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Integrated methodology to design and manage work-in-process buffers in repetitive building projects

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An integrated methodology to design and manage buffers in repetitive building projects using work-in-process at conceptual level is proposed. The buffer design framework employs the Multiobjective Analytic Model and Simulation-Optimisation techniques, applied at strategic and tactical scheduling levels. The buffer management framework uses a statistical model to predict work progress, the Reliable Commitment Model, applied at operational scheduling level. The integrated methodology provides a new buffering approach for scheduling repetitive building projects, which considers: (1) a general production framework covering all the production levels from top to bottom; (2) a general modelling structure suitable to any type of repetitive building project; and (3) a sound theoretical and practical framework describing different production scenarios. The benefits of using this methodology are illustrated through a hypothetical project application.

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Keywords: buffer design and management; multiobjective analytic model; Pareto front; simulation-optimisation; reliable commitment model; work-in-process

1. Introduction

Variability management is one the most recognised challenges in production systems. In manufacturing, it is understood as *the quality of nonuniformity of a class of entities* (Hopp and Spearman, 2000). In construction, variability is commonly characterised by varying production rates, labour productivity, schedule control and cost control. The harmful effects of variability over production performance have been broadly documented in manufacturing (Deming, 1986; Hopp and Spearman, 2000) and in construction (Goldratt, 1997; Tommelein *et al*, 1999; Ballard, 2000; Thomas *et al*, 2002).

One of the strategies to shield production systems from the ill-effect of variability is the use of buffers, which allow a production process to be isolated from the environment and the processes depending on it. There are several types of buffers in production; these are inventory buffers (eg, materials, work-in-process (WIP), and finished goods), capacity buffers (eg, in-excess labour and/or equipment capacity), and time buffers (eg, time contingencies and/or floats) (Hopp and Spearman, 2000). While the manufacturing industry has been characterised by the use of very well-designed and rational buffering strategies (Hopp and Spearman, 2000), traditionally the construction industry has applied informal and not very consistent buffering strategies (González and Alarcón, 2010). On the other hand, current research in construction has only provided too theoretical buffering approaches and/or too difficult methods to be implemented on-site (González *et al*, 2009). Thus, the development of sound, general and practical buffering strategies in construction is required.

To overcome these problems, an integrated methodology to design and manage WIP buffers in repetitive building projects at conceptual level is proposed. In construction, WIP can be understood as the difference between cumulative progress of two consecutive and dependent activities or processes, which characterises work units ahead of a crew that will perform work (González *et al*, 2009). In repetitive building projects, for example, high-rise buildings, multi-storey buildings, and repetitive residential projects, WIP is more apparent as activities are performed in discrete repeated units. This methodology is part of a comprehensive buffer research that has been carried out during the last years by the authors (González and Alarcón, 2009, 2010; González *et al*, 2009, 2010, 2011). The integrated

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methodology provides a new buffering approach based on analytic tools for scheduling repetitive building projects, which considers: (1) a general production framework covering all the production levels from top to bottom; (2) a general modelling structure suitable to any type of repetitive building project; and (3) a sound theoretical and practical framework describing different production scenarios. Variability reduction and value-adding activities increase are the lean production principles supporting theoretically this methodology (Womack and Jones, 1996). Also, the integrated methodology has different modelling components that were developed, tested and applied in theoretical and real construction projects in an individual basis. This research puts together these components for creating a more integrative approach to cope with buffers.

The following sections describe: the tested hypotheses, a brief review of the buffering strategies in construction, the research scope and methodology, the previous research, the overall modelling approach and the integrated methodology framework to design and manage WIP buffers. For simplicity, each component of the integrated methodology is separately explained, describing in detail: (1) the conceptual and modelling framework; and then, (2) an illustration for the application of the corresponding component. Finally, discussions and conclusions including further research are addressed.

2. Tested hypotheses

In order to logically develop this research, a number of assumptions or hypotheses were tested:

H1: *A robust scheduling methodology to deal with WIP buffers in repetitive building projects can be developed taking into account their design and management functions. Three different scheduling levels should be considered: strategic, tactical and operational.*

H2: *An optimum WIP buffer size can be estimated in order to reduce the negative impacts from variability and improve the system performance in terms of cost, schedule or productivity. So that the WIP buffer size can be modelled as a dependent variable of different production parameters in repetitive building projects, which in turn represent the independent variables.*

H3: *For implementing effectively a buffering approach in construction, it is necessary not only to have a robust framework, but also a practical framework.*

