DESIGN OF WORK IN PROCESS BUFFERS IN REPETITIVE BUILDING PROJECTS: A CASE STUDY

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ABSTRACT

Variability in construction projects usually leads to schedule delays, cost overruns and productivity losses. Among the different techniques and tools employed to manage a construction project the use of buffers is a common approach to handle variability and to protect production processes from its negative impact. Time float, resource inventories and budget contingencies are examples of buffers used in construction in an intuitive and informal way. Empirical evidence recently collected about existing inefficiencies in the use of WIP (Work-in-Process) in construction projects highlights the double-opportunity to improve current practice of WIP and variability management by using WIP as buffers. The paper addresses the use of WIP buffers in construction schedules of repetitive building projects and proposes an approach for WIP buffer design. A discrete simulation model to study the impact of the optimum WIP buffer size on construction schedule was developed and this paper presents its application to a real project (case study). Finally, simulation results and the potential of WIP buffers to implement production strategies based on Lean Construction principles in construction projects are analyzed.

KEY WORDS

Buffers, Lean Construction, Simulation Optimization, Variability, Work in Process.

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INTRODUCTION: PRELIMINARY REMARKS AND LITERATURE REVIEW

The construction industry demands increasingly shorter project schedules. This situation pushes contractors to permanently struggle to reduce project execution time. The situation is aggravated by uncertainty resulting from urgent requirements, non-consistent construction sequences, lack of coordination in the supply chain, project scope changes, poor quality, among other factors. The combined effect of uncertainty and complexity in a project produces variability in construction systems (Horman, 2000). Variability is defined by Hopp and Spearman (1996) as non-uniformity in quality of certain types of entities closely related to the randomness of a phenomenon. Koskela (2000) distinguishes between two types of variability in production: (1) in the process time of a task executed at a workstation and (2) in the workflow arrival at workstation.

In general, construction projects entail high levels of variability that lead to inconsistent estimations and assumptions, and general project performance deterioration (waste). Alarcón and Ashley (1999) showed the impact of variability can increase the project duration by 25%. Similarly, Shen and K. H. Chua (2005) found that increased activity duration variability can raise the project cycle time up to 12%. Alarcón et al (2005), in a study of a large number of projects using the Last Planner System (LPS) (Ballard, 2000), found evidence that average Percent Plan Complete (PPC) reaches just a 67% in a construction sample (100 industrial and building projects). Ballard and Howell (1994) found that work packages with PPC lower than 50% increased their cost by 15% in a large industrial project.

By using a buffer, a production process can be isolated from the environment and the processes depending on it, and the negative impact of variability can be reduced in the production chain (Koskela, 2000). Buffers can avoid loss of throughput, wasted capacity, inflated cycle times, larger inventory levels, long lead times and poor customer service shielding a production system against variability (Hopp and Spearman, 1996). Nevertheless, current practices like using material inventories, time and cost contingencies, excess labor and equipment capacity, etc., are examples of how projects deal with variability in intuitive and informal ways. This could be explained by the lack of sound methodological approaches to systematize variability management. Recently, some researchers and practitioners have proposed new approaches to manage variability in construction (Alarcón and Ashley, 1999; Ballard, 2000; Goldratt, 1997; Tommelein, 1998, among others).

This research is based on several lean principles for construction proposed by Koskela (2000): i) Reduce the share of non value-adding activities, ii) Increase the efficiency of the value-adding activities, iii) Reduce variability and iv) Reduce the cycle time. But, they are focused under a main lean objective: to optimize the performance of a production system as a whole (Womack and Jones, 1996).

These *Lean Construction* principles provide a theoretical framework for buffer design and management (BDM) in a more rigorous approach for variability management (González et al, 2004) and they allow to optimize the overall process outputs. In the case of Repetitive Building Projects, the existence of repetitive and accessible cycles make these kind of projects suitable to study the design, control and monitoring buffers in construction projects.

