to provide some quantitative data on this matter. The paper tests the hypothesis that smaller buffers lead to better performance on the rebar fabrication and placement activities of three multi-story commercial projects in Brazil. The analysis focuses on inventory buffers. The results show that better labor performance occurs with small to medium sized buffers between activities. Amongst other things, the results indicate that buffers play a valuable role in achieving construction performance and that we need a more sophisticated characterization of how buffers should be used in construction.

CHARACTERIZING THE RELATIONSHIP BETWEEN BUFFERS AND PERFORMANCE

The relationship between buffers and performance is the key interest of this paper. Buffers absorb variations in production, problems with defective products, etc. Although there are different mechanisms that can operate as buffers (such as deliberate and unintentional delays, queues, labor and machinery capacity), this analysis focuses on inventory buffers. Inventory or subassemblies (sometimes called work-in-process (WIP)) are established between production steps. When disruptive events occur, production is maintained by drawing on the stock in the buffer. Buffers provide a mechanism to absorb fluctuations and variations in the production system. However, inventories between steps incur carrying costs, require increased management, dissipate system responsiveness to changes and variations, and increase production lead times. Time delays extend production times. Large amounts of labor or equipment can be expensive if not utilized (Wild 1995). Thus, in certain circumstances, larger buffers can increase performance, but in others, they reduce performance.

The size of inventory buffers between production steps is the focus of this study. In this case, buffers involve both inventory and time lag (lead time). Inventory refers to the material and preparatory work needed for the next phase in the construction process. Time lag refers to the duration between tasks. At the very least, time lag involves the time to build inventory, but in some cases it also involves a waiting period where other activities are completed before the next phase can commence. Generally speaking, some amount of time lag is needed between tasks to obviate conflicts caused by uncertainties between tasks, and inventory is produced during the time lag. Time lags allow project managers to avoid delays caused by the overlapping of the preparatory tasks and the task-at-hand. Figure 1 shows the relationship between inventory and time lag. Two (idealized) curves show the progress of fabrication and installation in this study. Progress is measured by a percentage of total amounts of installed or fabricated reinforcement bar. Here, inventory is the amount of prepared reinforcement bar, calculated as the cumulative amount of fabrication minus a cumulative amount of installation on the particular day. The vertical difference between the two curves is defined as inventory and the horizontal difference between the two curves is defined as the time lag on the day.

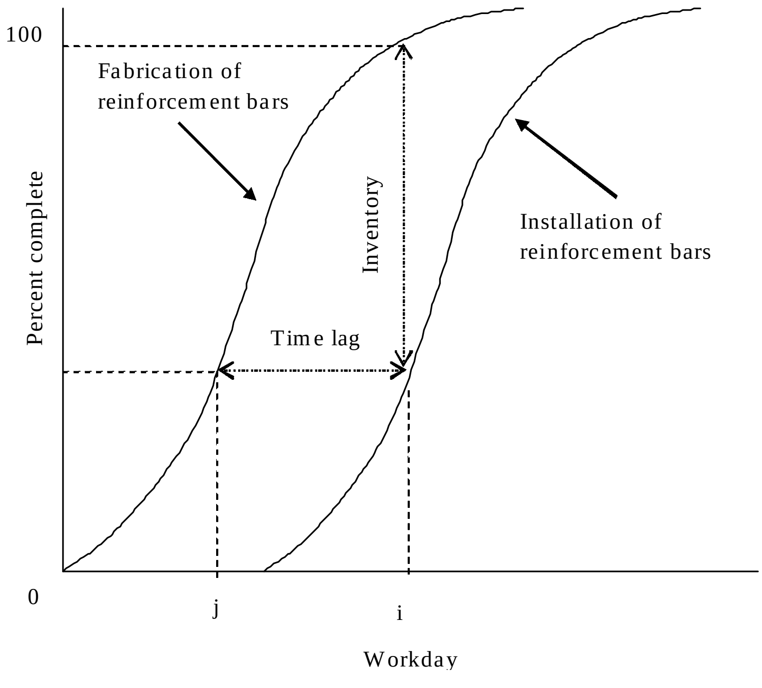

Figure 1: The inventory and time lag associated with buffers. Source: Buck (2000)

The hypothesis being tested in this paper is that better performance occurs when buffers are small. It can be seen in Figure 1 that if the time lag (the distance) between the two curves is small, then the project will complete sooner and better performance will have resulted. However, if the two curves intersect, the likelihood of which increases in variable circumstances and with smaller buffers, then delays occur and performance is adversely affected. Clearly, the size of the buffer has important consequences for performance and is worthy of further analysis.