3. Buffering strategies in construction: a brief review

In manufacturing, buffering strategies have been rationally used from the application of the Inventory Theory to modern manufacturing techniques (Hopp and Spearman, 2000; Jodlbauer and Huber, 2008). On the other hand, construction is a different kind of production than manufacturing, more uncertain and complex. It is mainly the design and assembly of objects fixed-in-place, characterised by a site production, a unique product, and temporary teams (Ballard and Howell, 1998). Therefore, the same type of buffer strategies used in manufacturing can be applied in construction, as long as they are adapted to the peculiarities of its production environment. However, traditional buffering practices in construction have been mainly based on intuition and experience, in a production environment where constructors have traditionally neglected more robust and analytical tools in decision-making (Laufer *et al*, 1994; McGray *et al*, 2002). Therefore, there is a lack of systematic approaches for managing buffers, which leads to poor performance when current buffering approaches are applied in projects (González and Alarcón, 2010).

Over the last 15 years, buffer management in construction has been actively studied by practitioners and researchers (Goldratt, 1997; Alarcón and Ashley, 1999; Ballard, 2000; Park and Peña-Mora, 2004; Bashford *et al*, 2005; Walsh *et al*, 2007; González and Alarcón, 2010, among others). These studies have attempted to adapt existing buffer manufacturing approaches (inventory, capacity, and time) to the nature of production in construction with a relative success (González and Alarcón, 2010). They have also allowed the construction industry to partially avoid informal and intuitive approaches for managing buffers, which has contributed to a more effective use of buffer-based production strategies. However, most of them have been either too theoretical in design or too difficult to apply in practice (González *et al*, 2009). In fact, little evidence exists of any use of practical buffering approaches in construction (Park and Peña-Mora, 2004). In summary, there is a need for sound, general and practical frameworks to deal with buffers in construction (Cohen *et al*, 2004; Park and Peña-Mora, 2004; González *et al*, 2009).

4. Research scope and methodology

In this paper we use an integrative approach of different modelling frameworks for designing and managing with WIP buffers in repetitive building projects. Some of the modelling frameworks have different nature, so that this research matches these modelling frameworks with the corresponding component of the buffers design and management. The research methodology consists of four stages: (1) Development of the conceptual modelling approach and definition of different scheduling and managerial function levels; (2) Selection of the modelling approach such as the Multiobjective Analytic Model (MAM) and the Simulation-Optimisation (SO) technique (González *et al*, 2009) and the Reliable Commitment Model (RCM)

(González *et al*, 2010, 2011); (3) Integration and association of the MAM, SO and RCM modelling approaches to each of the scheduling and the managerial function levels proposed by González and Alarcón (2010); and (4) Illustration of the integrated methodology implementation by a project scheduling example. In this paper, the projects studied are horizontal, focused mainly on housing projects with discrete production units (ie, house units). In addition, the conceptual nature of this research limits the opportunity that a full implementation of the integrated methodology takes place at this point. However, this provides the starting point for further research.

5. Integrated methodology frame

5.1. Previous researches and overall modelling approach

The use of WIP buffers is controversial as 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. Even the leanest production systems do not avoid the use of buffers (Hopp and Spearman, 2000). However, the use of large WIP buffers to ensure throughput will inherently increase cycle times and costs. Therefore, it appears that a 'balance-problem' (or trade-off) exists between the use of WIP buffers to reduce variability impacts and overall production system performance based on lean principles (González *et al*, 2009). The integrated methodology is supported by the explicit recognition of this balance-problem. Previous research has allowed a number of mathematical approaches for modelling WIP buffers to be proposed, which represent the basis of the integrated methodology. These modelling approaches were: (a) MAM (González *et al*, 2009 and González and Alarcón, 2010), a mathematical meta-model based on Pareto Front principles; (b) SO (González *et al*, 2009 and González and Alarcón, 2010), a discrete-event simulation modelling approach with an embedded optimisation algorithm; and (c) RCM (González *et al*, 2010, 2011), a statistical model that uses Multivariate Linear Regression (MLR) models. These modelling approaches allow an overall modelling framework for WIP buffers to be studied in detail in this paper (González and Alarcón, 2009). This framework has been splitted up into its scheduling levels (strategic, tactical and operational) and managerial function levels (design or management). Thus, each scheduling level and managerial function has a specific modelling approach. The underlying rationale behind the outline of different scheduling and management function levels as well as their relationship with the above-mentioned modelling approaches is described in the following sections.