Traditional approaches to project management are mainly based on assumptions that do not consider the project complexity and its non-linear nature (Bertelsen, 2003). McCray et al (2002) state that poor systematic rules or heuristics to deal with the dynamic nature of projects lead to poor decisions. Table 1 describes current practices related to buffer use in construction and the deficiencies existing in its design and management.

In manufacturing, Work-in-Process (WIP) is the converse of a product or products at various stages of completion throughout the plant. It includes all the materials employed from the raw material after release for initial processing up to completely processed material awaiting final inspection and acceptance as a finished product (APICS, 1995). In construction, WIP can be related to the difference between cumulative progress of two consecutive and dependent activities. This difference characterizes the work units ahead of a crew, which can be employed to perform work. WIP can be designed as buffers to preclude the negative impacts of variability (e.g., idle time or wait time of crews, slow work, ineffective work, schedule delays), so it supports the Lean Construction principles discussed above.

Table 1. Current Practices of BDM in Construction.

Buffer Type	Current Practice Description	Deficiencies
Contingencies	Reserves in schedules and budgets used to compensate adverse effects of variability and uncertainty. The reserves quantities are proportional to their cost and duration. Current techniques for risk management are used to estimate these contingencies.	Several researches show that these techniques are not well developed in the construction industry (Bing et al, 1999; Leach, 2003; Ford; 2002) where contingencies are mainly based on intuition, judgement and experience and probably the project contingencies are underutilized (Goldratt, 1997).
Inventories of Materials	Materials acquired deliberately in excess to protect production flows from variable and uncertain conditions related to the materials procurement process.	"Matching problem" between the supply chain and project production flows (Tommelein, 1998). Excess of inventories and processes time, waiting times and physical looses (Arbulu et al, 2003). Loss of productivity (Rojas and Aramvareekul, 2003). CII (1988) demonstrated that poor inventories management lead to higher costs during construction.
Inventories of WIP	Work units downstream the production chain that allow the outline of the work that must be carried out by the productive units in a construction project (Tommelein et al, 1999).	Inadequate WIP design and management (González and Alarcón, 2003) lead to lack of work units available for labor (Alarcón and Ashley,1999; Tommelein et al, 1999).
Time (Float)	Float time of non-critical activities in a construction schedule is usually used to distribute scarce resources and protect the critical path from time variation in non-critical activities.	Over-estimation of float times during schedule resource leveling when resource-dependant restrictions between critical and non-critical activities is unknown (Kim and De la Garza, 2003). Float times do not protect the schedule critical path from variability when inadequate activities durations have been estimated (Merge Event Bias).
Capacity	Allocation of project labor and equipment deliberately in excess as a protection from variable project demands.	Allocation of labor is carried out for the project minimum uncertainty (Horman 2000) and the project maximum capacity (Howell et al, 2001). Over-allocation of labor decreases project productivity (Thomas and Arnold, 1996) and maintenance of idle labor can be costly (Alves and Tommelein, 2003).
Plans	LPS defines them as Workable Backlogs (WB) available downstream the project production chain that realistically can be executed (Ballard and Howell, 1995).	Plan buffers allow reduce the uncertainty of the project enviroment shielding the production flow. Currently, the LPS implementations have showed that the current construction projects do not understand and do not use properly this kind of buffer in the planning process (Alarcón and Calderón, 2003)

Recently, empirical evidence has shown problems in construction WIP management. Alarcón and Calderón (2003) gathered data on the Reasons for Non-Completion (RNC) of weekly plans in 100 construction projects that implemented the LPS (building and industrial projects developed between 2001 and 2003). The incidence of the RNC "Lack of WIP" came second with 12.8%. A close examination of a sample of 23 repetitive building projects during the same period showed that the incidence of "Lack of WIP" was increasing over the years. The empirical evidence highlights the double-opportunity to improve WIP management and to use them as buffers in managing project variability.

