INVESTIGATING THE RELATIONSHIP BETWEEN LABOR PRODUCTIVITY AND WORK-IN-PROCESS BUFFERS: A CASE STUDY

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ABSTRACT

In the last two decades, buffer-driven production strategies have been an emerging issue among lean construction researchers and practitioners alike. However, an in-depth understanding about the extent to which buffers impact system performance is still limited in construction, reducing the potential of using them to improve performance. To overcome this, the relationship between task-level labor productivity and buffer levels in a repetitive building project is investigated. In this research, a specific kind of inventory buffer is studied: work-in-process (WIP). A specific process was selected and analyzed in-detail as a case study to understand this relationship. The main result of this research indicates, through a linear regression, that an improvement in task-level labor productivity may be achieved when WIP buffer sizes greater than the size proposed by the lean ideal or the industry practice. However, this suggests a more in-depth investigation about the mechanisms operating in theory and practice in managing buffers in construction. Further research should focus on improving the analytical description of the relationship productivity/buffer on-site, as well as the understanding of the mechanisms at task and multiple task levels working in this relationship, and developing practical ways of using buffers to improve project-level performance.

KEY WORDS: Buffers, Labor Productivity, Work-In-Process, Performance.

INTRODUCTION

Variability is an inherent feature of production systems and is one of the factors that adversely affect the performance of construction projects. This phenomenon is seen daily in construction projects in the variable behavior of factors such as production rates, labor productivity, and construction schedules, (González et al, 2009). One of the collateral consequences of such variability is the use of buffers, which can protect the production processes against the negative impacts arising (Hopp and Spearman, 2000).

Hopp and Spearman (2000) provide a generic classification of buffers, which is applicable in construction, namely: inventory buffers; buffer capacity; and time buffers.

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Elsewhere, buffers that relate specifically to construction have been defined: plan buffer (Ballard and Howell, 1995) and technical information buffer (González et al, 2004).

In the last two decades, research in the field of Lean Construction has helped to better understand the role of buffers as a production strategy in construction (Alarcón and Ashley, 1999; González and Alarcón, 2010; González et al, 2009 and 2011; Horman, 2000; Tommelein et al, 1998; among others). These authors claim that a planned and deliberate use of buffers in construction has a positive impact upon project performance. Buffer-driven production strategies can minimize the impacts of variability, thereby achieving significant reductions in lead times, waste and costs associated with projects. Horman (2000) suggests that when a buffer is used correctly, it not only provides a cushion or protection, but it also increases the ability to respond efficiently to changing conditions, and thus may be used to maintain or even increase system performance. Otherwise, a theoretical buffer level of zero is desirable from a lean standpoint. Nevertheless, even the leanest production system needs a certain level of buffer to perform work. In other words, it appears that a 'balance problem' exists between the use of buffers to reduce variability impacts and overall production system performance based on lean principles (González et al, 2009). Then, it is argued that a more in-depth understanding about the extent to which buffers impact system performance is necessary.

In this research, the relationship between task-level labor productivity and inventory buffer levels in a repetitive building project is investigated to promote a progress in the understanding of this 'balance problem'. Thus, a specific kind of inventory buffer is studied: work-in-process (WIP). Hopp and Spearman (2000) define inventory buffer as in-excess stock of raw materials, WIP and finished goods, categorized according their position and purposes in the supply chain. In construction, WIP can be defined as the difference between the cumulative progress of two consecutive and dependent processes, which are characterized by units of work in front of a crew to perform their work (González et al, 2009).

Whilst some studies have analyzed the relationship between buffer and labor productivity, it would appear that little research has been undertaken to understand this relationship: For instance, Horman (2000) analyzed the impact of process dynamics on labor performance. Also, Horman and Thomas (2005) studied the impact of material buffers on labor productivity. However, previous researches have been either rather specific or have practical limitations in application.

