WORK-IN-PROCESS BUFFER MANAGEMENT USING THE RATIONAL COMMITMENT MODEL IN REPETITIVE PROJECTS

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ABSTRACT

The use of buffers (Bf) has been a common production strategy to protect construction processes from the negative impact of variability. Construction practitioners and researchers have proposed different buffering approaches for different production situations and contexts, but practical solutions to manage Bf at operational level in construction projects are not obvious. This research proposes an operational level methodology for Work-In-Process (WIP) Bf management in repetitive projects, using the rational commitment model (RCM). RCM is an operational decision-making tool for production planning and commitment negotiation. RCM helps determine WIPBf sizes for a short-term planning horizon using field information and planning reliability indicators at the construction level instead of variability levels. RCM allows managing WIPBf among different crews involved in construction processes. The proposed methodology was validated in real repetitive projects. An application is used to illustrate the robustness and practicality of RCM to manage WIPBf on-site, which can become a key factor for industry penetration of Bf production strategies based on Lean Production principles.

KEY WORDS

buffer, lean production, rational commitment model, work-in-process

INTRODUCTION

Variability has been one of the most important research topics in the lean construction community for more than 15 years. Its negative impact on project performance in construction projects has been widely investigated (Alarcón et al. 2005; Ballard, 2000; González et al. 2008, Thomas et al. 2003; among others).

Lean production principles have been applied to study variability in production systems in construction (Koskela 2000). Buffers, which is one of the lean production strategies used to deal with variability, can circumvent the loss of throughput, wasted

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capacity, inflated cycle times, larger inventory levels, long lead times, and poor customer service, by shielding a production system against variability. Hopp and Spearman (2000) define three generic types of Bf for manufacturing, which can be applied in construction:

- Inventory: In-excess stock of raw materials, Work in Progress (WIP), and finished goods, located in the supply chain..
- Capacity: Allocation of labor, plants, and equipment capacity in excess so that they can absorb actual production demand problems.
- Time: Reserves in schedules as contingencies used to compensate for adverse effects of variability. Float in a schedule is analogous to a Bf for time since it protects critical path from time variation in non-critical activities.

Several researchers and practitioners have recently proposed new Bf approaches to manage variability in construction (Ballard 2000; Bashford et al. 2003; González et al. 2006). These methods, however, have been either too theoretical or too difficult to apply in practice. In fact, there is limited evidence showing any use of practical Bf approaches in construction practice (Park and Peña-Mora 2004).

In this research is addressed a more practical way to deal with Bf, using WIP in repetitive building projects. In construction, WIP can be defined as the difference between cumulative progress of two consecutive and dependent processes or activities, which characterizes work units ahead of a crew that will perform work (González et al. 2006). In repetitive building projects (e.g., high-rise buildings, multi-storey buildings, and repetitive residential projects, etc.), WIP is more apparent since activities are performed in discrete repeated units (Ipsilandis 2007) so a WIPBf may avoid starvation of downstream activities by the lack of work to perform from upstream activities (González et al. 2006).

This research proposes a practical WIPBf management approach, which can be applied at the operational level in on-site construction operations using Rational Commitment Model (RCM), a decision-making tool for production planning and commitment negotiation (Mundaca 2006; Bustamante 2007). RCM allows designing and managing WIPBf sizes for a short-term planning horizon using production information from the field and planning reliability indicators at the construction level, instead of explicit variability levels.

RATIONAL COMMITMENT MODEL FRAMEWORK

PLANNING COMMITMENT: INTUITION AND RATIONALITY

The Last Planner System (LPS™), a production planning and control system based on lean production principles developed by Ballard (2000), provides a management technique to deal with variability of construction projects from a production control standpoint. LPS™ promotes actions to improve planning reliability and to reduce the negative impacts of variability, monitoring the Percentage of Plan Completed (PPC) in a short-term planning horizon and controlling the Reasons for Non-Completions (RNC). In the last decade, LPS™ has been widely applied in the construction industry around the world and many benefits on project performance have been reported (Alarcón et al. 2000; Auda et al. 1998; Ballard 2000; among others).