There is a body of knowledge about BDM developed during the last fifteen years in the construction sector, which shows the urgency for developing new tools and approaches in order to manage variability and reduce its impact on project performance. Particularly, several researches have studied WIP BDM through repetitive processes (Alarcón and Ashley, 1999; Alves and Tommelein, 2004; Bashford, 2003; Howell et al, 1993, Lee et al, 2003; Park and Peña-Mora, 2004; Tommelein, 1998, among others). These researches show the growing
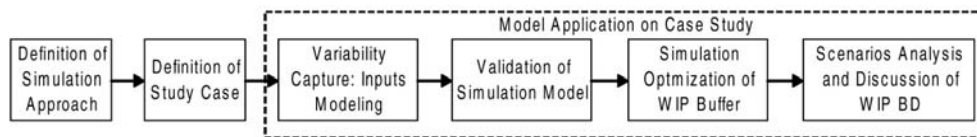
progress toward the understanding of variability and buffer management. Park and Peña-Mora (2004) confirm the relevance of buffer research in the construction sector and its contribution for establishing a conceptual buffering framework. In contrast, they criticize that practical buffering approaches that can be applied in construction processes are rarely found. The literature reviewed does not provide methodologies for modeling variability and designing WIP buffers in construction. Only general heuristics and practical rules to WIP BDM are found in the construction literature. As a result, there is a gap between buffer theory and practice.

Several researchers have used simulation techniques to model the effect of buffering strategies in production systems or supply chains in construction (Alarcón and Ashley, 1999; Alves and Tommelein, 2004; Arbulu and Tommelein, 2002; Horman, 2000; Lee et al, 2003; Tommelein, 1998; Walsh et al, 2002, among others). However, they address specific cases and do not provide procedures for capturing the variable nature of project environment (variability) and modeling the buffering strategies in a sound, practical and simple way.

This paper proposes a WIP buffer design (BD) methodology based on a simulation approach that captures the project construction variability and considers the modeling of buffering strategies; the details of this approach and the application of this methodology in a case study are presented in the next two sections. The last section contains our conclusions and some ideas for further research.

THE SIMULATION MODELING APPROACH

In our simulation methodology, the dynamic behavior of construction projects is modeled in a simple way, and variability is captured through activity production rates using the Probability Density Function (PDF) of activity durations. The production rate is the reciprocal value of the activity duration PDFs (production rate = [1/ activity duration PDF]). The activity duration PDFs can be obtained from empirical data or subjective information. Within the simulation methodology, an optimization approach is proposed to obtain the optimum WIP buffer size that can reduce or minimize the total cycle time in a real construction project. As a result, the methodology helps developing a construction schedule to apply WIP buffer strategies. The methodological steps of the proposed methodology are shown in Figure 1.

Figure 1. WIP BD Methodology.

Extend™, a discrete simulation software was selected to perform simulation optimization (SO) due to its powerful features to visualize and handle highly dynamic and complex systems (Extend v6 User's Guide, 2002).

Alarcón and Ashley (1999) developed an initial approach to model WIP buffer in construction which was elaborated on this research. The simulation model framework was

based on the "Parade of Trades" (Tommelein et al, 1999), where the impact of production rate variability on processes that succeed one another on a linear sequence is showed. Figure 2 shows the simulation model architecture proposed in this paper, which is made up by two kinds of hierarchical blocks: processes and WIP buffers. Within these blocks there are individual blocks, logical decision processes and probabilistic inputs (i.e. production rates). Work units flow through the system from "INPUT" according to the amount specified in "PROCESS 1" production rate. Once they are processed, these units are accumulated in "WIP BUFFER" until the specified amount of work units is reached at this block. Finally the released units by "WIP BUFFER" are processed in "PROCESS 2" and they are released to leave the system by "OUTPUT". The total cycle time is completed when all work units have been processed by all process hierarchical blocks.

The following types of WIP buffers were studied: i) The Minimum WIP buffer (MWIPBf) is the minimum amount of work units ahead of a crew from which they can perform their work without any technical problems (e.g., to avoid crew congestion). This is a boundary condition for the simulation models. ii) The Initial WIP buffer (IWIPBf) is the amount of work units ahead of a crew allocated at the beginning of the downstream processes to protect them from the production rate variability of the upstream processes (e.g., to avoid waiting time by lack of production units to perform work). The MWIPBf and IWIPBf represent intermediate inventories between processes and they are restrictions applied only at the beginning of the processes in simulation runs.

