UNDERSTANDING THE RELATIONSHIP BETWEEN PRODUCTIVITY AND BUFFERS IN CONSTRUCTION: A SIMULATION-BASED CASE

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ABSTRACT

Buffer-driven production strategies represent an effective mechanism to shield the production system performance from the ill-effects of variability. In construction, these production strategies have been an emerging issue among lean construction researchers and practitioners alike. However, there is still room to better understand the relationship between performance and buffers in construction, in order to develop suitable buffer management approaches in projects. In this exploratory research, the relationship between productivity and buffer levels in repetitive projects is investigated by using Discrete-Event Simulation (DES) modelling. Also, a specific kind of inventory buffer is studied: work-in-process (WIP). A number of simulation scenarios with varying production parameters such as production amount, production rate, variability levels and initial WIP buffer size were tested. Results show that even though WIP buffer may not contribute to improving productivity rates, but they provide very good protection to productivity levels in case of variability conditions in projects. This effect makes WIP buffer suitable for use in large scale repetitive projects where a small disruption in production can lead to heavy losses. Also mathematical relationships between productivity and WIP buffer were analyzed, finding some good non-linear relationships able to explain to a certain extent the impact of the WIP buffers sizes on productivity.

KEY WORDS

Buffer, Discrete-Event Simulation, Productivity, Repetitive Projects, Variability, Work-In-Process.

INTRODUCTION

Construction Projects seldom happen as ideally as planned. Nature's uncertainty induces variability to spoil plans and becomes a major factor in affecting project performance and productivity. Variability leads to ineffective production, increased cycle times, increased cost, and derailed plans. Philosophically, this is better embodied in the form of Hofstadter's Law, which states, "It always takes longer than you expect". Variability is a common phenomenon observed in production systems (Hopp and Spearman, 2000). In construction projects, variability manifests as the variable behaviour of factors like production rate, labour productivity, and construction

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schedules (González et al. 2009). Using buffers is one of the ways to counter the negative effects of variability in construction projects, especially mitigation of productivity loss (Hopp and Spearman, 2000). In construction, buffers are generally classified as inventory buffers, capacity buffers, and time buffers.

Research in this field of lean construction in the last two decades has improved our understanding of 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).

In this research, the relationship between labour productivity and inventory buffer levels for repetitive building projects in a simulation-based case is investigated to deepen the understanding on the nature of this relationship. Thus, a specific kind of inventory buffer is studied: work-in-process (WIP). 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). Then, we argued that a more in-depth understanding about the extent to which buffers impact system performance is necessary by performing further large-scale studies.

It seems to be that little research has been undertaken to understand the relationship between buffers and labour productivity: For instance, Horman (2000) analyzed the impact of process dynamics on labour performance. Also, Horman and Thomas (2005) studied the impact of material buffers on labour productivity. Gonzalez et al (2011b) analyzed the relationship between labour productivity and buffers in a real repetitive construction project. However, previous researches have some limitations in terms of scope and purpose.

On the other hand, different studies have used WIP buffers in construction (Alarcón and Ashley, 1999; Alves and Tommelein, 2004; Bashford et al. 2005; González et al. 2009, 2011a and 2011b; González and Alarcón, 2010; Sakamoto et al. 2002; Tommelein et al. 1998; Walsh et al. 2007). All these researches have produced interesting theoretical and practical results in terms of the WIP buffer use in construction. However, they still provided limited information on the relationship between performance as productivity and buffers. By using the powerful capabilities of computer simulation, this research attempts to provide more insightful information and knowledge on this relationship between productivity and buffer sizes. 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, a Discrete Event Simulation (DES) modelling approach was used as the main research methodology. DES is a suitable approach as construction projects consist of events in the form of completion of discrete units of work in a chronological order. Work was performed in the following order: 1) Literature review of buffers and their management in relation to project productivity and performance. 2) Forming a DES based computer model for simulating a repetitive building project (RBP), specifying parameters for relating productivity and WIP buffers based on the Gonzalez et al. (2009) research (Figure 1 shows a simplified schematic of the model). 3) Developing test cases and experiment parameters corresponding to the test cases. 4) Doing simulation for the test-cases and generating the required data; and finally. 5) Processing the data and understanding the required relations we chose to seek.