METHOD

Labor performance was assessed for the reinforcement fabrication and installation crews on three multi-story commercial buildings in Brazil and compared to the size of the buffer established between the rebar fabrication and installation steps (Sakamoto 2002). Both inventory and time lag are analyzed in this study. The data from each set on each project is compared to ascertain whether better total labor performance could be associated with smaller or larger inventories or time lag. The method for assessing labor performance, and for calculating inventory and time lag are described in this section.

This analysis burrows down to activity level detail, but importantly, maintains a production focus. The concentration on the fabrication and installation crews is able to provide detailed information about the impact of buffers on the performance of the crews. This is necessary detail in the current situation. While a larger sequence of activities might have been preferable, the scope of this research did not allow this. The approach taken here could be easily be used on a larger sequence of activities. Both steps in this process are treated as a complete system and productivity performance is assessed at this level. Within the system, this means that the optimal performance of all crews involved is the goal (Tommelein et al. 1998) and makes this a production management issue.

LABOR PERFORMANCE

Labor performance is determined by collecting information on labor productivity. This information is obtained by direct observation of the crews over a number of days and is used to form the Project Waste Index (PWI) (Thomas 2000). Rules of credit are used to convert different types of work to a standard to enable comparison. A smaller PWI indicates better performance and is calculated with the following equation.

$$PWI = \frac{(\text{Cumulative productivity} - \text{Baseline productivity})}{\text{Expected productivity}} \quad (1)$$

The PWI compares the actual quantities of work installed and labor hours used to the quantities and labor of the best ten percent of days (Thomas 2000). The cumulative productivity is formed from the data on actual quantities of work installed and labor hours used. The quantities and labor of the best ten percent of days form the baseline productivity. Graphical comparison is also made between daily productivity and the baseline productivity to assess the variability of the projects.

The PWI measures the impact of waste on labor performance. The baseline productivity represents close to the best a contractor can do. By definition, it occurs when the material, equipment, and information flows are good and the plan is adequate. As PWI is a measure of the difference between the baseline and actual productivity, it provides a measure of the impact of poor material, equipment, and information flows and inadequate planning. This makes it a measure of waste. The PWI is not likely to indicate all waste in a system as even in the best ten percent of work there is likely to be some waste. However, the indicator can be seen as a good approximation.

Reduced waste can lead to better flow and throughput, and also to better system productivity. While throughput is important, it is not the only concern of production managers. An operation is more efficient if it is less wasteful and requires less total labor hours to complete work (Womack and Jones 1996, Hopp and Spearman 2000, Wild 1995). System productivity is an important part of performance for production managers.

INVENTORY & TIME LAG

Inventory is calculated by determining the difference in completed work of the fabrication and installation tasks according to the following equations.

$$\text{Fabrication (\%)} = \frac{\text{cumulative quantity of fabrication on the particular day (kg)}}{\text{total quantity of fabrication (kg)}} \tag{2}$$

$$\text{Installation (\%)} = \frac{\text{cumulative quantity of installation on the particular day (kg)}}{\text{total quantity of installation (kg)}} \tag{3}$$

$$\text{Inventory (\%)} = \text{Fabrication (\%)} - \text{Installation (\%)} \tag{4}$$

Charts are plotted showing the progress of the fabrication and installation over time. The vertical distances between the two curves indicate the size of the inventory buffer. The time lag is calculated by assessing the horizontal distances between the two plotted curves.

PROJECT BACKGROUNDS

Three projects are used in this study and Table 1 provides summarized information for them. The table shows the type, number of floors, and footprint are of the buildings. SP45 is in São Paulo, SP73 in Campinas, and SP62 is in Praia Grande. In the buildings, the structural components analyzed were columns, beams, slabs and stairs.

Table 1: Characteristics of the projects

Ref	Type of Building	Floors	Footprint Area (m^2)	Rebar Needed in One Floor (kg)	Crew Size	Observation Days
SP45	Residential building	21	12,500	10,089	4	95
SP73	Residential building	14	5,252	6,428	4	41
SP62	Residential building	13	5,000	5,955	3	35

The tasks for each structural component were categorized into “fabrication” and “installation”. Cutting longitudinal pieces, cutting transversal pieces, bending longitudinal pieces, and bending transversal pieces formed the fabrication activity. Pre-assembling, moving bars to a floor and final assembling formed the installation activity.