LPS™ provides a stable production environment in projects, creating reliable Work Plans. In LPS™, activities should only be committed if they can be performed (e.g., all resources and prerequisites that are needed must be available). Frequently construction projects outsource most of the work to subcontractors, and commitments are arranged between project managers and subcontractors. Project managers should strive to obtain reliable commitments from the subcontractors. However, many of them assign work to subcontractors based on their intuition and experience, resulting in unreliable commitments.

It has been shown that there is a strong relationship between reliability of planning commitments and performance of activities executed by subcontractors (González et al. 2008; Sacks 2006). Using intuition and experience to plan commitments limits project performance, while more rational approaches help overcome this limitation.

RATIONAL COMMITMENT MODEL CONCEPTUAL FRAMEWORK

One of the key steps of LPS™ for improving the reliability in planning commitment is the analysis of constraints on planned activities that could limit or prevent its execution. The most common constraints are design, materials, prerequisite work, space, equipment, and labor (Ballard 2000). RCM regards several of these constraints as prediction variables to estimate the progress of an activity. To determine these variables, a database with information of the results of the LPS™ implementation in 77 construction projects (industrial and building), from 12 Chilean construction companies, carried out by the Production Management Center (GEPUC), was used (Alarcón et al. 2005).

RNC data was used to define the RCM variables. After three years of LPS™ implementation, projects showed remarkable repetition patterns in three RNC: Lack of Labor, Lack of Bf, and Poor Planning. The basic hypothesis for RCM is that the progress of an activity can be predicted, for a short-term planning horizon, using only three variables: labor, buffer, planned progress.

MODELING APPROACH AND MEASUREMENT OF PREDICTION ACCURACY

RCM uses multiple regression to formulate the model, which assumes the following form: $y= \beta_0+ \beta_1 x_1+ \beta_2 x_2+\ldots+ \beta_n x_n+\varepsilon_i$, where y is the dependent variable, x_i are independent variables, β_i are the corresponding parameters of the dependent variables, and ε_i is the random error. The expression for predicted progress in RCM is:

$$PRP = \beta_0 + \beta_1 W + \beta_2 WIPBf + \beta_3 PP \quad (1)$$

where:

PRP is the Predicted Progress for an activity in the short-term planning horizon (typically 1 week). Units may be m2, m3, linear-meters, houses, apartments, etc.

W is the number of workers for an activity in a short-term planning horizon. W is the sum of workers in the planning horizon. For instance, if the planning horizon is 1 week of 5 days, and there are 5 worker-days, W is 25 workers.

WIPBf is the available work for an activity at the beginning of the planning horizon. So, if the planning horizon is 1 week, the WIPBf for the painting activity, which depends on the wall-stucco activity, is the available work produced by the wall-stucco activity, measured at the beginning of the week, before painting begins. Units are m2, m3, linear-meters, houses, apartments, etc.

PP is the planned progress for an activity in a short-term period (typically 1 week). Units are m2, m3, linear-meters, houses, apartments, etc.

RCM uses regression models to estimate the activity progress at the operational level, based on historical data. Only significant variables are selected in the models, since including redundant variables may lead to incorrect analysis of scenarios. The variable selection process uses the coefficient of determination (R2) and the P-value, leading to a trade-off between the number of variables, and the R2 and P-values. In general, regression models with the least number of variables, and with the highest R2 and low P-values are preferred.

The prediction accuracy of RCM is evaluated using two indicators: Process Reliability Index (PRI) (González et al. 2008) and Commitment Confident Level (CCL). PRI is defined as:

$$\mathrm{PRI}_{i,j} = \left(\frac{\mathrm{AP}_{i,j}}{\mathrm{PPi, j}}\right)\times 100 \qquad (2)$$

where:

PRI$_{i,j}$= Process Reliability Index for week i and activity j (%). i=1…n; j=1...m.

AP$_{i,j}$= Actual Progress for week i and activity j (m^2, m^3, linear-meters, houses, apartments, etc.)

PP$_{i,j}$= Planned Progress for week i and activity j (m^2, m^3, linear-meters, houses, apartments, etc.)

PRI is a planning reliability index that measures the fulfillment planning commitment at the activity level. When AP is higher than PP, the PRI value is limited to 100% (González et al. 2008).