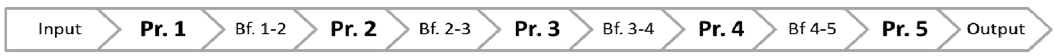

Figure 1: Simplified model of an RBP consisting of 5 sequentially dependent processes (Pr. #) and the 4 intermediary WIP buffers (Bf. #-#) (adapted from Gonzalez et al. 2009).

PROBLEM DISCUSSION

We used simulation-modelling to study the relation between WIP buffers and Labour productivity. This allows us to study a very large variety of construction projects consisting of a large diversity in the range of the project parameters such as production amount, initial WIP buffer, estimated production rate, and variability. **Production amount** is the number of repeating units that are to be constructed. It represents the project size. **Production rate** is the estimated rate at which the construction would happen considering full efficiency of the labour and machines and considering perfect coordination between them with no effect of variability. **Initial WiP-Bf** is the size of the first buffer that is developed between any two sequential processes. The second process shall not begin until the requisite amount of production in the first process is completed to create the required initial buffer. **Variability** adds a statistical randomness to the estimated production rate using the coefficient of variation of duration (ratio between average and standard deviation of duration). We also used a Beta probability distribution to induce variability (Gonzalez et al. 2009).

We assume that all the sequential processes have the same estimated production rate and variability. It is also assumed that production is in terms of entities as 'units' and the unit time scale is taken as 1 day. WIP buffers (or 'buffer') and productivity are calculated on a daily basis. Daily productivity the actual production happening in a day is different from the estimated production rate (simply 'rate') due to all factors covered under variability.

The large variety in the generated data allows us to observe the buffer-productivity relations from several dimensions. The adapted simulation model consisted of a project having 5 sequential processes resulting in 4 sets of buffers – one for each pair of sequential processes (see Figure 1). Here, we have analyzed only the first buffer (i.e. the buffer between process 1 and 2), as it is the one directly affected by the variability of the preceding process (process 1). All subsequent buffers are affected by the buffers preceding them too, resulting in a compounded effect of variability and a more complex behaviour to understand. Since this is an exploratory work, we are not stating a very definite hypothesis except that buffers help counter negative effects of variability on project performance. As we are not hypothesizing and only exploring possibilities, we shall like to consider a large range of values of the project parameters to be able to draw out significant quantitative and qualitative relations between buffers and productivity.

TEST CASES

In total, 260 test cases are defined to generate the dataset. Each test case is simulated 100 times and results from all 100 runs are averaged to get stable values. The Project parameters and their values used are given in Table 1. Due to the large number of cases, we used a standard format for denoting cases; this is given in Table 2, along with a concise list of the cases. ExtendSim software was used for simulation using the DES model previously discussed and later Matlab was used to process the data.

Table 1: Value ranges of the project parameters used in simulation

Parameters	**Abbreviation**	**Levels**
Production Amount	Prod.Amt	25-500 units
Production Rate	Prod.Rate	0.1-10 units/day
Initial WiP-Bf	IWiP-Bf	1-100 Units
Variability	Var.	25% - 98%

Table 2: Overview of test cases grouped by prod.amt
since other parameters are limiting ones

Cases & their Parameter Ranges (Case No./Prod.Amt/IWiP/Prod.Rate/Var)	**Cases**
(001-036) / 25 / (1, 5, 10) / (0.1, 0.5, 1) / (25, 50, 75, 98)%	36
(037-116) / 100 / (1, 5, 10, 25) / (0.1, 0.5, 1, 2.5, 5) / (25, 50, 75, 98)%	81
(117-260)/500/(1,5,10,25,50,100)/(0.1, 0.5, 1, 2.5, 5, 10)/(25, 50, 75, 98) %	126

Technically the project consumed over 2000 hours of computation time and human effort – processing several billion numerical values and several hundred tables and graphs for all logically relevant combinations of test cases. A few representative graphs were selected for analysis and discussion in this paper.