All projects were significantly variable. Figures 2, 3, and 4 show the daily productivity rates for each of the respective projects. The saw tooth curves in all cases show the degree of variability in daily productivity.

RESULTS

Labor performance is reported for each project. Inventory and time lag, calculated in the manner described in the method, are also reported.

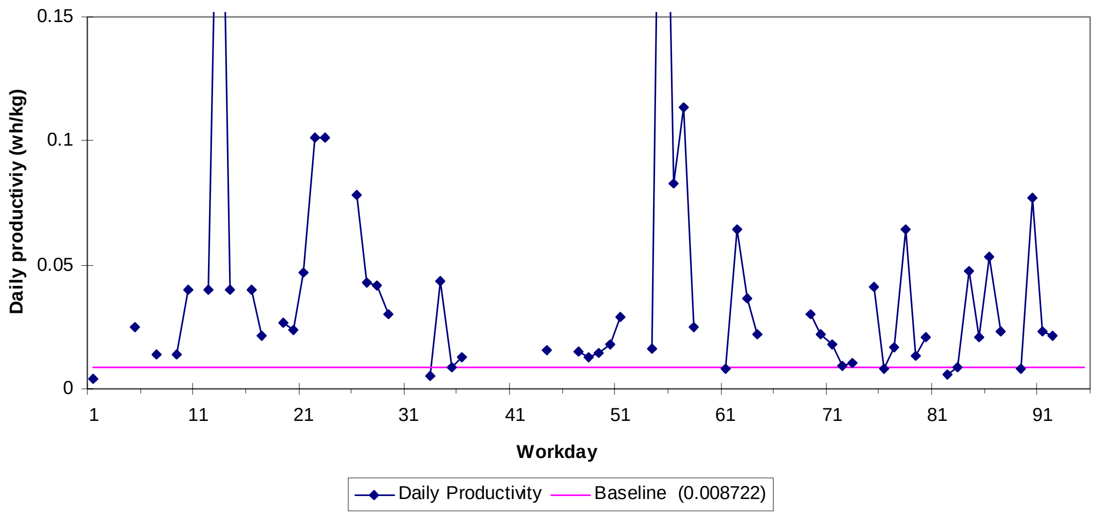

Figure 2: Daily productivity and baseline productivity on SP45

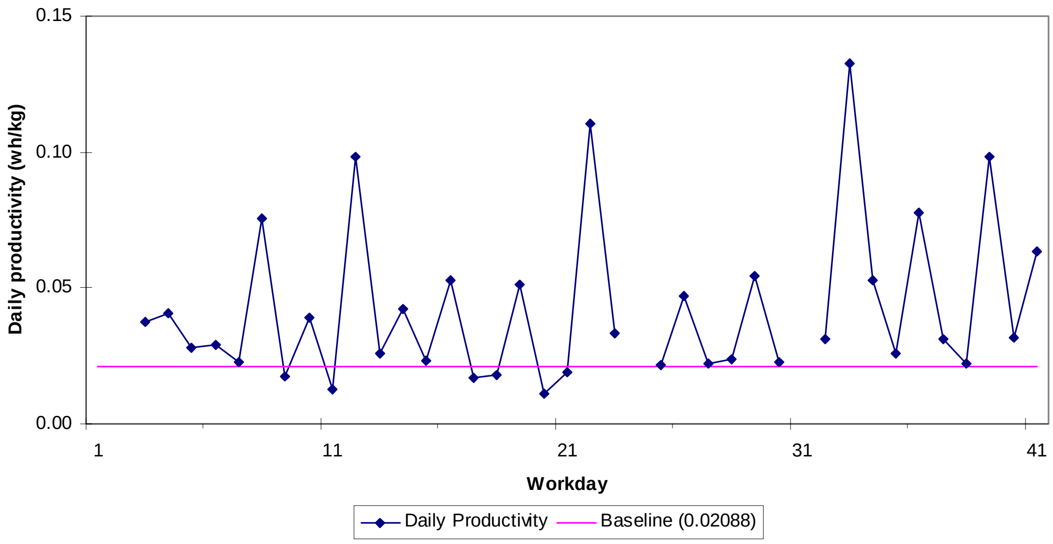

Figure 3: Daily productivity and baseline productivity on SP73

LABOR PERFORMANCE

The project waste index (PWI) was computed for each project to measure labor performance. Table 2 shows the PWI results for each project. Daily productivity was also compared to cumulative productivity as shown in Figures 2 to 4.