On the other hand, different studies have used WIP buffers in construction. Alarcón and Ashley (1999) analyzed the impact of these buffers on the project duration and cost, as well as the variability of production. Alves and Tommelein (2003, 2004) modeled the supply chain for sizing buffers, addressing their impact on system performance, WIP and delivery times, in the processes of design, manufacturing and installation of metal ducts. Bashford et al (2005) applied the Little's Law to model WIP Bf which fitted quite well to the production behavior of construction at project level and for a long time horizon. Sakamoto et al. (2002) analyzed the influence of WIP buffers on the performance of three commercial projects, and used the so-called project waste index (PWI) to measure waste in labor performance. Tommelein et al. (1998) illustrated, through the use of a simulation game, the impact of workflow variability and WIP buffers in a production system. Walsh et al. (2007) proposed general equations for WIP and cycle time for unsteady state at process level and limited run production, using the Little's Law and conservation of mass concepts. González et al (2009 and 2011) and González and Alarcón (2010) proposed the use of a general methodology for WIP buffer design and management in repetitive projects.

All these researches have produced interesting results in terms of WIP buffer understanding and its application in construction projects. But more detailed research is still necessary in relation to the impacts of such buffers upon project performance, in this case labor productivity, during the construction processes on-site.

The following sections address the research methodology and the case study before moving to discussion and the main conclusions of this research.

RESEARCH METHODOLOGY

In this paper, the case study approach has been used. The following stages define the research conducted: 1) Literature review in relation to buffer management and productivity impacts; 2) Selection of activities following an exploratory field analysis to become familiar with the project under study; 3) Gathering information, in which productivity and WIP buffers data were collected; and finally 4) Analysis, in which statistical and linear regression analyses were performed between labor productivity and WIP buffers, seeking to understand the relationship between them. It is necessary to bear in mind that this research is exploratory and descriptive in nature and this has not the purpose to find out the “real” or “true” relationship between labor productivity and WIP buffers. Otherwise, this research effort tries to provide a more precise explanation between these variables, if possible, with the available data and limitations of this research.

CASE STUDY

The selected case study was a multistory building project located in the city of Valparaiso, Chile. The project comprises of a two-tower building of fourteen floors each, with multiple apartments on each floor (eight apartments levels 2-11 and nine apartments levels 12-14). This study was performed in the finishes stage of the construction programmed. At the beginning, the researchers selected a number of field activities. In consideration of the quality of measurements and continuity of work, two specific and interdependent activities were selected; ‘tiling’ and ‘fixtures and fittings’ activities (the latter represents the subsequent activity). The tiles were laid on floors and walls in the apartments, in bathrooms and kitchen, while fixtures and fittings comprised of fixed units in kitchens and vanity units in bathrooms. Both activities were subcontracted out, and performed by different subcontractors.

MEASUREMENT APPROACH

To analyze the progress of each activity a ‘standard apartment’ was defined. This enabled the measurement of equivalent progress in work units compared to this ‘standard apartment'. It was essential to use the same unit of measure in both activities in order to investigate the relationship between activities for accumulated progress (.e.g. velocity charts) and determine the WIP buffer. Table 1 illustrates the estimation approach using the tiling activity. This table shows the different type of apartments available in the project and the tiling area considered in each case. Apartment E is selected as the "standard apartment" due to it has the lower number of work units, i.e. area. Then, the equivalent number of "standard apartments" was calculated for the rest of the apartments. One of the limitation of this approach is that neglects the influence of the available space over the labor productivity. But, a similar approach has been applied with good results in other researchers [see for instance Gonzalez et al. (2009)].

Table 1: Estimation approach for standard apartment for tiling activity.