The simulation modeling approach does not consider a *warming up period or initial data deletion* (Law and Kelton, 2000) because it emulates a real construction project which begins its work at the beginning of the production chain (initial process) without work units (state condition of the system at time 0). Once the simulation model runs (time ? 0), the initial process begins to perform its work and at least produce the MWIPBf for the following process and so forth for the rest of the processes, so that it is not need a *warming period*. The modeling framework uses simulation optimization experiments that explore the impact of IWIPBf size on project performance.
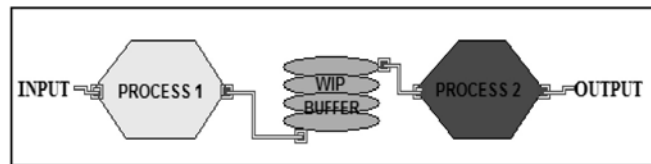

Figure 2. Simulation Modeling Architecture.

On the other hand the Extend™ Evolutionary Optimizer Module is used to optimize the required parameters during the simulation runs. We consider the minimization of Total Cycle Time in the construction schedule as an objective function. Extend™ Evolutionary Optimizer Module is based on evolutionary algorithms called Evolutionary Strategies (ES). The ES are algorithms similar to Genetic Algorithms that mimic the principles of natural evolution as a method to solve parameter optimization problems (Carson and Maria, 1997).
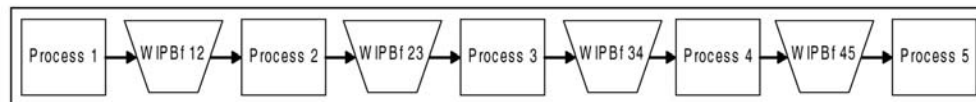
CASE STUDY: REPETITIVE BUILDING PROJECT

A case study was selected to model different WIP buffer strategies that would serve as simulation modeling basis (number of simulated processes, production rates, cycle time, etc.) and to show the application of the proposed methodology in a real project. It was a home building project split into 9 stages. Table 2 summarizes some production characteristics.

This project was applying the LPS at the moment the buffering strategies were deployed, nevertheless, the low use and understanding of LPS elements and principles limited the improvements obtained. The third stage analyzed in this paper, had a total 29 production units. Each production unit was made up by two houses that shared a common wall, with an area of approximately 185 m². The simulated activity package had a finish-start precedence relationship and it was formed by five processes and four WIP buffers (Figure 3).

Table 2. Production characteristics of simulated processes.

Process N°	Type of Activity	(*)Planned Production Rate (units/day)	Planned Cycle Time (days)	Planned Total Cycle Time (days)	Minimum Work-in-Process Buffer (units)
1	2° Floor DryWall Ceeling	0.6	49		
2	2° Floor Partition	0.6	49		
3	Doors Installation	0.6	49	54	0.6
4	Waterproof	0.6	49		
5	Kitchen Floor (Tiles)	0.6	49		

(*)Planned Rhythm of the construction processes

Figure 3. Process and WIP Buffer Diagramming.

The model was developed between November 2005 and March 2006. Meetings with project personnel were held to introduce the main concepts related to variability and buffering strategies in construction. With these meetings the simulation model activity package was selected (Table 2) and the modelling process started.

Production rates variability was captured using the reciprocal value of activity duration PDFs. Subjective probabilities to estimate activity duration PDFs were used (based on expert judgment) due to the lack of historical data. In the prior stages of the project analyzed, detailed performance indicators were not measured since only global contract indicators were measured (i.e. daily production rates of activities were not measured, in contrast, contract indicators as monthly cumulative progress of activities for cost control purposes were measured). A Beta PDF was selected to model the duration parameters of construction activities in an efficient and accurate way according to Fente (1999). An algorithm proposed by AbouRizk et al (1991), called VIBES (Visual Interactive Beta Estimation System), was used to obtain the parameters of a Beta PDF from expert judgment. For this research the minimum, maximum and more frequent duration (mode) plus an arbitrary percentile for obtaining a Beta PDF were considered

(as inputs for VIBES). The final parameters are showed in Table 3 and they include the Beta PDF Parameters ("a" and "b" shape, minimum and maximum parameters), the crew composition and work crews used in simulation models. The production rate in this kind of project is generally balanced to offset the productivity differences among crews.