Figure 2 shows the daily productivity for project SP45. While SP45 has the best baseline productivity, 0.0087wh/kg, the cumulative productivity is 0.0201wh/kg, which is more than twice the baseline productivity. This means this project was a disrupted project. Although it had the best PWI of the three projects, the crew performed very inefficiently on several days as indicated by the peaks in Figure 2.

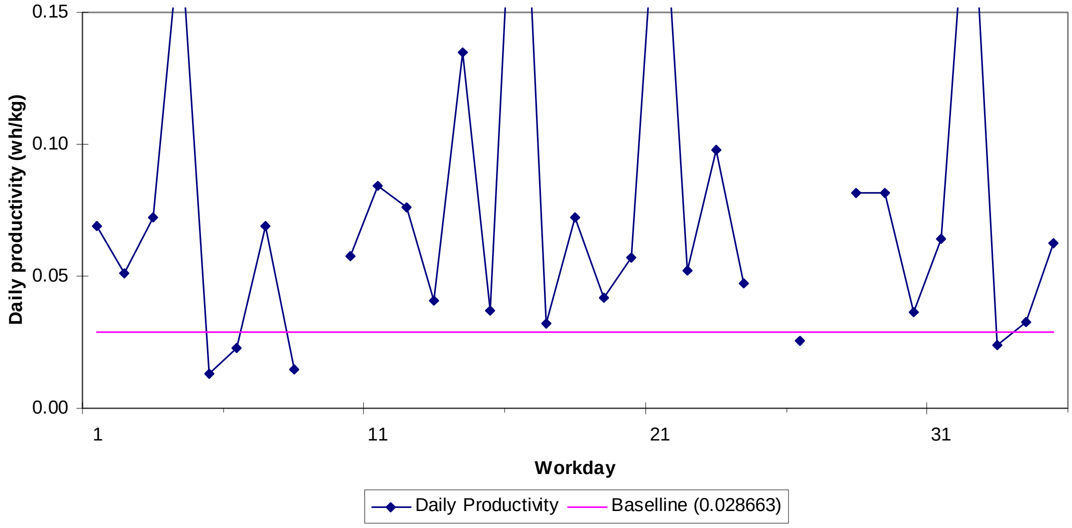

Figure 4: Daily productivity and baseline productivity on SP62

Table 2: Project Waste Index

Ref	Cumulative Productivity (wh/kg)	Baseline Productivity (wh/kg)	Expected Productivity (wh/kg)	PWI
SP45	0.0201	0.0087	0.0098	1.161
SP73	0.0340	0.0209	0.0098	1.339
SP62	0.0540	0.0287	0.0098	2.585

Figure 3 shows the daily productivity for project SP73. While the baseline productivity of 0.0209 wh/kg is more in line with the cumulative productivity is 0.0340 wh/kg than SP45, they reflect poor labor performance. This is supported by a PWI of 1.339 and chart that shows disrupted performance.

The results shown in Table 2 and Figure 4 indicate that SP62 is the worst management project. While the baseline productivity of SP62 is 0.0287wh/kg, cumulative productivity is 0.0540wh/kg, which is almost twice the baseline productivity, and PWI is 2.585. This shows that this project was significantly disrupted.

INVENTORY & TIME LAG

The amount of inventory and time lag between the fabrication and installation steps was calculated for each project. Figures 5, 6, and 7 show the progress of fabrication and installation for each of the projects analyzed. Table 3 shows the average time lag, average inventory and PWI for all of the projects. The inventory and time lag between fabrication and installation varied throughout project SP45. Figure 5 shows that size of the buffer in this project was larger than the other two projects. Fabrication and installation curves frequently crossed in SP73 as shown in Figure 6. This indicates that adequate buffers were not maintained through the project. However, performance in this project was not the worst (refer Table 3). In project SP62, small buffers were maintained and there were no disruptions. However, this project had the worst PWI among the three projects.