ID Apartment	Area with tiles (m^2)	Apartment Unit
A	73.75	2.55
A1	65.95	2.28
B	46.17	1.60
B1	47.21	1.64
C	48.23	1.67
C1	46.15	1.60
C2	44.55	1.54
D	33.29	1.15
D1	32.35	1.12
E	**28.87**	**1.00**
F	39.48	1.37

To determine the labor productivity associated with the chosen activities, both the activity progress and number of workers were measured and recorded in a daily basis by direct observation of crews in the field. The activity progress was collected using the "standard apartment" unit, herein named as "apartment" unit; while the number of workers in workers-day. Thus, the daily productivity is determined as the ratio between activity progress and daily workers.

The WIP buffer was calculated by subtracting the cumulative progress of dependent and consecutive activities, using the technique of velocity charts. Thus, several kinds of WIP buffers were identified and analyzed: 1) Monday buffer, which is the WIP buffer size at the beginning of a workweek (see details of this type of buffer in Gonzalez et al, 2010); and 2) The weekly average buffer, which is the arithmetic mean of the daily WIP buffer size measured in a workweek of 5 workdays (from Monday to Friday). Having calculated the daily productivity, one could estimate the weekly average daily productivity as the arithmetic mean of the daily labor productivity measured in a workweek (5 workdays).

More in detail in this research, the WIP buffer is the difference between the cumulative progress of the ’tiling’ and ‘fixtures and fittings’’ activities. We contend that the WIP buffer analyzed influences the task-level labor productivity of the subsequent activity, (i.e. ‘fixtures and fittings’ activity), as one of a number of possible influencing factors. Other possible influencing factors may include items such as team formation, skills and training, sickness, site conditions etc. It was not possible to isolate such factors, and hence is a limitation of this study. Also, the learning effect was neglected just to develop an exploratory description of the analyzed relationship, having in mind the limited number of data and the differences in the work units measured (different apartment dimensions). Another limitation was to ignore the effect of subcontractors' setup at the beginning of a workweek, which could be affected by the Monday buffer size. That is to say, crew composition or changes in construction practices were not analyzed when buffer is increased or reduced at the beginning of a workweek.

In terms of the associated variables, the labor productivity of the ‘fixtures and fittings’ activity depends on the WIP buffer size generated at the end of the previous day by the ‘tiling’ activity. Both buffer and productivity are considered to be related as ordered pairs for purposes of further analysis.

DATA ANALYSIS

Data was collected for productivity and buffers for the tiling activity for a period of 35 consecutive days, and similarly for the ‘fixtures and fittings’ for 23 consecutive days. Figure 1 shows the labor productivity evolution for both activities during the measurement period.

From the records of cumulative progress for the “Tiles Installation” and “Furniture Installation” activities, it was possible to determine the WIP buffer for the “Furniture Installation” activity. In figure 2, the cumulative progress of both activities is shown through a velocity chart, which also shows the evolution of the WIP buffer. Note that the two-tower project has a total number of 214 apartments. Otherwise, figure 2 shows a higher number of apartments for the cumulative progress of both activities. The reason for this is the use of the ‘standard apartment’ in the calculation of cumulative progress, which was mentioned earlier.

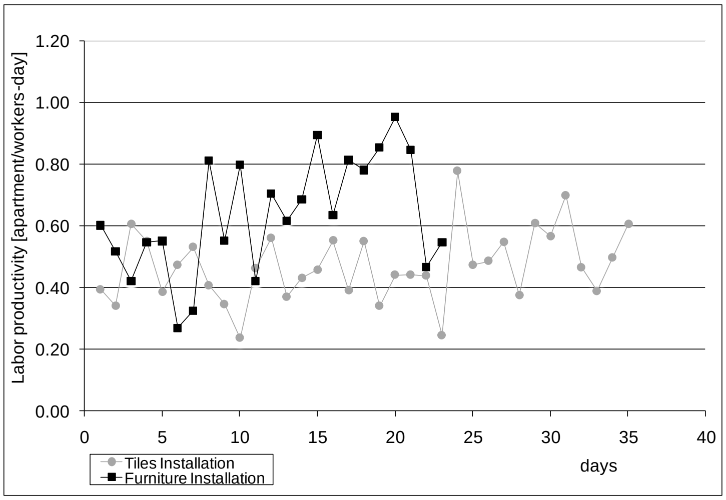

Figure 1. Evolution of labor productivity over time: □tiling□ and □fixtures and fittings□ activities.