CCL is defined as:

$$\mathrm{CCL}_{i,j} = \left(1-\left(\frac{\mathrm{PredictedPRI}_{i,j} - \mathrm{ActualPRI}_{i,j}}{\mathrm{ActualPRI}_{i,j}}\right)\right)\times 100$$

(3) where:

CCL$_{i,j}$= Commitment confidence level for week i and activity j (%).

Predicted PRI$_{i,j}$= Predicted Process Reliability Index for week i and activity j. Predicted PRI replaces AP in equation (2) by PRP using the RCM.

Actual PRI$_{i,j}$ = Actual or Real Process Reliability Index for week i and activity j. Actual PRI is computed using equation (2).

CCL measures the commitment accuracy of the activity progress prediction, comparing the predicted PRI with the actual or real PRI. Note that CCL does not measures confidence on the net predicted progress activity. When the ratio in (3) is less than 0, its value is set to 0.

NOMOGRAPHS TO RCM AND APPLICATION METHODOLOGY

RCM is implemented using nomographs, which relate mathematical and graphically planned progress with the other production variables (Bustamante 2007). PRI can also be understood as:

$$PRI = \left(\frac{PRP}{PP}\right) \Rightarrow PRP = PRI \times PP \quad (4)$$

Replacing equation (1) in equation (4) results in:

$$PP = \left(\frac{\beta_0 + \beta_1 W + \beta_2 WIPBf}{PRI - \beta_3} \right) \quad (5)$$

Note that PRI in equation (5) is the planned PRI for a week. Figure 1 illustrates a nomograph for a repetitive housing project.

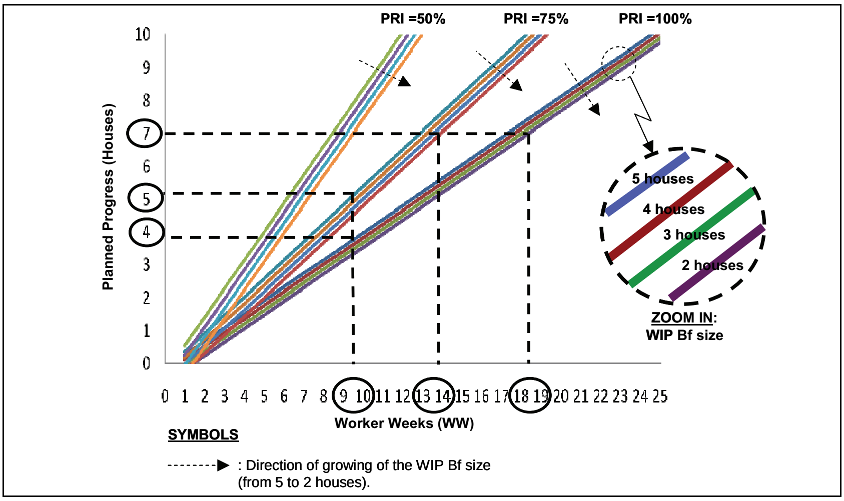

Figure 1: General Nomograph to estimated Planned Progress based on RCM.

For instance, if a project manager is planning 7 houses for next week, Figure 1 shows that, for a given WIPBf size of 2 houses, the required workers for next week will range between 18-19 and 13-14 to achieve PRI levels of 100% and 75%, respectively. This can help the project manager determine the optimum number of workers needed during the week, to reach the objective.

If the project manager were restricted to say 9 to 10 worker-weeks, Figure 1 shows that with a WIPBf of 5 houses, 4 houses can be planned with a PRI=100% or 5 houses with a PRI=75%. Figure 2 summarizes the RCM methodology.

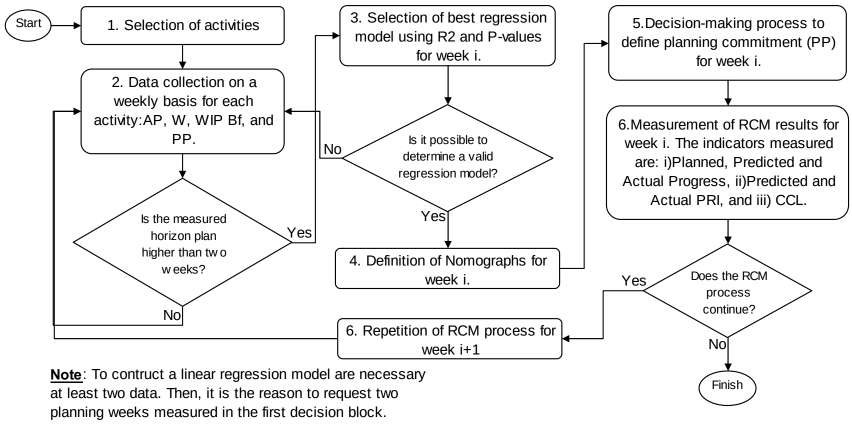

Figure 2: Methodology to implement the RCM.