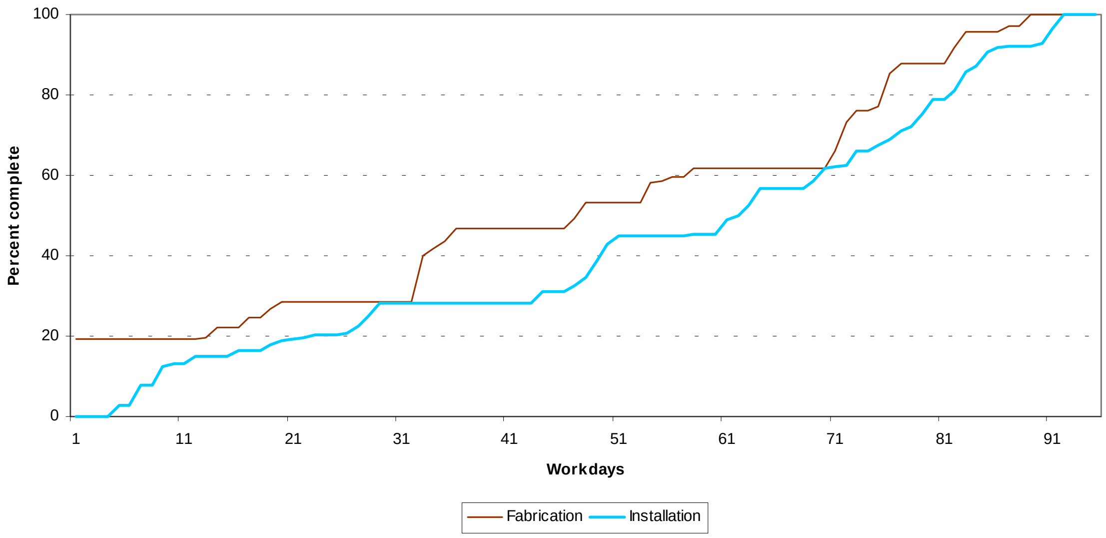

Figure 5: Progress curve on SP45

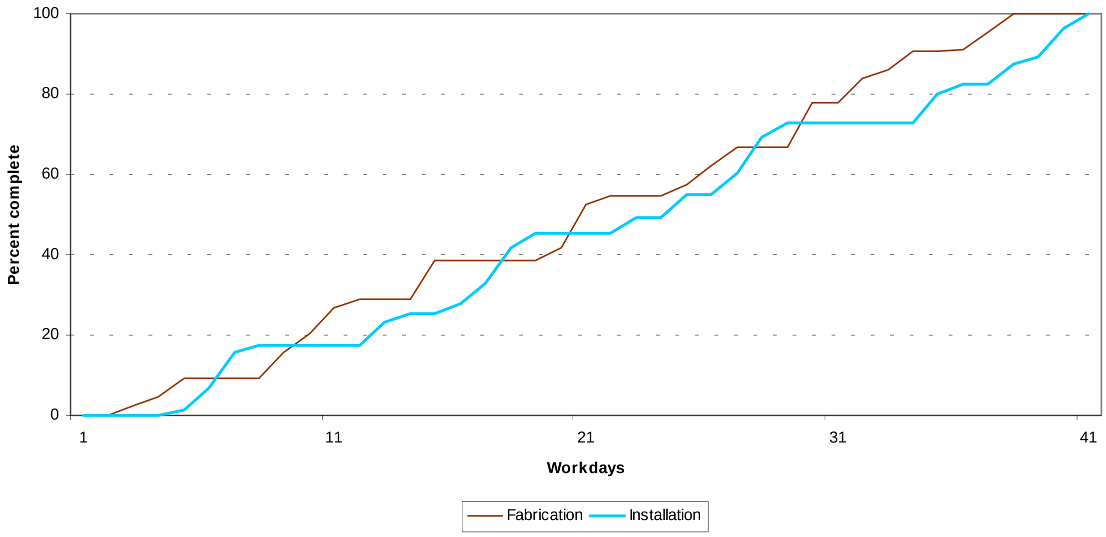

Figure 6: Progress curve on SP73

Table 3: Average time lag, inventory, and labor performance

Ref	Ave. Time Lag (Days)	Ave. Inventory (%)	PWI
SP45	8.6	8.7	1.161
SP73	6.4	2.8	1.339
SP62	5.2	1.9	2.585