Figure 2. Cumulative Progress of □tiling□ and □fixtures and fittings□ activities and WIP Bf size evolution over time.

The WIP buffer curve generated was compared with the productivity of the "fixtures and fittings" activity, which is illustrated in Figure 3. It is possible to make some observations and possible interpretations from this figure:

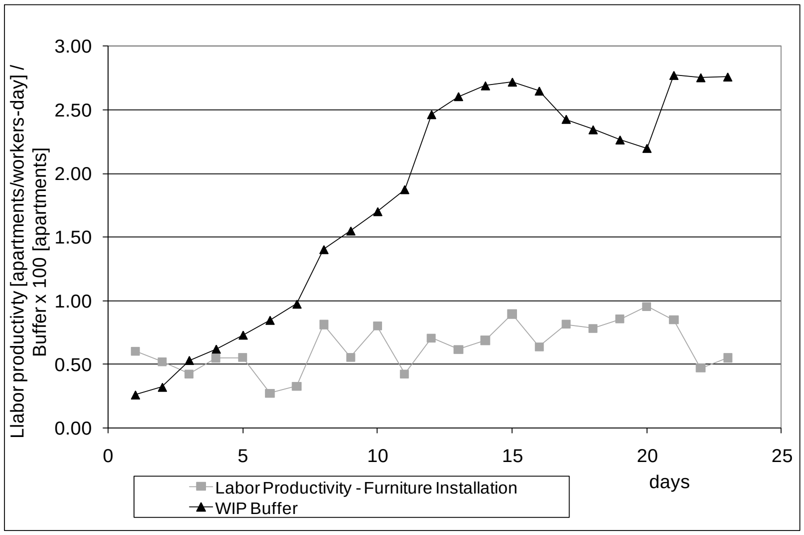

Figure 3. Evolution of labor productity for the ¤fixtures and fittings¤ activity and the WIP Buffer over time.

1. There appears to be an improvement in productivity around the 7th day, which may be as a result in the increased in the size of the buffer.
2. Between the 7th and 20th day there is no apparent improvement on the labor performance.
3. Productivity shows significant variations in its behavior over the whole period. It was observed that such behavior was a consequence of common problems not related to buffer management (e.g. lack of materials, fails in equipment, etc.).
4. Towards the end of the period, between 20th and 25th days, there appears to be a reduction in labor productivity. This phenomenon may be as a result of the reduction of buffer size in the previous few days.

Due to the fact that this analysis is not entirely clear, a deeper analysis was performed to better understand the relationship between the variables involved. Simple statistical analyses using correlation coefficient (R) and coefficient of determination (R^2) were used. Also, linear regression models were constructed for the labor productivity and buffer. In this sense, the WIP Buffer was defined as the independent variable and the labor productivity as the dependent variable. For the purpose of this analysis, the weekly average buffer, the Monday buffer and the weekly average daily productivity were calculated. The graphs generated are shown in Figure 4 and Figure 5. Note that these figures present filtered data, in which those data out of the trend observed, were eliminated. In other words, those days in which different problems appear other than the buffers influence (e.g. lack of materials, fails in equipment, etc) were eliminated. By doing so, it was tried to isolate the influence of the WIP buffers over labor productivity.