The simulation model was validated in a meeting specially held for this purpose. The project personnel examined initial and intermediate inputs, and cycle times of the activity packages selected (for each activity and for the activity package). The participants validated the different inputs and outputs produced by the model according to its own experience in this project and other similar projects.

Table 3. Beta PDF parameters selected and crew composition.

	Process 1	Process 2	Process 3	Process 4	Process 5
Minimum (days)	1,250	2,000	2,000	1,000	3,500
Maximun (days)	2,500	2,500	3,000	1,500	5,000
Shape a	1,000	1,418	1,000	1,000	1,694
Shape b	1,000	1,418	3,322	3,322	2,388
Number of men by crew	4	2	4	1	2
Number of Crew	1	2	2	1	4
Total number of men	4	4	8	1	8

A base case was developed to validate the simulation model and the simulation results are showed in Figure 4 (Cumulative Progress v/s Time). The parameters studied were:

P_i= Process i, where i denotes the number of activities; P_1, P_2,…., P_5.
m_i= Mean Production Rate for process i (units/day).
SD_i= Standard Deviation of Mean Production Rate for process i (units/day).
CV_i= Coefficient of Variation of Mean Production Rate for process i (%).
CT_i= Cycle Time for process i (days).
TCT= Total Cycle Time for activity package (days).
$MTBf_{ij}$= Minimum Time Buffer between process i and j (days).
$MWIPBf_{ij}$= Minimum WIP Buffer between process i and j (units).
$ITBf_{ij}$= Initial Time Buffer between process i and j (days).
$IWIPBf_{ij}$= Initial WIP Buffer between process i and j (units).

The simulation results showed in Figure 4a consider a MWIPBf equal to 0.6 production unit (according to the initial construction schedule – see Table 2). The simulated TCT for the base case after 1000 runs is 75.7 days and it confirmed that the model was a valid representation of the project reality according to the answers of project personnel. It was necessary to perform 100 additional simulation runs to determine the production responses, i.e., mean production rate, individual cycle times, etc. In particular, the mean production rates were subjected to an ANOVA (Analysis of Variance) process to justify if the number of runs (size) had statistical meaning to determine these production responses (see analysis of the p-value in Figure 4).

SIMULATION OPTIMIZATION OF WIP BUFFER

The SO model takes into account the same parameters as the base case (Figure 4). But as the optimization goal is to minimize the TCT, the decision variables are the IWIPBf sizes (different

to MWIPBf sizes). Then, the SO aims to find the values of $IWIPBf_{12}$, $IWIPBf_{23}$, $IWIPBf_{34}$, and $IWIPBf_{45}$ which minimizes TCT and it can be represented as below:

$$TCT = ITBf_{12} + ITBf_{23} + ITBf_{34} + ITBf_{45} + CT_5 \qquad \text{Equation (1)}$$

$$ITBf_{ij} = (IWIPBf_{ij})/m_i \qquad \text{Equation (2)}$$

$$CT_i = TP/m_i \qquad \text{Equation (3)}$$

$$TCT = (IWIPBf_{12})/m_1 + (IWIPBf_{23})/m_2 + (IWIPBf_{34})/m_3 + (IWIPBf_{45})/m_4 + TP/m_5 \qquad \text{Equation (4)}$$

Where, TP= Total Production, (units).

