A METHODOLOGY FOR INTEGRATED BUFFER DESIGN AND MANAGEMENT IN REPETITIVE CONSTRUCTION PROJECTS

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ABSTRACT

One important challenge of production systems in both manufacturing and construction is the management of the harmful impacts of variability. While both industries have commonly used buffer-based production strategies to deal with the variability issue, construction is characterized for using intuitive, non-general and wasteful buffering strategies. For overcoming these limitations, this paper describes a conceptual approximation for an integrated buffer (Bf) design and management methodology using Work-In-Process (WIP) in repetitive building projects. The Bf design component uses the Multiobjective-Analytic-Model (MAM) and Simulation-Optimization (SO) modeling, while the Bf management component uses the Rational-Commitment-Model (RCM), an operational decision support tool based on statistical analysis. Each individual component has been previously tested and validated in different case projects.

This integrated methodology provides a comprehensive approach to deal with variability using WIP Bf, which explicitly considers: (i) a general production framework which covers the production levels from top to bottom; (ii) a general modeling framework which is suitable to any repetitive building project; and (iii) a sound theoretical framework for describing different production scenarios in repetitive building projects. The main characteristics, advantages, perspectives and limitations of the integrated methodology are addressed in the paper.

KEY WORDS

Buffer design and management, work-in-process, multiobjective analytic models, simulation-optimization, rational commitment model, repetitive construction projects.

INTRODUCTION

Variability management is one the most recognized challenges in production systems in both manufacturing and construction industries. To understand the effect of variability on production processes, Hopp and Spearman (2000) distinguished two kinds of variability in manufacturing systems: 1) the time process of a task and 2) the arrival of

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jobs or workflow at a workstation. Koskela (2000) proposes a similar classification to variability in construction systems, where the processes duration and the flow of preconditions for executing construction processes (e.g., space, equipment, workers, component and materials, among others) are understood as variable production phenomena. From a practical standpoint, construction practitioners everyday observe this behavior in the project environment through varying production rates, labor productivity, schedule control, cost control, etc.

The harmful effects of variability over production performance have been nicely documented in manufacturing (Deming, 1986; Hopp and Spearman, 2000) as well as in construction (Alarcón and Ashley, 1996; Tommelein et al, 1999; Goldratt, 1997). One of the mechanisms to deal with variability is the use of buffer-based production strategies. By using a buffer (Bf), a production process can be isolated from the environment as well as the processes depending on it. Bfs can circumvent the loss of throughput, wasted capacity, inflated cycle times, larger inventory levels, long lead times, and poor customer service by shielding a production system against variability. There are several types of Bfs which are defined as Inventory Bf (e.g. materials, work-in-process, and finished goods), Capacity Bf (e.g. in-excess labor and/or equipment capacity), and Time Bf (e.g. time contingencies and/or floats) (Hopp and Spearman, 2000).

Even though these industries have commonly used buffering strategies in their production systems, the way in which they have been applied is fairly different. In manufacturing, buffering strategies have rationally and systematically used from the application of the Inventory Theory to modern manufacturing techniques such as Material Requirement Planning (MRP), Just-In-Time (JIT), and Constant Work-In-Process (CONWIP), among others (Hopp and Spearman, 2000). In construction, however, traditional buffering practices have mainly been based on intuition and experience, in a production environment where constructors have no history of accepting and successfully applying analytical tools in decision-making (McGray et al, 2002). Therefore, sounder frameworks to deal with Bfs are neglected; leading to use poor mechanisms to protect construction processes from negative impacts of variability (González et al, 2009). On the other hand, the Bf issue has received much attention from the academic world during the last fifteen years, improving the fashion in which these production problems are perceived today by researchers and practitioners in construction. However, this attention has been focused over theoretical or specific problems, avoiding the explicit development of general and practical frameworks to deal with Bfs (González, 2008).

For overcoming the prior limitations, an integrated Bf design and management methodology is proposed. This methodology is part of a comprehensive Bf research in construction which was carried out during several years by the authors (González, 2008). This methodology provides a sounder and rational framework based on analytic tools, enhancing the decision-making process related to the design and management of Bf in construction. Variability reduction and adding-value activities increment from a system standpoint are the main lean production principles supporting theoretically the integrated methodology (Womack and Jones, 1996), which uses Work-In-Process (WIP) as Bfs in repetitive building projects. WIP can be defined as the difference between cumulative progress of two consecutive and dependent processes, which characterizes work units ahead of a crew that will perform work (e.g., work units that have not been processed yet, but that will be) (González et al, 2009).