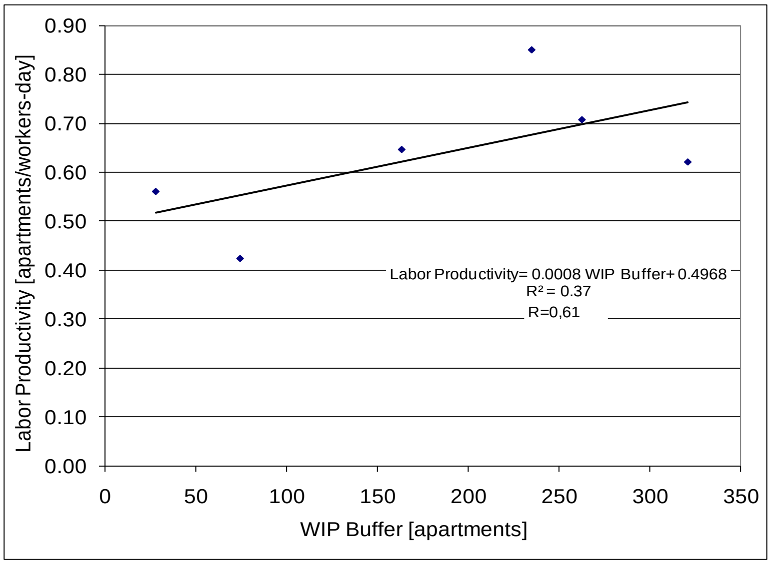

Figure 4. Relationship between the Weekly Average Daily Productivity and the Weekly Average Buffer.

Figure 4 shows the relationship between the weekly average daily productivity and the weekly average buffer for the ¤fixtures and fittings¤ activity. It can be seen from this figure that the linear regression model has an R^2 equal to 0.37 for the considered variables, which implies that the model accounts for approximately 37% of the variability of the data, which implies that is a model of low quality. However, there is good correlation between the two variables given by an R equal to 0.61, suggesting a positive linear behavior and moderate relationship between them. That is to say, when the weekly average buffer size grows, this can influences linearly the increase of the weekly average daily productivity.

By developing more aggregated analysis in Figure 5, it is possible to find out more significant results than in Figure 4. Figure 5 shows the relationship between Monday buffer and weekly average daily productivity for the ¤fixtures and fittings¤ activity. The linear regression model shows an R^2 equal to 0.53 of fitting to the analyzed information. In other words, the model takes into account approximately 53% of the variability of the data, which means that is a model of a better quality than the model in Figure 4 and would allow developing certain predictions of the labor productivity behavior in relation to the size of the buffer with more confidence. It seems to be that the buffer available at the beginning of the week has a more significant role on the performance of labor, in comparison to the daily variation of size. This finding is similar to that found by one of the researchers in relation to the management of WIP buffers (Gonzalez et al., 2009, 2011). In addition, this analysis shows a better and stronger correlation of both variables than Figure 4, given by an R equal to 0.73. That is, when the Monday buffer size grows, this can influences linearly the increase of the weekly average daily task level productivity of the subsequent activity.

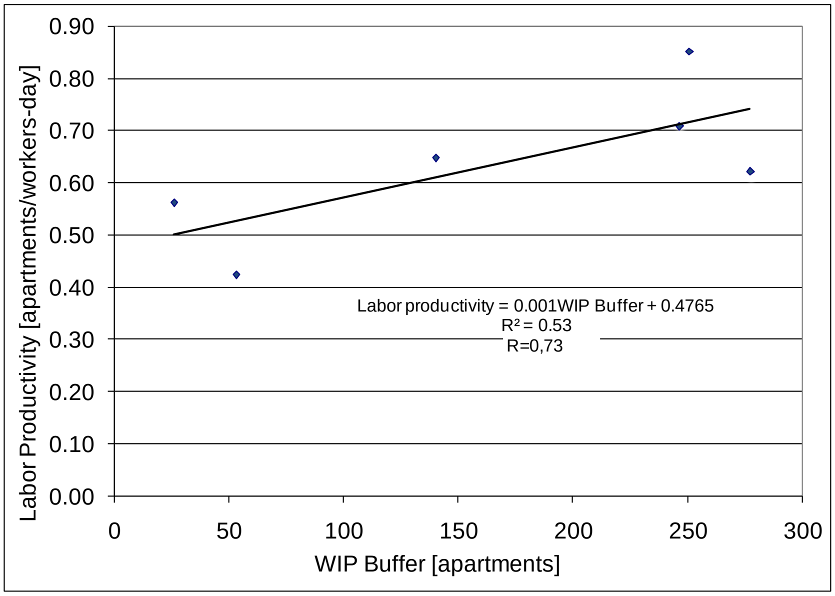

Figure 5. Relationship between the Weekly Average Daily Productivity and the Monday Buffer.