And 0.6 units = IWIPBfij = 13 units limited the solution space where the optimum solution can be searched. The IWIPBf sizes according to the SO algorithm were searched among whole values to facilitate the possibilities of applicability in construction schedules. The simulation result can be seen in Figure 4b after 1766 simulation runs, 12 hr of computer time and a convergence level of 99.51% for the optimum IWIPBf sizes that minimize TCT (73.9 days).

Figure 4a shows, for the case base, that the m_i is similar for all processes (apparently balanced production). Moreover, it shows that variability grows almost linearly throughout the production chain according to the CV_i of each process. It suggests that variability is passed from one process to another generating a "ripple effect" (Hopp and Spearman, 1996). In all the processes the m_i is lower than the initial estimation (0.6 units/day) and the CT_i too (49 days). The planned TCT increased by 40% to 75.7 days from 54 days (see Table 2).

Figure 4b shows the estimated mi and CTi for the buffered case. The planned TCT is increased by 37% (see Table 2), but it reduces the TCT compared to the base case by 2.4%. The small improvement can be caused by the small activity package size, which does not allow to properly capturing the ripple effect. Likewise, there is no balance among activities because processes 2, 3, 4 and 5 improve their mi and CTi. Meanwhile, process 1 seems to be the bottleneck because it has similar production responses that base case.

The improvement focus seems to be the reduction of CVi and CTi through the use of IWIPBf. On the one hand, the CVi reduction narrows the transfer of variability on downstream processes and can reduce crew waiting time, idle time, loss of throughput, among others. On the other hand, the CTi reduction (i.e., CT5 is reduced from 64 to 55 days or 14%) implies a reduction on the effort of crew management (supervision), crew congestion and project costs. The latter is reduced by means of cutting overhead costs related to the fall in TCT and the crew management costs reduction due to the fall in CTi.

The proposed methodology allows designing WIP buffer sizes adaptable to many situations within the repetitive projects context (different amount of processes, production rates, variability levels, crew balance, WIP sizes and project optimization objectives) through the modeling simulation approach. This is possible due to the flexibility of the simulation approach that only needs a few inputs and production parameters to model WIP buffer sizes. Also the necessary inputs for simulation models are easily understood by the project personnel given their familiarity with them. The direct output of the WIP buffer design process is an optimized construction schedule (e.g., Line of balance, Gantt chart, etc.) which explicitly shows the location and size of WIP buffers between processes (similar to Figure 4b) and minimizes the TCT. The designed WIP buffer sizes can be applied on project site through construction schedules. Since this is only an initial restriction between consecutive construction activities it can be easily managed (the project supervision should oversee the departure of the crews to maintain this initial restriction; after that the crews should perform their work normally).

Figure 4b shows that processes have enough work units to perform their work preventing their starvation, so that a continuous production flow is assured and the cycle times and production rates are optimized (as long as there is not a lack the production resources). Figure 4b shows that production rates (m_i) are improved and their patterns do not allow accumulation of WIP.