Three scheduling levels are defined using the Ballard and Howell's (1998) guidelines: Master Plan or Strategic Planning (long-term period), Lookahead or Tactical Planning (breakout of master plan in a medium term period—typically 4–8 weeks), and Work Plan or Operational Planning (short-term period—typically 1 week), which are progressively more detailed from top to bottom (however, the term period can eventually be another guided by the decision-maker management preferences).

On the other hand, the two functions levels are defined regarding the way in which the WIP buffers are manipulated during the scheduling process. The first level refers to the design function that is related to a greater abstraction degree in the scheduling process. The WIP buffer size is designed (regarding different detail), but its onsite implementation to perform work is not considered yet. The second level refers to the management function that is related to the direct application of the WIP buffers when undertaking work. As shown in Figure 1, each component of the integrated methodology uses different modelling strategies. The design level applies Pareto Front concepts by using the MAM and SO modelling approaches, as these also represent the strategic and tactical levels of scheduling, respectively. More detail and production information is progressively obtained from the strategic to the tactical level. Even though the tactical level implies a more detailed construction schedule, the site implementation is not developed yet. The management level uses statistical models through the RCM and also represents the operational scheduling level.

As the nature of the work at this level necessarily represents the implementation of the construction schedule and execution of work, the model used is more flexible in terms of its practical application. Figure 1 conceptually shows the flows of information and the relationship between the different levels and components of the integrated methodology that will be further explained in detail.

Next sections will explain the integrated methodology by presenting the conceptual and modelling framework, the methodological steps and an illustration of its application, corresponding to each stage of the methodology. The illustrations are based on the project scheduling cases elaborated by González *et al* (2009, 2011).

5.2. Buffer design function

The design of WIP buffer is based on the concept of Parade of Trades (Tommelein *et al*, 1999), in which two key characteristics appear influencing the location and the size of the WIP buffers for repetitive projects: process interdependence and workflow variability. Figure 2 shows a linear scheduling diagram in which 'n' processes in a repetitive project with their different production parameters and the WIP buffers are illustrated. Let the 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