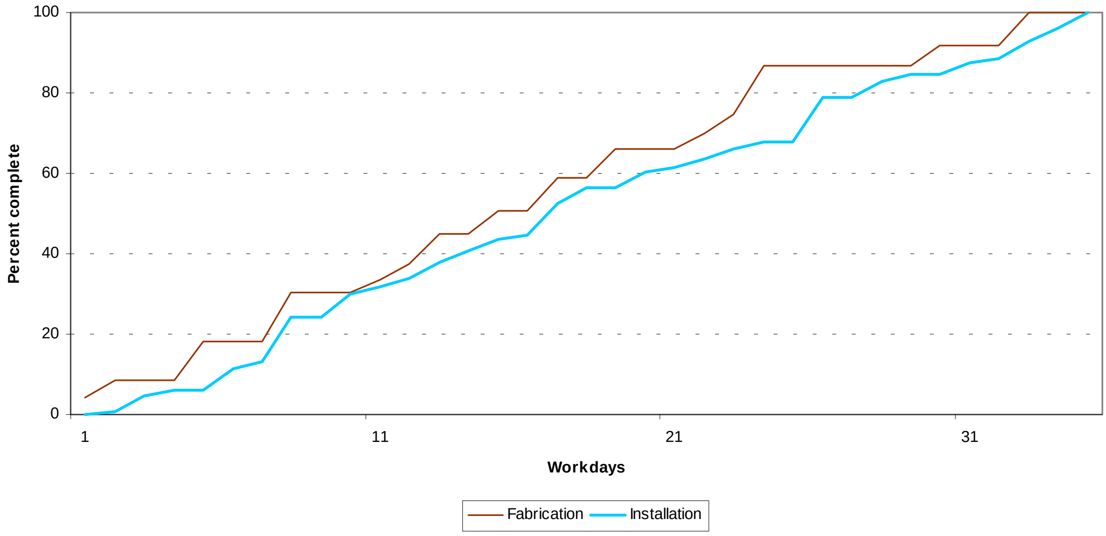

Figure 7: Progress curve on SP62

Further analysis was undertaken to see if the size of buffers was related to performance in any way. Patterns begin to emerge from the data and the significant findings are presented here. Figure 8 compares the daily productivity for the installation step of production to the size of inventory for project SP73. On four days when inventory is zero, productivity worsened. These have been marked on the figure. Figure 9 compares the daily productivity for the installation step to the daily inventory for project SP45. The inventory is shown in descending order to see if productivity changed in any way. It can be seen that there is little change in performance with inventory size, which at its peak, is almost at 20%. It seems that zero inventory is related to poor performance, while an excess inventory does not help improve performance.

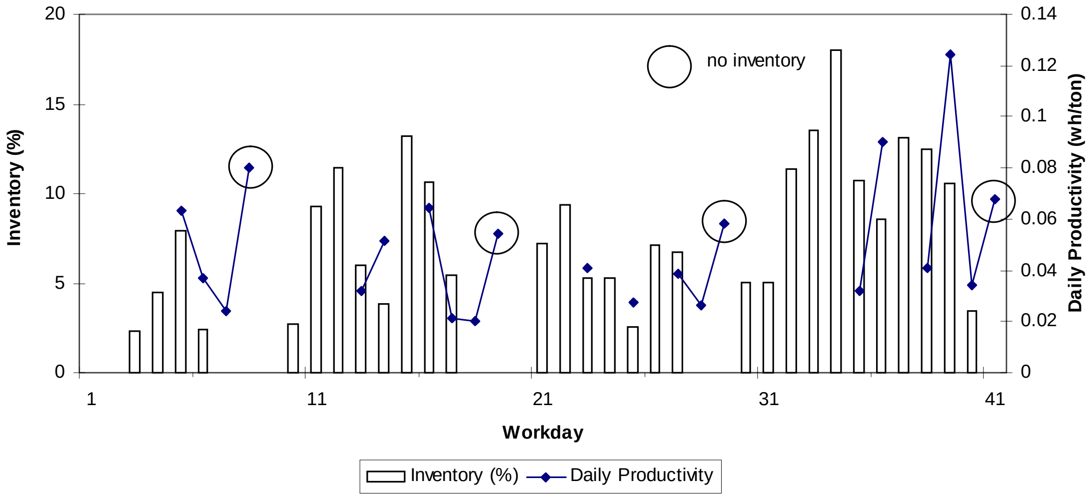

Figure 8: Inventory (%) and daily productivity for installation on SP73

A question that follows this analysis is what critical size of inventory is needed to keep workflow running sufficiently smoothly to achieve best performance. Average inventory