VALIDATION OF THE RATIONAL COMMITMENT MODEL: CASE STUDIES

The validation process of RCM was developed in two stages. The first one tested the robustness and theoretical coherence of the mathematical formulation of the RCM and the second addressed the validation and application in action of the RCM.

First Stage of Validation

During a 4 months period, 3 repetitive construction projects and 15 activities were studied to develop a preliminary validation of the RCM (Bustamente, 2007). RCM may use different regression models and/or different parameters values, from one week to another, depending on the data. Model results were compared with real behavior in a backward process, to determine weekly predicted PRIs and CCLs. Then, the mean Predicted PRI and CCL were computed.

Table 1 shows that the mean Predicted PRI is close to the Actual PRI. In fact, the mean CCL of 92.0% illustrates the accuracy of RCM for describing production behavior and predicting the fulfillment of planning commitments. Note that not all the models used all the variables. W is the most frequently used variable, followed by a combination of W, WIPBf, and PP. The best results were obtained using the least number of variables and the higher R2-value.

Table 1: Results of First Stage Validation Process.

Project Type[a]/ Activity	Analysis Period (weeks)	Regression Model, R^2, P-value test model[bc]	P-value test parameters[bc]	Mean Act. PRI	Mean Pred. PRI	Mean CCL
P1/ Stucco	7	PP=205xW-788.5; R^2:91.0%; P:0.0001	P_W:0.0009	77.0%	78.0%	95.0%
P1/ Floor Ceramic	6	PP=13.2xW-4.3; R^2:85.0%; P:0.009	P_W:0.009	75.0%	77.0%	93.0%
P1/ Wall Ceramic	6	PP=13.3xW+59.1xWIPBf+ 0.3xPP-24.5; R^2:99.0%; P:0.012	P_W:0.008; P_{WIPBf}:0.039; P_{PP}:0.028	70.0%	70.0%	98.0%
P1/ Interior Painting	7	PP=23.0xW+8.7xWIPBf-0.1xPP+131.6; R^2: 72.0%; P: 0.226	P_W:0.307; P_{WIPBf}:0.536; P_{PP}:0.827	89.0%	89.0%	96.0%
P2/ Floor Ceramic	9	PP=19.0xW-17.2; R^2: 91.0%; P:0.00006	P_W:0.0001	72.0%	76.0%	77.0%
P2/ Wall Ceramic	8	PP=24.2xW+17.5; R^2: 92.0%; P:0.0002	P_W:0.0002	74.0%	75.0%	92.0%
P3/ Masonry	8	PP=23.5xW-305.7; R^2:87.0%; P:0.002	P_W:0.0023	77.0%	77.0%	89.0%
P3/ Slab Concrete	8	PP=0.716xW+1.2; R^2: 95.0%; P:0.0008	P_W:0.008	84.0%	85.0%	96.0%
			Mean	**77.3%**	**78.4%**	**92.0%**

[a]P1 and P2: Multi-storey Building; P3: Multi-family Residential Building. Pn indicates different construction projects, with the same or different nature.

[b]To an α=0.05 (confidence level of 95%).

[c]There is statistical significance if P≤ α-value.

Second Stage of Validation

RCM was applied over 5 months in 3 repetitive construction projects, analyzing 7 activities. The guidelines provided by the preliminary validation allowed us to use the general heuristic related to R^2 and the number of variables to define the best regression model. Since the decision-making process in RCM is dynamic (see Figure 2), only the main results of the application are summarized in Table 2. At the end of the 2nd week, construction of regression models began; therefore, a large amount of data related to them was generated during the application period for each activity. Reliable predictions were developed from the 4th week, showing all possible combinations of variables (W, WIPBf, and PP) in regression models. The main results showed a difference of 11.5% between mean Actual and Predicted PRI values. Mean CCL reached a value of 69.2%, ranging from 67.5% to 78.8%. The application of RCM in real problems shows that it produces reliable predictions, thus improving the reliability of planning commitments.