In this paper, the integrated Bf design and management methodology is proposed as a conceptual approximation, whose particular components were previously tested and validated by González, (2008), González et al (2008) and González et al (2009). The following sections describe both theoretical and practical characteristics of the integrated methodology, and an application example which is simultaneously involved with the conceptual discussion (for the sake of simplicity). Finally, its main perspectives and limitations as an industry tool in construction are addressed.

INTEGRATED BUFFER DESIGN AND MANAGEMENT METHODOLOGY

OVERALL MODELING APPROACH

The use of WIP Bf is controversial from a lean production perspective since the lean ideal suggests that zero inventories, or non-buffered production systems, are desirable (Womack and Jones, 1996). Nevertheless, a production system without WIP implies a production system without throughput. Hopp and Spearman (2000) recognize this issue and state that even pull mechanisms in a production system do not avoid the use of Bfs. However, the use of large WIP Bf to ensure throughput in production systems will inherently increase cycle times and costs. Therefore, it appears that a 'balance-problem' (or trade-off) exists between the use of WIP Bf to reduce variability impacts and overall production system performance based on lean principles (González et al, 2009).

In short, the research problem in this paper deals with several issues of the Bf topic in construction, which is supported by the core notion of the balance-problem. Thus, the research problem leads to state an integrated WIP Bf design and management methodology that is general, sound and suitable to any repetitive building project (mainly, multifamily residential and multistory building projects). Figure 1 shows the overall modeling framework for the integrated methodology, which is divided according to its scheduling levels (strategic, tactical and operational) and function levels (design or management).

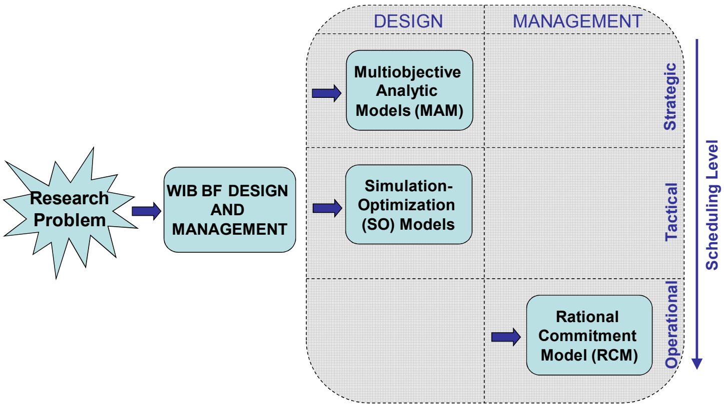


Figure 1: Overall Modeling Framework to WIP Bf Design and Management (Adapted from González, 2008)

On the one hand, three levels for construction planning suitable to scheduling were defined using the Ballard and Howell (1998)' planning hierarchies: Master Plan or Strategic Planning (long term period), Lookahead or Tactical Planning (breakout of master plan in a medium term period), and Work Plan or Operational Planning (short-term period), which are progressively more detailed from top to bottom. On the other hand, functions levels are defined according to the way in which WIP Bfs get involved in scheduling process. In other words, design level is related to a higher abstraction degree of the scheduling process in which WIP Bfs work, where their size is designed (regarding different detail) but on-site implementation to perform work is not considered yet. While management level is related to direct application of WIP Bfs in performing work.

Also, each component of the integrated methodology shown in Figure 1 uses different modeling strategies. While the design level applies Pareto Front concepts and simulation-optimization modeling, the management level uses statistical models. Next sections will explain each stage of the integrated methodology.

BUFFER DESIGN: CONCEPTUAL AND MODELING FRAMEWORK

The design of WIP Bf is based on the concept of Parade of Trades (Tommelein et al, 1999), in which two key characteristics appear influencing the location and size of WIP Bfs for repetitive projects: process interdependence and workflow variability. Figure 2 explains it through a linear scheduling diagram in which 'n' processes in a repetitive project with their different production parameters and WIP Bfs is shown. Let repetitive processes $P_1, P_2, \ldots, P_{n-1}, P_n$ with average production rates and standard deviation called $m_1, m_2, \ldots, m_{n-1}, m_n$ (units/day) and $SD_1, SD_2, \ldots, SD_{n-1}, SD_n$ (units/day), respectively. Production rates (m_i) for each process are an average value with a certain variation (SD_i). This variable behavior can be mathematically captured by means of probability density functions (PDF) of duration by production unit. Figure 2 shows the duration PDF, f(x), with an expected duration by production unit, μ_D, and a certain standard deviation, σ_D, for actual cumulative progress (a similar analysis could be done from the production rate viewpoint) (González et al, 2009).