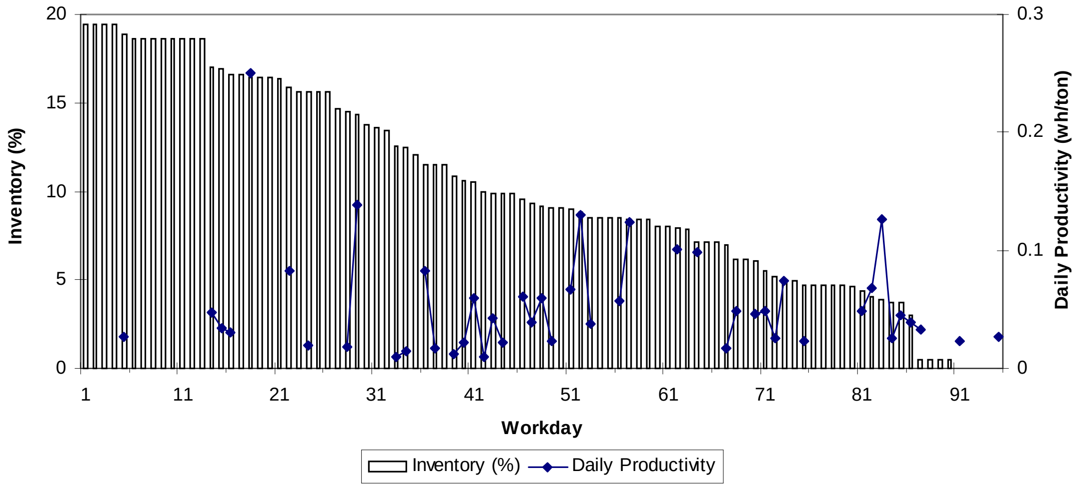

Figure 9: Inventory (%) in descending order and daily productivity for installation on SP45.

and average productivity for installation was compared across each floor in all projects to determine the optimal size of inventory. Table 4 shows the best performance achieved and the corresponding size of inventory. As can be seen, the average across these is approximately 5% inventory. Best performance was obtained in the projects when inventory was maintained in the range 4.5-7.5%.

Table 4: Inventory with best performance

Ref	Floor with Best Performance	Average Productivity (wh/kg)	Inventory (%)
SP45	4	0.029	5.31
SP73	2	0.034	4.22
SP62	1	0.048	4.29

Time lag was also compared to daily productivity. While inventory and time lag are highly correlated in most cases, there are instances when changes in one do not have the expected change in the other. Figure 7 shows different instances where the same size time lag has correspondingly different amounts of inventory. The analysis of time lag and daily productivity show that where time lags are short, there seems to be a disrupting effect. Figure 10 compares daily productivity for the installation step of production to the size of the time lag for project SP73. On days where there is zero time lag, productivity is low. These events have been marked on the figure. This seems to support Howell's (1993) contention that tightly linked processes are easily disrupted because the sequence is usually invariant and the interactions are immediate. It seems that performance is not influenced by the size of time lag when a minimum amount of time lag is supplied.

The issue arose as to the optimal amount of time lag for projects. It was found that inventory in the range 4.5-7.5% was more effective than less than 4.5% inventory for these projects. To determine the time lag associated with an inventory of 4.5-7.5 %,