Table 2: Results of Second Stage Validation Process.

Type of Project[a]/ Activity	Analysis Period (weeks)	Mean Actual PRI	Mean Predicted PRI	Mean CCL
P4/Floor-Wall Ceramic	8	62.4%	81.4%	70.0%
P5/Plastering	12	80.7%	88.8%	78.8%
P5/Partitions	14	68.0%	80.9%	67.5%
P5/Floor-Wall Ceramic	11	76.9%	90.4%	62.8%
P6/Plastering	12	61.8%	65.8%	66.7%
	Mean	**70.0%**	**81.5%**	**69.2%**

[a]P4 and P5: Multi-storey Building; P6: Multi-family Residential Building. Pn indicates different construction projects, with the same or different nature.

WIPBF MANAGEMENT APPROACH USING RCM

One of the capabilities of the RCM is that it allows managing WIPBf at an operational level, mainly in repetitive building projects. By using regression models and/or nomographs, as shown in Figure 1, the WIPBf size and its relationship with the other production variables can be determined on a weekly-basis (or any short-term period). However, the use of RCM is limited to situations in which productivity of activities are sensitive, not only to labor, but also to the WIPBf size.

We will illustrate next the application of the RCM in the WIPBf management at operational level. The example application is based on collected data from the P6 project for "Plastering" activity (Table 2). Figure 3 shows the RCM nomograph for this activity. The PRI value has been assumed as 100% ignoring other values, since a lower PRI implies a lower project objective, which can be directly estimated from the nomograph. For instance, Figure 3 shows a planning objective for next week (13th week) of 500 m2, given a PRI of 100%, i.e., it is expected that the planned progress reach the total 500 m2. On the other hand, if another planning objective with a PRI of 75% is considered, the new plan will result in a planned progress of 375 m2. Instead of accumulating a large amount of graphical information in nomographs, planning reliability is directly used from PP-axis, changing planning objectives with respect to a value base.

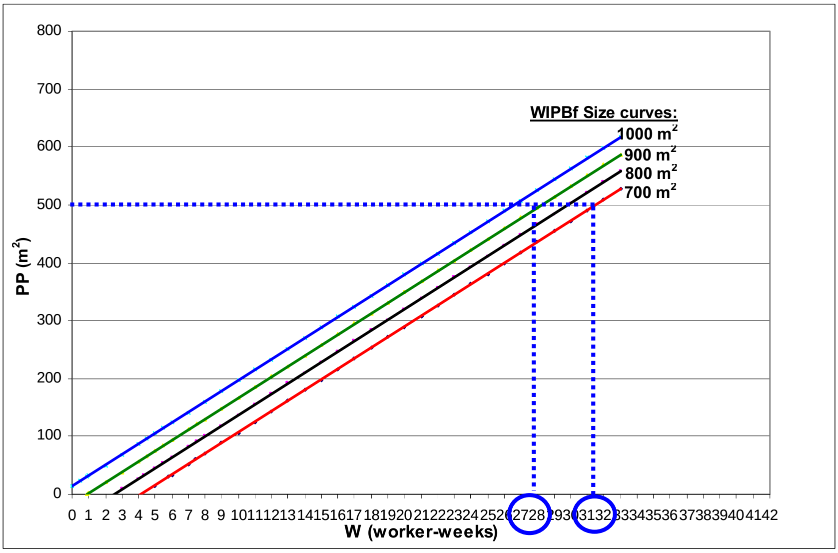

Figure 3: RCM Nomograph for Plastering activity in P6 project. PRI=100%; Regression Model PRP=-286.4+18.3W+0.3WIPBf; R2=61.3%; Predicting Progress to 13th planning week.

If a project manager wants a plastering PP of 500 m^2 for next week, it will require a different number of workers for different WIPBf sizes, as shown in Figure 3. Thus the notion of crew congestion and the effect of an optimum WIPBf size that allows avoiding this issue is addressed. This should maximize productivity of crew work without interruptions, idle and/or waiting times, as shown in Tables 3 to 5.