CALCULATIONS

Data from ExtendSim was as tables of cumulative production vs. time giving discrete integral values of cumulative production in each process and the time-step at these points (Figure 2). All buffers and IWiP-Bf are shown in Figure 2. Warm-up and trailing periods shown are periods in a project with no buffer in the system and are ignored for buffer and productivity calculations. The processed simulation data is as simple buffer vs. productivity tables. Although we discussed earlier that in this study we shall look at only the buffer between the first two processes, but we process data for all processes considering further research beyond this study.

Buffer size is the difference between the cumulative productions of consecutive activities at any point of time. Daily productivity values are the differences between the production values for a single activity between consecutive days. Both, the buffer and productivity are shown graphically in Figure 2. The buffer size on day 'm' is related to the productivity on day 'm+1'. Hence, these processed tables are stateless – that is, they do not bear any information regarding the particular time of the project that they represent; they just provide a correspondence between the buffer-size on one day and the productivity levels on the next day.

For a structured analysis, several groups of cases were created based on certain criteria of parameter values; these shall be explained in subsequent sections. During analysis, several graphs with different sets of parameters were developed and a few representative ones were chosen for discussion. We observed that a power-function approximation provides good and relatively better correlations (i.e. good coefficient of determination, R^2) compared to other curve fitting methods – thus all representative graphs have been developed using the power-function approximation

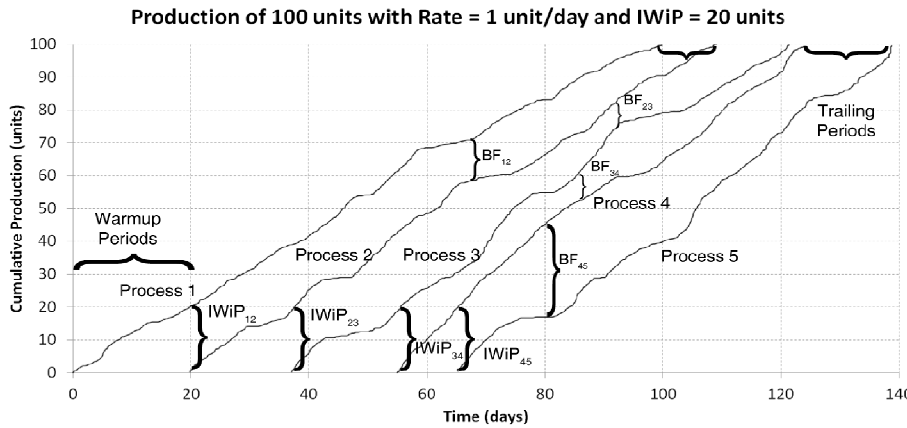

Figure 2: Time-based progress of a project having 5 processes, 100 units of production, a prod. rate of 1 unit/day, an IWiP of 20 units and a variability of 25%.

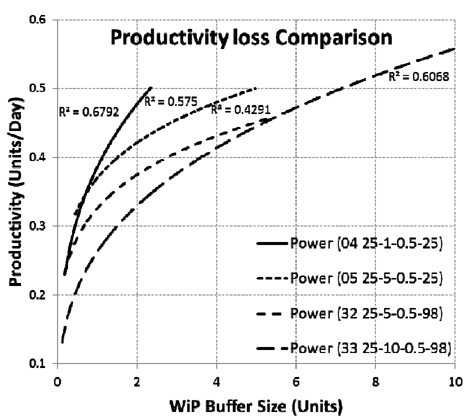

Figure 3: Productivity-Buffer curve for small project and variable IWiP

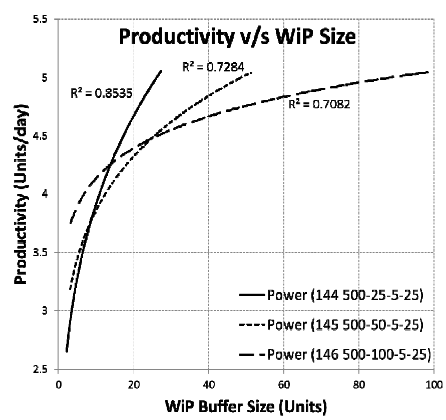

Figure 4: High IWiP gives better productivity-loss mitigation as Bf reduces

VARIABLE INITIAL BUFFER SIZE (IWIP)

Our first criterion is to understand the productivity vs. buffer-size relation with changes in the IWiP-Bf. Figure 3 and Figure 4 represent two widely apart ranges of Prod. Amt and IWiP-Bf amongst the test cases. In both figures, for every unit reduction of buffer, the percentage productivity degradation is lesser for higher IWiP. In Figure 3, we see that productivity is falling as the buffer size reduces but is not increasing much beyond the production rate. Productivity values as such are lower for higher variability (hence, in Figure 3, Case 05 has higher productivity than Case 32).