Workflow variability of a process, represented by the duration PDF, impacts the succeeding processes. For instance, P_1 variability impacts P_2, P_2 variability impacts P_3, and so on. Variability has a cumulative effect from upstream processes to downstream processes in repetitive production systems given its inherent interdependence (i.e., a ripple effect). WIP Bfs decrease this effect, isolating and protecting downstream processes from upstream processes variability (Alarcón and Ashley, 1999; Tommelein et al, 1999). Also, the location and size of WIP Bf for repetitive project can be seen in Figure 2. Let WIP $Bf_{1,2}$, WIP $Bf_{2,3}, \ldots,$WIP $Bf_{n-1,n}$ which have the corresponding Time Bf called T $Bf_{1,2}$, T $Bf_{2,3}, \ldots,$T $Bf_{n-1,n}$, respectively. The main assumption relating to the location and size of WIP Bf within production processes is that there are restrictions applied only at the beginning of processes. Thus, WIP Bf size can be changeable during process progression (González et al, 2009).

The modeling approach imposes two states as boundary conditions to WIP Bf sizes: a)Minimum WIP Bf (MWIP Bf) is the minimum amount of work units ahead of a crew, which avoids any technical problem relating to buffering (e.g. the Bf to avoid crew congestion). Its Time Bf is defined as Minimum Time Bf (MT Bf); and b)Initial WIP Bf (IWIP Bf) is the amount of work units allocated ahead of a crew, protecting it from the workflow variability of the upstream processes (e.g., the Bf to avoid waiting time for lack of production units to perform work). Similarly, its Time Bf is defined as Initial Time Bf (IT Bf) (González et al, 2009a).

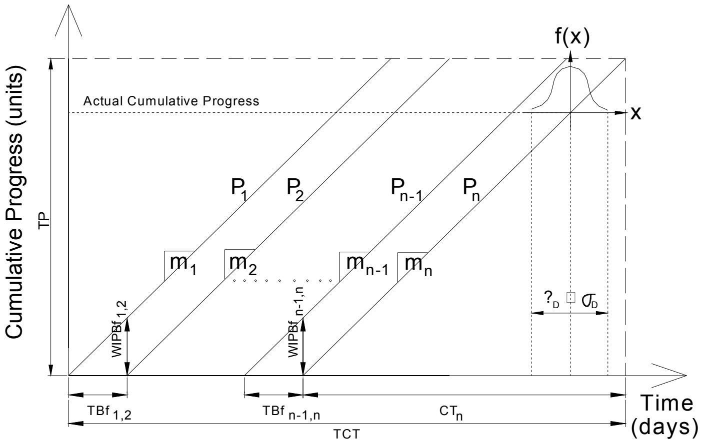


Figure 2: Graphical Representation of Model for WIP Bf Characterized by Unitary Duration PDF and n Processes PDF (Adapted from González et, 2009a)

At design level, the integrated methodology uses discrete event simulation (DES) to implement the modeling framework. A DES software, Extend™, was selected to perform simulation modeling given its powerful features to visualize and to handle highly dynamic and complex systems (Extend v6 User's Guide, 2002). The WIP Bf balance-problem at design level suggests an optimization process which is developed through simulation-optimization (SO) (González et al, 2009). Basically, the SO approach allows optimizing (to maximize or minimize) a key output performance measure (the optimization goal), finding the best combination of input variables (Law and Kelton, 2000). Extend™ allows developing SO process through its Evolutionary Optimizer Module 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). In this research, minimization of cost and schedule as well as maximization of productivity were defined as the main optimization goals for decision makers, where the IWIP Bf size was the decision variable (González et al, 2009a). The following sections briefly explain the integrated methodology at the WIP Bf design level, using examples for every scheduling level.

STRATEGIC SCHEDULING LEVEL

Multiobjective Analytic Model

Multiobjective Analytic Model (MAM) is a mathematical metamodel which is basically an output of SO modeling to design WIP Bfs at strategic scheduling level (long-term period). Basically, SO modeling uses a general simulation-architecture of repetitive construction process based on the conceptual representation shown in Figure 2. Also, it uses as the main simulation input a general Beta PDF for process duration given its well-known flexibility and adaptability to construction processes (AbouRizk et al, 1991). These assumptions allowed assuring the generality and reliability of MAM as a mathematical approximation. Also, MAM uses Pareto Front concepts applied on the typical cost-time trade-off problem for the conceptual definition of simple and practical nomographs (as the used in hydrologic engineering) to design WIP Bf sizes. In this problem, a Pareto Front line is stated to represent a resource mix for a given project (crew sizes, equipment methods, technologies, etc.), which holds at least one solution (resource combination) partially better in cost or time than other solutions. In general, the whole Pareto Front line is bound in the cost-time trade-off problem for those solutions which minimize time and cost (Feng et al, 1997).