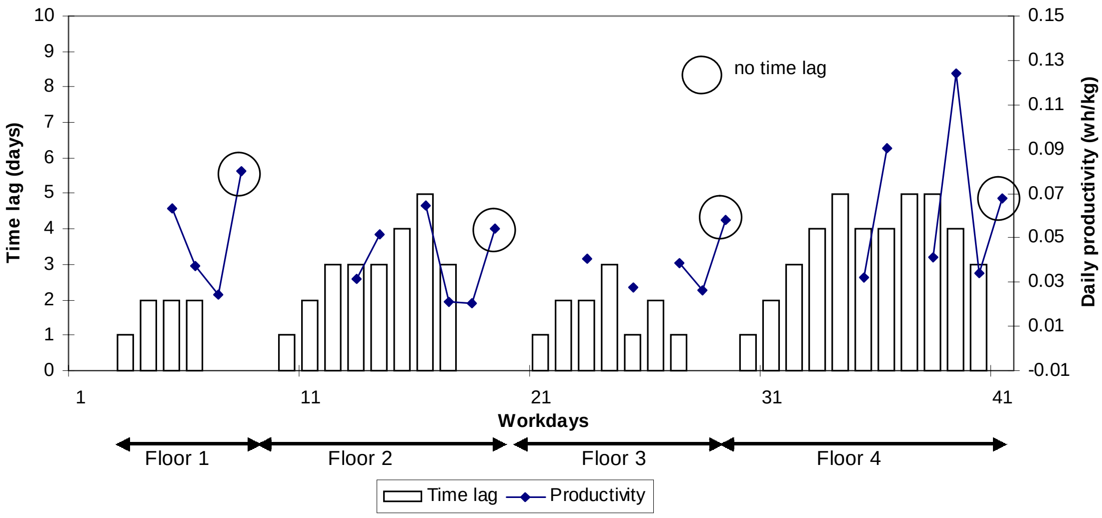

Figure 10: Time lag and daily productivity for installation on SP73

Table 5 was computed. It shows the average time lag in all projects when the inventory was within the ranges specified. This table indicates performance should be the best when the time lag is around 4.5 days.

Table 5: Time lag vs. inventory

Inventory (%)	Average Time Lag (Days)
0-4.5	3.160
4.5-7.5	**4.455**
over 7.5	8.564

DISCUSSION AND CONCLUDING REMARKS

In the studies analyzed in this paper, buffers of moderate size yielded the best performance. A build-up of inventory in the range of 4.5-7.5% between the fabrication and installation steps of reinforcement bar construction generated the highest performance in these studies. Inventory in this range enabled a time lag of approximately 4.5 days between the steps. A smaller buffer did not seem to effectively shield rebar installation from variability and resulted in reduced labor performance due to disruption. Medium-sized buffers provided conditions for best performance as larger buffers provided no additional performance benefits.

The results of this study seem to support the work of recent lean construction authors who argue that some buffer provides superior performance. Consequently, it also seems to contradict some of the basic lean tenets that argue buffers are a waste and should be removed from an operation in order to improve performance. Buffers, although non-value adding, need to remain in construction, it seems, because they prevent/reduce other forms of waste. It may be that as more lean production methods are used in construction projects, buffers will diminish in usefulness. It is worth remembering that it took Toyota more than twenty years to make their dramatic reductions in cycle times (Womack et al. 1990). However, it may also be that the uncertainty and variability inherent in construction means that buffers will always be a necessary non-value added component (waste). In the circumstances of this study, there seems to be no obvious benefit to reducing buffers to zero.

It is clear from this study, and others, that variability must be managed in construction, although there is no certainty about the best way to do this. The source of variability in the fabrication and installation activity in this study is not apparent from the data analyzed and, unfortunately, is unavailable from the source projects. It is possible to speculate that at least some of the variability might be reduced with better planning, especially planning focused on workflow, like the *Last Planner* (Ballard and Howell 1994). This is likely to mean that the optimal size of buffers could be reduced. However, even with improved planning, not all variability will be reduced and it is probable that there will always be some need for a buffer between these two production steps. Other buffers might be used in place of inventory and time if these proved to be more effective. For instance, Horman (2000) suggests the use of capacity buffers in certain circumstances.

It is also possible to think that buffers might be an advantageous way to manage certain circumstances. Clearly excessive buffers adversely impact performance. However, the advantage of the buffer is to establish a production goal for the operatives. Focusing on the fabrication and installation steps in the projects of this study, the goal might be to maintain inventory between 4.5-7.5% between steps at all times. This creates a 4.5 day time lag between steps that will absorb most problems. With this goal in place, the operation becomes more straightforward to manage. The advantage for management is clear: they no longer have to micro-manage every aspect of production, and their time can be released for more important and critical activities. Granted, considerably more work is needed to develop and test this idea, but it is an interesting area of further potential research. It is also not likely to be suitable for all circumstances.

There is a growing need to articulate lean production more clearly and more research will assist this pursuit. This paper tested the effect of buffers on the performance of a simple construction operation. A quantitative study showed that some buffer is needed between steps to achieve best performance. It was shown that buffers need to be used carefully and not be the only method to manage activities. However, in some circumstances, they may prove to be the best means of managing the conditions of construction. Further analysis is needed to see of these results extend to projects beyond those of this study.

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