We observed similar results for projects of larger size as in Figure 4, having the highest prod. amt. amongst the test cases coupled with a high prod. rate. Again, the relative productivity loss is lower for higher IWiP. In Figure 4 we also observe a saturation in productivity for very large buffer-sizes as the curve is asymptotic. At this point, we can say that there exists a 'balance-problem', which discourages us to use very large initial buffer sizes. It also discourages very small initial buffers, which result in steep productivity loss with a reducing buffer-size. In the folowing sections, we explore other project parameters and study how they affect productivity.

PRODUCTION RATE AND PRODUCTION AMOUNT FACTOR

It is possible that production disruption can perhaps be less problematic for a larger project as it has many chances to bounce back on track due to its large time-scale. Similarly projects with very low production rates may have a greater possibility of a bounce-back at some point due to the inherently long schedule. Projects having a very high production rate must have processes running continually at a good efficiency or else a bounce-back to normal schedule might be difficult as everything is happening so quickly in it. To understand this, we take up 3 situations as follows:

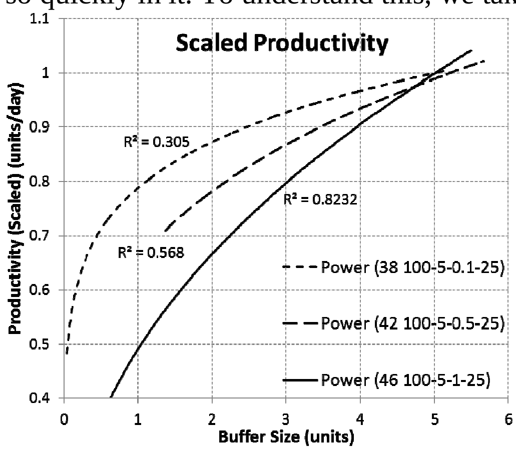

Figure 5: Scaling Productivity allows comparing performance of projects with varying prod. rates

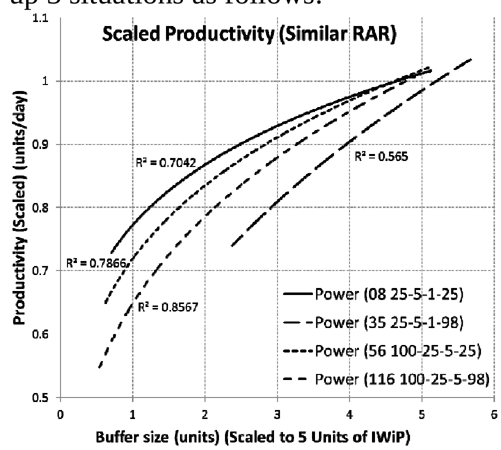

Figure 6: Scaled Productivity for projects with a similar RAR

1. Medium project size and normal production rate values (Figure 5)

Production rate varied from 0.1 to 1 unit(s)/day. We observed that in the case with production rate of 1 unit/day, there was a greater impact of buffer-size reduction on productivity as compared when production rate was 0.1 units/day. Thus, higher rate projects were more affected by variability.

2. Projects with similar Prod. Rate to Prod. Amt. Ratio (RAR) (Figure 6)

Here we choose cases with an RAR of 0.04-0.05, which is constant enough considering that it varies from 0.0002 to 0.05 across all test cases. After scaling the productivity values to unity, we see in Figure 6 that productivity loss in all the cases is similar

– differing only by an offset value. The offset seems to be the result of interaction between the production amount and variability and it reduces as the production amount increases from 25 to 100 units. Relative productivity degradation for 25% variability is lesser than for 98% variability. Projects with a high RAR seem to benefit from higher variability probably because such fast projects can quickly recover from setbacks and get back on schedule quickly, without much help from WiP buffers. This shows that when RAR is fixed, productivity degradation due to variability follows a predictable pattern and that buffers help mitigate variability effect more when the variability is low. Thus, we realize that RAR is a key factor in deciding the effect of buffers on productivity.