Thus, previous research demonstrated that a typical MAM nomograph is constructed as follows (González et al, 2009a): 1) A whole Pareto Front line is bound using the SO process, obtaining those IWIP Bf sizes that minimize schedule (time) and maximize productivity, respectively (Note that the IWIP Bfs protect system from variability impacts); 2) The Pareto Front Line is completed estimating the intermediate Bf sizes between the previous IWIP Bf; and 3) Schedule and productivity responses for every IWIP Bf size are estimated by simple simulation runs.

In practice, data estimated earlier allowed developing multiple non-linear regression models relating IWIP Bf sizes with their production responses. Thus, MAM nomographs were implemented. Figure 3 shows one example. The main inputs that the SO process requires to generate nomographs are: 1) number of sequential processes hold in the critical path (n); 2) the expected duration by production unit, μ_D, and its standard deviation, σ_D ; and 3) variability levels (VL) which use the Coefficient of Variation (COV) of process duration (ratio between σ_D and μ_D). The main SO outputs are: 1) IWIP Bf sizes, 2) Productivity for every IWIP Bf characterized as the difference between expected and actual values of average m for all the processes (ΔTm); 3) Schedule for every IWIP Bf characterized as the difference between actual and planned project schedule considered for processes in critical path (ΔTCT); and 4) Project cost for every IWIP Bf as the difference between actual and planned budget (ΔTC), which is estimated using analytic expressions whose inputs are ΔTm, ΔTCT and budget data. Also Figure 3 shows that $\Delta ATm_i=f(\Delta TCT_i)$ and IWIP $Bf_i=f(\Delta ATm_i, \Delta TCT_i)$ are the multiple non-linear regression models that can be stated starting from the data of nomographs.

Finally, a decision-maker can use the nomographs from Figure 3 to develop a sensitivity analysis for ΔTCT, ΔATm and ΔTC and define the optimum IWIP Bf size according to his/her preferences on project objectives (see more MAM details in González et al, 2009).

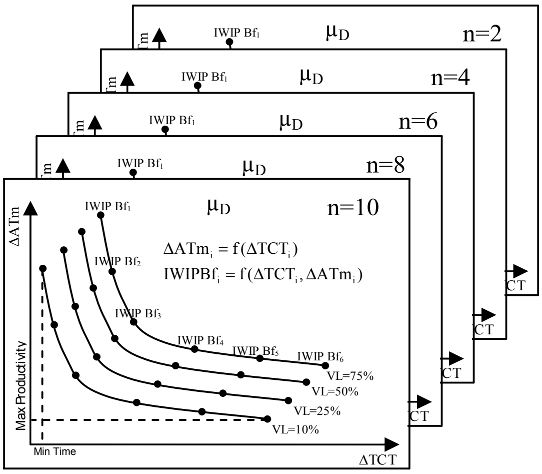


Figure 3: WIP Bf Design Nomographs for Different Production Parameters

Example at Strategic Level

To illustrate the integrated methodology, a repetitive building project of 10 sequential processes, with the μ_D (and m_i) by process and a total cumulative progress of 100 units (e.g. work units as houses or apartments) is depicted in the linear scheduling diagram shown in Figure 4 (obviously, these processes are along the critical path and for the sake of simplicity non-critical processes are not considered). Also, the strategic scheduling level is shown in Figure 4 through a Buffered Master Plan with 10 processes ($P_1 \ldots P_{10}$). Due date for the Buffered Master Plan in this example is 14.5 weeks. At this level, the following steps can be followed:

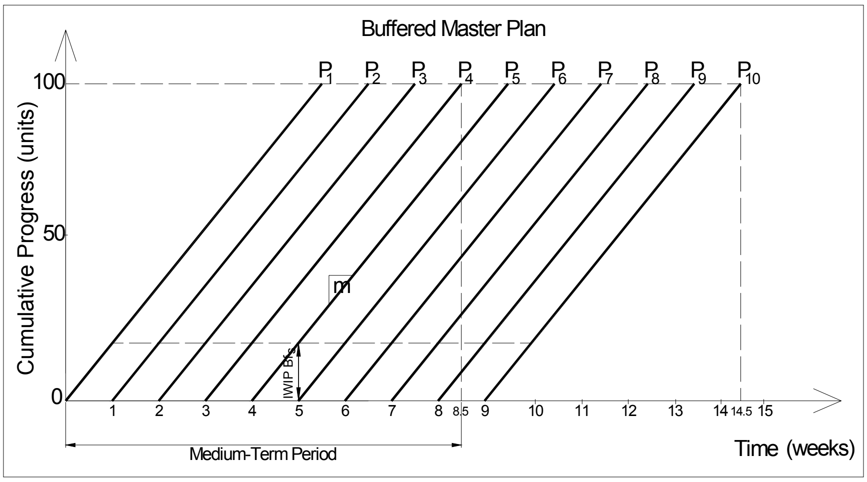


Figure 4: WIP Bf Design at Strategic Scheduling Level

1-Selection of Nomograph: One could assume that there is a set of nomographs available previously developed for several production situations. According to the number of processes in the critical path and μ_D in the project, a nomograph is selected.