In summary, Figures 3, 4 and 5 indicate that higher levels of WIP buffer seem to promote improvements on the labor productivity in the "Furniture Installation" activity analyzed. However, a more complete description of this relationship such as a non-linear relationship was not possible to fit due to the fact that there was a lack of data. This is especially important to understand the role of Monday buffer over productivity.

CONCLUSIONS

The research carried out through a case study, and presented in this paper, would indicate that improvements in task-level labor productivity are possible by management of WIP buffer sizes. In this particular case study the task level productivity of an activity (furniture installation), dependent upon a previous activity (tile installation), was found to improve seemingly by increasing the WIP buffer size. This is not a surprising result, and the efficiency gains can be explained by the increased availability of the workface in the latter activity. One possible explanation is the learning of crews. However, this was not studied in this research given, for instance, the non-uniformity of work units. This indicates that a possible mean for improving productivity in construction is to increase WIP buffer sizes between activities to a certain extent. From a practical standpoint, this sounds somewhat contrary to standard construction practices, in which the notion of starting the work "as soon as possible" is predominant. Perhaps a more efficient approach in general could be delivered by adopting a notion of starting work "as late as possible reaching an optimum performance". From a theoretical standpoint, the increase of WIP buffers is contrary to the "lean ideal" of zero inventories. Then, it is necessary to maintain a balance between the necessary buffer to keep processes working and the lean ideal. The underlying idea is to find out an optimum between both goals. Nonetheless, this is not possible only describing linear relationships.

Note that, given the limited amount of empirical data as evidence, we found a simple linear relationship between the buffers and labor productivity. Other types of relationships and behavior patterns (e.g. non-linear) that may exist are hidden, due to the limited scope and nature of this research. This is a key aspect to understand the mechanisms involved in this relationship and to what extent is possible to improve labor productivity given a certain buffer level. In other words, to what extent the productivity curve would be asymptotic or declining. Therefore, there is still uncertainty about the "real" or more reliable behavior between these variables. At last, it could contribute to complement the body of knowledge in terms of the “construction physics”.

On the other hand, it seems to be that the buffer size at the beginning of a workweek may have a stronger relationship than daily buffer size with labor productivity. The reasons why there is a stronger correlation between productivity and WIP buffer size on Mondays has not been investigated qualitatively in this research. However, a speculative reason may be that contractors (and subcontractors) typically establish weekly forward work plans on Mondays. It is likely that weekly work targets are established at commencement of the week based on the WIP as of Monday morning, and not then checked during the week unless there is a significant change against expectation. This could can have a significant application in the practice of construction project management, since the buffer size could be a production variable explicitly managed to improve the performance of labor at a weekly level.

We recognize that the primary role of buffers is to reduce the negative impact of variability in production systems. As we mentioned earlier, we also understand that, from a lean thinking view, the goal of a production system is to minimize buffers, and that a theoretical ideal production system would have a zero buffer level. However, we believe that in construction there is a trade-off between the theoretical goals of buffer minimization in lean thinking with the pragmatic implications of optimizing buffer sizes in construction. This is due in part to the practical implications of physical access to the workface, limitations of skilled labor, the need to optimize efficiency whilst at the same time using buffers to manage risk. We acknowledge that this study has several limitations, and as such further investigations are necessary in order to achieve a deeper understanding of these relationships, to provide strong managerial tools to deal with the buffer issue in construction.

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