3. Large project size and very low production rate values (Figure 7)

With an RAR of 0.0002 (500 units at 0.1 units/day) we have a very slow and large project in Figure 7. We see that productivity remains almost unchanged for all sizes of daily buffer and initial buffer sizes. There seems no productivity loss mitigation and hence no significance of buffers. Given the size and rate of the project, it seems the project can be on track by itself, without a buffer's help.

VARIABILITY EFFECT

Variability seems to have a double role; the negative role of hampering productivity has been discussed already. However, if variability can reduce productivity, it can sometimes increase it too. As in Figure 8, due to the high 98% variability, the productivity and buffer size could get bumped up at times to levels higher than the production rate and IWiP respectively. However, for 25% variability, the productivity and buffer sizes were more range bound. Hence, due to inherently high buffers sizes, the 98% variability cases enjoy better productivity loss mitigation without any added effort. Also, for 98% variability, there is not much difference in the productivity levels when varying the IWiP; which although is significant for 25% variability.

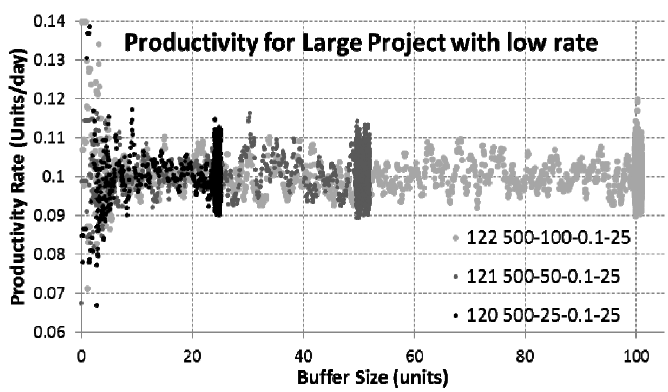

Figure 7: Very high Prod. Amt. and low Prod. Rate has no benefits from buffers. Productivity is almost constant throughout with fluctuations for very low buffer sizes.

It seems that variability alone does not degrade productivity, but a combination of production rate and variability seems much more responsible for it. A low production rate cannot keep up with variability induced obstacles, but a high production rate can cover up quickly and also overcome any reductions in buffer sizes – restoring the project back on schedule. This allows "high-production-high-rate" projects to self-mitigate their productivity degradation project a positive impact of variability.

These observations can be further understood from Figure 9 showing normalized productivity levels of small and medium sized projects. We see that the solid lines (lower production rates) are situated below the dashed lines (higher production rates). Further, for the same production rate, productivity levels are lower for higher variability – the negative role of variability coming in. Thus, for a given variability, a higher production rate project will be more efficient. Conversely, for a given production rate, a lower variability will result in better efficiency. Also, in Figure 9, the RAR is similar for the cases and hence we do not see stark differences in productivity levels due to variability change as in the case of Figure 8 although the observations are similar.

DISCUSSION

Upon exploring the results, it was clear that productivity levels do not depend only on the buffer levels but also on other factors and their combinations, such as:

- Interaction of Production Rate and Variability.
- Interaction of Production amount and Production Rate.
- All three parameters together (Production rate, Variability, Production Amount)

It is highly indicative that a power relation governs the relationship between productivity and buffer-size. The power relation consistently resulted in the best correlation amongst all possible function approximations performed.