2-Selection of a Specific Pareto Front Line: The decision-maker must choose a variability level for the project according to his preferences and project information availability (past experiences, type of project, project cost and schedule, risk attitudes, project complexity, etc.). By doing so, a unique Pareto Front line can be stated to design the IWIP Bfs.

3- Estimation of IWIP Bf Responses: By using the specific MAM nomograph and its specific relationships for cost, schedule and productivity, the different production responses for its IWIP Bf sizes can be computed. Table 1 shows a calculation example for different IWIP Bf sizes.

Table 1: Strategic IWIP Bf Production Responses (Adapted from González et al, 2009).

IWIP Bf (units)	Actual ATm (units/day)	Actual TCT (days)	Actual TC ($)	ΔATm	ΔTCT	ΔTC
1	0.44	258	$2,009,216	11.49%	18.36%	6.02%
4	**0.48**	**275**	**$1,947,261**	**3.81%**	**25.98%**	**2.75%**
8	0.50	346	$1,951,267	0.81%	58.71%	2.96%
12	0.50	416	$1,972,811	0.06%	90.85%	4.10%

4-IWIP Bf Selection: According to decision-maker preferences on project objectives, an IWIP Bf size is chosen. Table 1 shows the sensitivity analysis to design an IWIP Bf size, which is selected according to the minimum project cost (letters in bold).

5-Development of Buffered Master Plan: The selected IWIP Bf size is inserted in the Master Plan, making a totally buffered plan with a constant IWIP Bf size at strategic scheduling level for all processes (subscripts “s”, “t” and “o” are used to refer the strategic, tactical and operational scheduling levels, respectively).

Notice that the Buffered Master Plan is the initial plan to execute the processes, being static in nature. Among the information that it provides, the project due date and the main milestones can be stated from this plan. Also, the most important characteristic of the Buffered Master Plan is the higher probability of achieving the project due date, since explicitly involves variability through the Bfs.

TACTICAL SCHEDULING LEVEL

Simulation-Optimization

At tactical scheduling level, the design of WIP Bfs is more dynamic where directly are used SO models. This scheduling level considers a smaller time window (short-term period) and is closer to the work front where a higher production detail is found. Therefore, the latter allows having a permanent feedback from site production to constantly update a lookahead plan that holds the designed WIP Bfs. Likewise, the WIP Bf sizes are simultaneously updated with the lookahead plan, being this process necessarily performed by SO models. Similarly, theoretical and practical SO modeling framework was previously tested by González et al (2009).

As mentioned earlier, the SO modeling uses a general simulation-architecture which is suitable to repetitive building project. Its main inputs are processes duration PDF which can be subjective (use of expert judgment) or objective (use of historical information). At this level, SO models minimize actual cost and schedule as well maximizes productivity using as decision variable the IWIP Bf size (González et al, 2009).

Example at Tactical Level

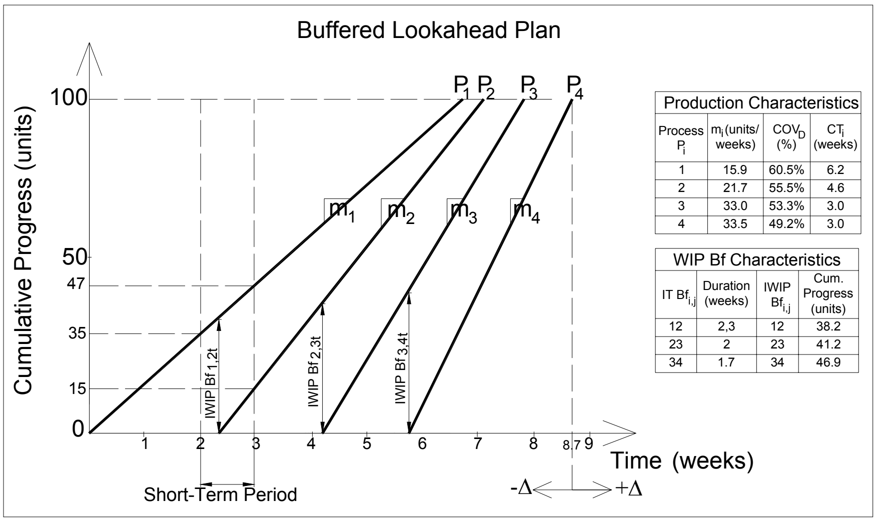
Figure 5 presents the Buffered Lookahead Plan which includes the different IWIP $Bf_{i,jt}$ as well as the average production rates (m_i) for the P_1, P_2, P_3, and P_4 processes. Due date for the Buffered Lookahead Plan according Figure 4 should be 8.5 weeks, being theoretically higher by effect of variability (see Figure 5). Also, Figure 5 shows two tables with hypothetical information such as the variability levels (COV_D) and individual cycle times (CT_i). The sizes of the IT Bf and IWIP Bf are also included. It should be noticed that the selected process package comes from the Medium-Term period mentioned in Figure 4, in which more enclosed processes appear than those described here. Therefore, a criterion to select them could be to consider only those processes that define the whole Medium-Term period (P_1, P_2, P_3, and P_4 processes). The following steps can be followed here:

1-Selection of the Medium-Term Period Size and Processes Package: From the Buffered Master Plan a Medium-Term Period is defined (typically from 4 to 8 weeks). Then, the processes held in this time window are chosen.

2-Capture Inputs for Simulation Models: In this stage the basic information necessary to run simulation models should be captured. It is described as follows:

2.1- Collection of actual construction costs, number of actual workers by process and MWIP Bf size. In addition, planned process duration should be considered.

2.2- Construction of process duration PDF by process, using historical data or expert judgment. Estimates from expert judgement are codified using Beta PDFs and the Visual Interactive Beta Estimation (VIBES) algorithm proposed by AbouRizk et al (1991).



Production Characteristics			
Process P_i	m_i (units/ weeks)	COV_D (%)	CT_i (weeks)
1	15.9	60.5%	6.2
2	21.7	55.5%	4.6
3	33.0	53.3%	3.0
4	33.5	49.2%	3.0

WIP Bf Characteristics			
IT $Bf_{i,j}$	Duration (weeks)	IWIP $Bf_{i,j}$	Cum. Progress (units)
12	2,3	12	38.2
23	2	23	41.2
34	1.7	34	46.9

Figure 5: WIP Bf Design at Tactical Scheduling Level

3- Modeling Validation and SO Process: The validation process basically analyzes the robustness of simulation inputs and outputs (being the simulation architecture previously validated). Also, the SO process to design the IWIP Bf is carried out in this stage. The sub-steps are the following:
3.1- Validation of simulation model with MWIP Bf, analyzing intermediate and final model outputs after a reliable statistical number of simulation runs, using historical data or expert judgement. This model can represent the base case as an unbuffered construction schedule.
3-2- A SO process search is developed to state the optimum IWIP Bf sizes according to different project objectives (González et al, 2009).
4- Optimum IWIP Bf Selection: Production responses are estimated to define the best IWIP Bf for each project objective. Thus, decision-makers select the optimum IWIP Bf sizes for the set of processes according to their project objective preferences. Table 2 shows an illustration for SO outputs with the optimum IWIP Bf sizes which minimize the construction schedule, i.e. Min TCT (letters in bold).

Table 2: Tactical IWIP Bf Production Responses (Adapted from González et al, 2009)

Simulation Experiment	**WIP Bf Strategy**	**WIPBf Size (units)[b]**			**Average Total Cycle Time (days)[a]**	**Average Total Cost ($)[a]**	**Average Production Rate (units/day)[a]**
		WIP $Bf_{1,2t}$	**WIP $Bf_{2,3t}$**	**WIP $Bf_{3,4t}$**			
Base Case	MWIP Bf	1	1	1	27.57±0.08	27,894.9±35.85	1.24±0.004
Min TCT	IWIP Bf	**1**	**1**	**13**	**27.50±0.08**	**27,127.8±35.64**	**1.37±0.004**
Min TC		24	1	23	41.25±0.08	25,288.8±16.8	2.20±0.004
Max ATm		28	21	28	55.85±0.09	26,105.2±17.1	2.22±0.003

[a]95% Confidence Interval
[b]WIP Bf sizes are different to those shown in Figure 5. However, it has only an illustrative purpose.

5- Development of Buffered Lookahead Plan: In this stage, the designed IWIP Bfs are incorporated in a buffered plan at a medium-term period. As shown in Table 2, these Bfs sizes can be different due to the stochastic nature of processes, with different average production rates and variability levels. For instance, Figure 5 shows that the new Medium-Term period is 8.7 weeks. However, this period could be lower or higher (±Δ) with other simulation inputs (i.e. different production situations).

It should be noted that the example in Figure 5 shows a Buffered Lookahead Plan with more realistic information, therefore, the planning periods can be more accurate. Due to the lack of production information (historical or expert opinion) at the beginning of project execution, could be necessary to wait a reasonable time for its generation and subsequent development of the Buffered Lookahead Plan.