Table 3 shows the PP for plastering activity considering a WIPBf of 900 m2. Figure 3 indicates that 27 to 28 worker-weeks are necessary during the week. Table 3 illustrates the hypothetical daily progress for 27 worker-weeks similarly distributed (real daily progress could be more variable, but this is a good approximation).

Table 3: Plastering Work Plans with an available WIPBf=900 m^2 on Monday.

	WIPBf= 900 (m2)					Total
	Monday	Tuesday	Wednesday	Thursday	Friday	
Daily Progress (m^2)	92.6	92.6	92.6	111.1	111.1	500
Worker-days	5	5	5	6	6	27

Table 4 shows a scenario for the plastering activity PP considering a WIPBf of 700 m2. Figure 3 indicates that more labor is necessary, ranging between 31 and 32 worker-weeks during the week. Table 4 illustrates the hypothetical daily progress for 32 worker-weeks. In general, several crews of different activities can concurrently work in the same space, causing congestion inefficiencies when their number is large. A proper WIPBf size can avoid this problem. If a proper WIPBf size is not foreseen by a project manager, crews will be available at the beginning of week but their work will be ineffectively executed or not executed at all. The latter situation is illustrated in Table 4, where on Monday there are 5 workers; however, there is no progress. To achieve the planning objective of 500 m2, it is necessary to increase the number of worker-weeks from 27 to 32.

Table 4: Plastering Work Plans with an available WIPBf=700 m2 on Monday.

	WIPBf= 700 (m2)					Total
	Monday	Tuesday	Wednesday	Thursday	Friday	
Daily Progress (m^2)	0	111.1	129.6	129.6	129.6	**500**
Worker-days	5	6	7	7	7	**32**

RCM can help analyze production scenarios to explore alternatives to avoid potential issues. Table 5 shows a scenario with a WIPBf size of 700 m^2 on Monday (similar to Table 4). The project manager can use the RCM nomograph (Figure 3) to determine that the PP of 500 m^2 can be accomplished using less workers and a higher WIPBf size of 900 m^2. However, it will require a delay at the on-site entrance of crews until the WIPBf size of 900 m^2 is generated by the upstream activity. It is assumed that the upstream activity requires only one day to produce the remaining 200 m^2 of WIPBf (in practice, on-site measurements, expert judgment or the same RCM can provide information about production rates from upstream activities to estimate these delays). Thus, the on-site entrance could be delayed by one day, i.e., starting its work on Tuesday with 27 instead of 32 worker-weeks.

Table 5: Plastering Work Plans with an available WIPBf=900 m2 on Tuesday

	WIPBf= 900 (m2)					Total
	Monday[a]	Tuesday	Wednesday	Thursday	Friday	
Daily Progress (m^2)	0	111.1	129.6	129.6	129.6	**500**
Worker-days	0	6	7	7	7	**27**

[a]Deliberated delay to entrance of crews is planned to produce the enough WIPBf by the upstream activity.

This example illustrates the use of RCM to manage WIPBf at operational level in repetitive building projects. RCM can help greatly improve the buffer management culture in the construction industry.

CONCLUSIONS

The use of RCM to manage WIPBf at an operational level is addressed in this paper. First, it is shown that RCM is a reliable and rational tool to predict planning commitments. Second, we show that RCM promotes a more coherent process of negotiation between project managers and subcontractors. Third, that RCM can help accumulate historical information in several production variables and to perform statistical analysis over them. Finally, we show that RCM is a sound tool to manage WIPBf in repetitive building projects, showing both analytically and graphically the impacts of WIPBf on congestion and labor productivity.

RCM can be instrumental to promote the introduction of changes in the buffer management culture in construction industry. Practice in project management tradition is dominated by intuition and experience. One of the elements that promotes these practices, is the lack of practical and sound tools to help make management decisions in construction. Buffer management is not the exception. This paper proposes a different approach to manage WIPBf at an operational level, using the RCM, in which the size of WIPBF can be a key production variable to influence labor productivity. Thus, RCM allows to effectively plan the work of different crews using WIPBf, Also, the paper shows how a pull approach could be applied when production on-site conditions (e,g., labor, WIPBf, planning reliability) are considered to plan work using the RCM.

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