The simulated construction schedule (Figure 4a) may be a more realistic "picture" of the project nature by the explicit consideration of variability. The buffered construction schedule (Figure 4b) may be more likely fulfilled (more reliable planning) by the explicit consideration of buffers appropriately sized. The characteristics of the WIP BD methodology discussed here provide a practical and simple framework that may be generalized to repetitive projects to apply production strategies based on buffers.
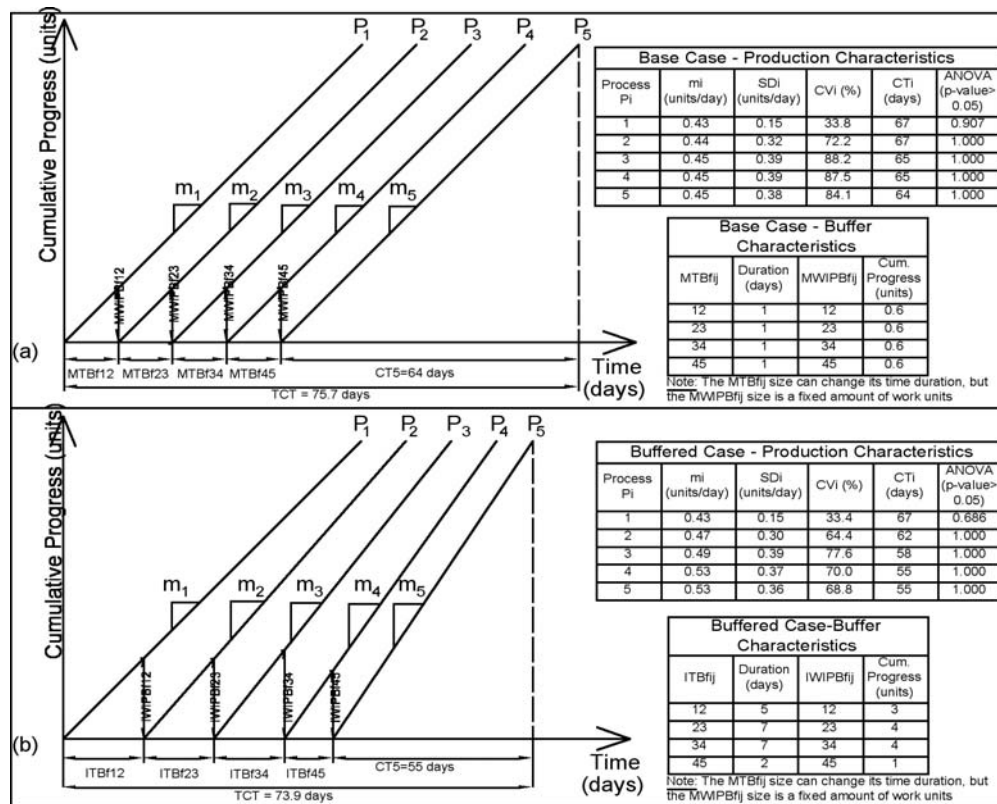

Figure 4. Simulation results. a) Base Case, WIP buffer is 0.6 units. b) Buffered Case, WIP buffer is variable.

In this case project effort was made to implement the recommended WIP buffer strategy on site. However, the actual project schedule did not closely reflect the proposed WIP buffer strategy and it was not possible to obtain enough measurements (production rates, productivity, etc.) to document the implementation.

CONCLUSIONS

Part of existing variability in production flows can be reduced through adequate production control techniques (e.g., LPS). Remaining variability must be managed through buffers utilization (Thomas et al, 2002). This paper addresses the notion of WIP as a buffer in construction and a double-opportunity is proposed: to improve the variability and WIP management based on Lean Construction principles.

The research results show the potential benefit that buffer strategies based on WIP can produce in construction projects at a global level (optimization of several performance indicators as cycle times, production rates, variability, waiting times, among others). The use of a real case to test the proposed WIP BD methodology shows the feasibility to apply it within the construction scheduling context in repetitive projects. In this sense, the authors think that the gap between theory and practice can be reduced by means of simple and sound approaches. However, a definitive test on site for this methodology is needed in order to measure its real project impact and to spread its application in repetitive projects.

The WIP BD methodology proposes: Firstly, an efficient way to capture the variability through well-known subjective probabilities. Secondly, a simulation approach that facilitates the understanding of the production processes complexity and the generation of results. Carrying out an experiment in the real world would take much longer and a simulation methodology can be used with the help of an expert to shorten this experimentation time. The proposed simulation optimization approach indeed reduces this time and may produce reliable output. As a result a practical scheduling approach is proposed to apply WIP buffer strategies in construction projects that may allow more realistic and reliable construction schedules.

Future research should: i) develop a complete and successful application in a real project of the WIP buffer strategies proposed here; ii) propose a sound methodology to manage de WIP buffer implementation (reliable scheduling commitment, measurements, etc.); iii) model the variability in construction projects in a general way (analytically); for this purpose, the subjective PDF used here could serve as a start point and it should be tested statistically with the purpose of expanding the approach discussed here (beyond Repetitive Building Projects); iv) consider other analytic forms to use WIP buffer in construction as robust methodologies (for construction planning and scheduling).

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