BUFFER MANAGEMENT: CONCEPTUAL MODELING AND FRAMEWORK

At operational scheduling level, the WIP Bf management is focused over a short-term period (usually one week), where work is performed and production involves even more sensitive variations and dynamic conditions. Therefore, modeling strategy is different, where multivariate linear regression (MLR) models and empirical data about the most relevant reasons that commonly decrease planning performance such as lack of labor, lack of buffer and poor planning are used. In such a way, a modeling framework that allows predicting the progress of weekly work using historical site information is developed. In turn, it allows weekly managing WIP Bfs, modifying their size according site information such as planned progress, variability/reliability of commitment planning and labor productivity (González et al, 2008; González, 2008).

Rational Commitment Model

Rational Commitment Model (RCM), a new decision decision-making tool, allows a more reliable prediction of work progress at operational scheduling level by applying MLR models (González et al, 2008). The RCM is stated through a MLR model which relates predicted progress (PRP) as dependent variable with the following independent variables: worker-weeks available during the whole planned week (W), Bf available at the beginning of the planned week (IWIP Bf), and planned progress regarded for the week (PP). In other words, a general expression as $PRP=\beta_0+\beta_2W+\beta_1IWIP\ Bf+\beta_3PP$ for the RCM is defined. Also, the RCM replaces the notion of variability in process duration used in WIP Bf design by variability of commitment planning or planning reliability. By doing so, the Process Reliability Index (PRI) is proposed, which is defined as the ratio between actual and planned progress of a process, varying between 0% and 100%. RCM was subsequently validated by González et al (2008).

MLR models can be parametrized to develop RCM nomographs that relates AP with W, IWIP Bf and PRI as shown in Figure 6a. In management of WIP Bf, RCM allows defining the optimum sizes according to the maximization of labor productivity. In other words, one could analyze how the size of an IWIP Bf size increases the labor productivity decreasing the W level given a defined PP and PRI levels. As a result, weekly sensitivity analysis could carry out to define the impact of the IWIP Bf size over process labor productivity (González, 2008).

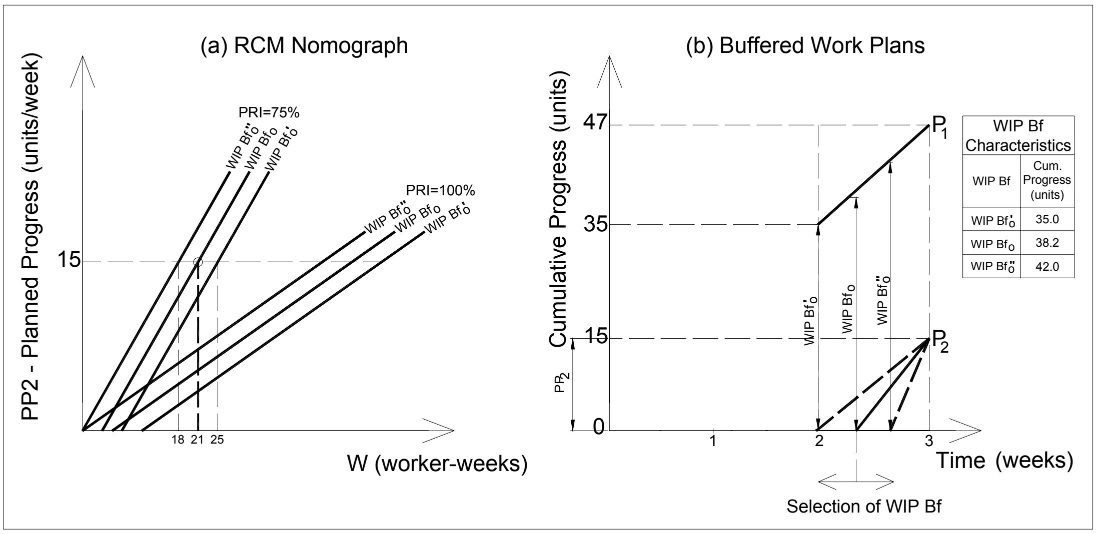
Example at Operational Level

Figure 6b shows an example of Buffered Work Plans. Figure 5 provides the Short-Term period of 1 week for the Buffered Work Plans which starts in the 2nd week. In this period, the P_1 and P_2 processes are analyzed, where the first one is still performing work, while the second one starts the work during this week. Figure 6b shows in-detail the planned progress for both processes. P_1 process starts the work at unit 35 and finishes at unit 47, having a planned progress of 12 units. While, P_2 process has a planned progress of 15 units (referred as PP_2 preserving the RCM nomenclature).