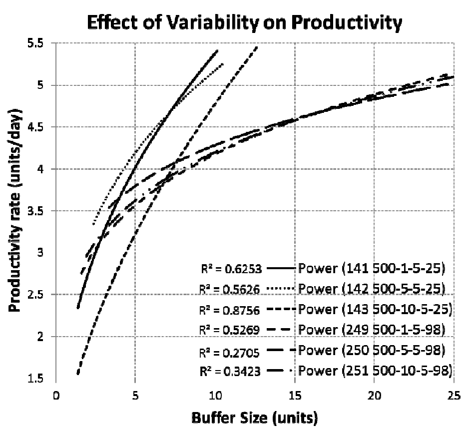

Figure 8: In large and fast projects, a higher var. results in larger Bf. sizes and hence more effective productivity loss mitigation

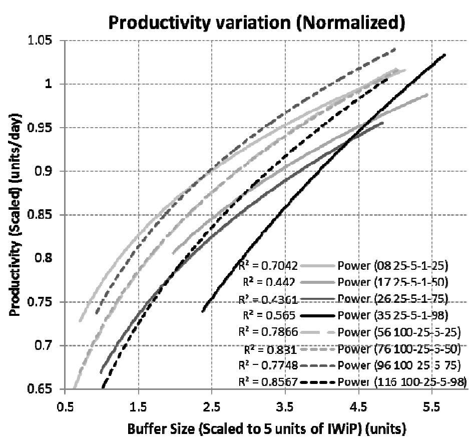

Figure 9: Projects with a similar RAR. Higher production rates seem to benefit slightly from high variability

The average daily labour productivity decreases as the buffer size reduces. A high IWiP size does not ensure higher productivity levels, but it does ensure better reliability and protection against negative effects of variability. For a given reduction in buffer size, a higher IWiP will result in the lowest relative loss of productivity. This means that buffers are much more important in large scale and highly demanding projects such that any production disruption can result in heavy losses. Further, productivity degradation is lesser in projects with lower variability than in projects with high variability. Also, this difference in degradation reduces as the production amount increases. Thus, buffers protect the project better during lower variability.

Variability has a two-faced role; the positive role shows in projects of high prod. rate and prod. amount. Also, for high variability, there is not much difference in productivity levels with varying IWiP – but it is significant when variability is low.

For very large buffers, there is saturation in productivity levels in an asymptotic nature. This indicates there is a 'balance problem' existing between the use of buffers to reduce variability impacts and overall production system performance based on lean principles (González et al. 2009). A small buffer suffocates production, but after a certain large size of buffer, any further increase in buffer size does not offer any significant advantage towards improvement of productivity, instead it merely adds to longer project schedules.

For projects with very low RAR, there seems no need for buffers. Here, productivity remains almost unaffected for all buffer levels and IWiP buffer sizes. The low production rate and long schedule ensures that the project is able to self-stabilize itself. RAR is a key factor in deciding the impact of buffers. Also, when the RAR is fixed, productivity degradation due to variability follows a fixed pattern. In practice this indicates that project performance can be predicted more reliably once we fix the RAR. So ideally, larger projects should progress at a faster rate with a large labour and smaller projects should progress with a slower rate with less labour. It would be meaningless to put a lot of labour in a small project and very less labour in a large project – both situations inefficient in their own respect. For the same production rate, productivity levels are lower for higher variability. For a given variability, a higher production rate will yield more productivity efficiency, and for a given single production rate, a lower variability will provide more efficient production.

This nature of productivity due to the interconnected interaction of variability, production rate, and production amount is very complicated and developing generalized empirical relations relating productivity and buffer sizes is very difficult for every possible situation. Even though this study produced a large amount of synthetic data, only simple quantitative and qualitative relations are easily drawn out from the results obtained. An even more greatly involved study is definitely required to arrive at concrete relations, which can be directly used on-site for construction projects.

CONCLUSION

The productivity vs. buffer size relation appears to be a "balance problem". Very small buffer sizes result in low productivity and high sensitivity of production towards variability. But beyond a certain buffer size, there is no significant advantage in mitigating productivity loss due to variability. Although, buffers are in general useful for protecting system performance – the improvements in productivity are within boundaries. We found these trends very clearly. However, in fast moving and large scale projects, variability does not have that large a negative impact as otherwise because the projects have very fast rate or ample time schedule to bounce back to the right schedule.

After the simulation experiments in this seminal research considering many factors, we realize that the relationship between productivity and buffer size is best explained by non-linear power functions. Through further large-scale studies, we can better understand the relations of productivity with other project parameters to have better manage buffers on-site in an effective way.

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