Furthermore, a table is shown with the hypothetical WIP Bf sizes analyzed at this level. In this case, the Bf analysis begins with the IWIP $Bf_{1,2t}$ shown in Figure 5, which is denoted as WIP Bf_o in Figure 6 (since it can be or not a IWIP Bf, especially when a process as P2 has started its progress). The analysis is focused on those processes for which WIP Bf (as work units) have been produced and there is available information about that. Also, these processes should be sensitive to the sizes of WIP Bf according to the RCM. At this scheduling level, the following steps can be followed:

1- Selection of the Short-Term Period Size and Processes Package: From the Buffered Lookahead Plan a Short-Term Period is defined. Then, the processes held in this time window are chosen, in which the WIP Bf is a key construction precondition.

2- Definition of PRI levels: The planned progress (PP_2), worker-weeks (W) and available WIP Bf should be defined for each process. Therefore, a decision-maker can state the planning reliability (PRI) for his estimates. Figure 6a illustrate this procedure, in which the PP_2 is 15 units with 21 planned worker-weeks and the $WIP\ Bf_o$. As a result, the planned PRI is 75% (see vertical line in bold in Figure 6a). This represents the buffering base case.



WIP Bf Characteristics	
WIP Bf	Cum. Progress (units)
$WIP\ Bf_o'$	35.0
$WIP\ Bf_o$	38.2
$WIP\ Bf_o''$	42.0

Figure 6: WIP Bf Management – Operational Scheduling Level

3- Selection of the WIP Bf and Labor Levels: Figure 6a and 6b shows an example of the different WIP Bf sizes that could be designed at this level, whose sizes are related as follows $WIP\ Bf_o' \leq WIP\ Bf_o \leq WIP\ Bf_o''$. Figure 6a shows that the lowest Bf size, $WIP\ Bf_o'$, has the highest number of worker-weeks (25) for the given PP_2 and PRI, and accordingly, Figure 6b shows that has the lowest production rate (lower slope of the straight line) to perform PP_2 in a week, which in turn means the worst labor productivity. In contrast, Figure 6a shows that the highest Bf size, $WIP\ Bf_o''$, requires the lowest number of worker-weeks (18) for the given PP_2 and PRI, while Figure 6b shows that has the highest production rate. In other words, the labor performance could be the best with a higher Bf size. In fact, the latter Bf strategy would improve the labor productivity from the buffering base case, $WIP\ Bf_o$, by 38% (from 0.6 units/worker-weeks to 0.83 units/worker-weeks). Finally, the decision-maker according to its preferences should select the WIP Bf size that he considers the best.

4- Development of Buffered Work Plans and Labor Planning: Once the WIP Bf size and the number of worker-weeks are defined, the WIP size is included in the Buffered Work Plans, as well as, labor is distributed during the work-days of the week. Since the selection of WIP Bf sizes implies time-delays in processes to begin performing the planned work (see Figure 6b), special care should be given to the labor distribution during the weekly work-days (González et al, 2008).

5- On-site Implementation of the WIP Bf: The on-site use of the WIP Bf leads to a collaborative work between project managers and subcontractors. By doing so, both project managers and subcontractors should fully understand the implications and potential benefits of applying WIP Bf strategies at operational level.

CONCLUSIONS

This paper proposed a general methodology to design and management WIP Bf in repetitive building projects at a conceptual level. This methodology integrates different approaches to deal with the WIP Bf problem, combining the MAM, the SO modeling, and the RCM. This integration is performed using the three hierarchical levels for construction scheduling: strategic, tactical and operational. Afterwards, the MAM, the SO modeling and the RCM are adapted to the strategic, tactical and operational levels respectively. Integrated methodology is general, sound and suitable to any repetitive building project, overcoming the current limitations in buffering practice and research. In other words, this methodology presents logical and rational procedures based on analytical tools, which provides a more consistent and accurate Bf design and management framework for construction practitioners, which explicitly shows the impact of determined buffering strategies over project performance (cost, time and productivity). As a result, it could promote the application of Bfs as production strategies in construction industry.

On the other hand, this methodology proposes some ways to face the interfaces between its levels and procedures to apply it in a reliable and practical way. However, this integrated methodology has not been tested as a whole yet, while their components were satisfactorily tested and validated in an independent way. Further research must be developed to: a)Generalize the integrated methodology for any production situation in repetitive projects; b)Better understand the interfaces or interactions between the different levels of the methodology; c)Analyze critical and non-critical processes; d)Test and validate the entire methodology; e)Design strategies and actions in order to implement the methodology within the project organization and to get engagement from constructors in repetitive building projects, among other questions. Further research should be carried out these topics to improve the integrated methodology capabilities.

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