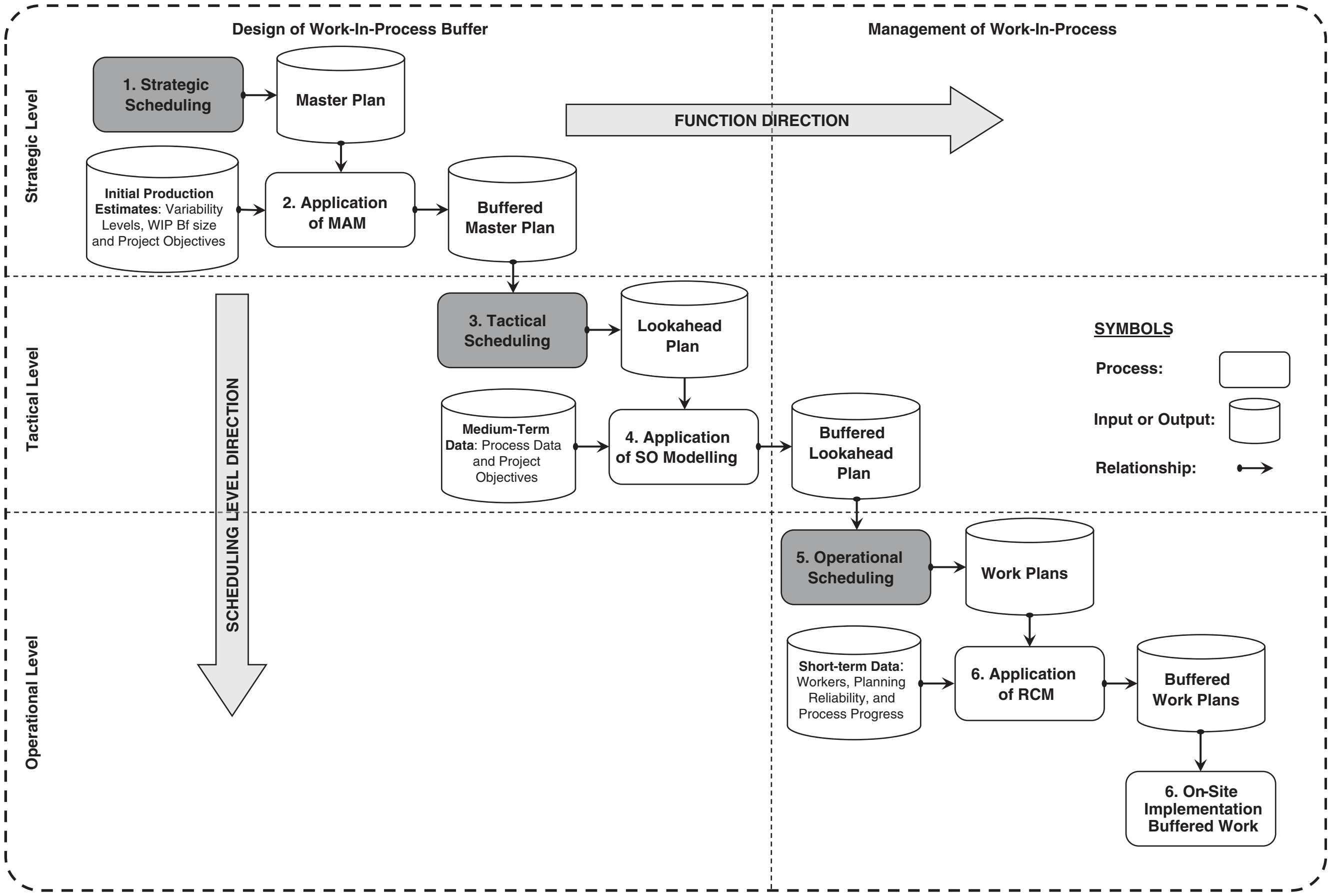


Figure 1 Overall modelling framework to WIP buffer design and management (adapted from González and Alarcón, 2010).

(units/day), respectively. Production rates (m_i) for each process are an average value with a certain variation (SD_i). This variable behaviour 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, given the cumulative progress or total production units, TP. In general, the WIP buffer sizes and TP are measured by construction units such as apartments, storeys, houses, etc (in this research we pay attention on houses).

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 (ie, a ripple effect), affecting the cycle time of individual processes, CT_i and/or the project schedule, TCT, among other impacts. The WIP buffers decrease this effect, isolating and protecting downstream processes from upstream processes variability (Alarcón and Ashley, 1999; Tommelein *et al*, 1999). The location and the size of WIP buffers for a repetitive project are shown in Figure 2. Let WIP buffer$_{1,2}$,

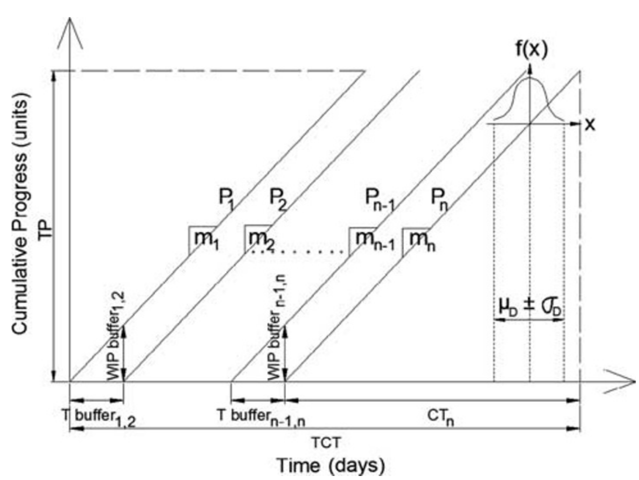


Figure 2 Conceptual framework for modelling WIP buffer characterised by unitary duration PDF and *n* processes PDF (adapted from González *et al*, 2009).

WIP buffer$_{2,3}$, ...,WIP buffer$_{n-1,n}$ which have the corresponding Time buffer called T buffer$_{1,2}$, T buffer$_{2,3}$, ..., T buffer$_{n-1,n}$, respectively. The assumption of location and size within production processes is that restrictions apply only at the beginning of processes. Thus, the WIP buffer size can be changeable during process progression until a limit that represents the minimum amount of work units ahead of a crew to perform (González *et al*, 2009).

At design level, the integrated methodology uses discrete event simulation (DES) to implement the modelling framework. The WIP buffer balance-problem at design level suggests an optimisation process which is developed through SO (González *et al*, 2009). In practice, an SO model allows for the optimisation (maximise or minimise) of a key output performance measure, finding the better combination of input variables (Law and Kelton, 2000). Thus, a simulator can represent a function $\Pi(x_1, \ldots, x_n)$ for some input parameter vector $x = (x_1, \ldots, x_n)$. The optimisation goal is to find out $\min_{x \in W} \mathrm{E}[\Pi(x)]$ or $\max_{x \in W} \mathrm{E}[\Pi(x)]$, where the response $\mathrm{E}[\Pi(x)]$ is the expectation of $\Pi(x)$ and W is a feasible range for the parameters (Buchholz and Thümmler, 2005). The selected SO modelling approach uses evolutionary algorithms so-called Evolutionary Strategies (ES). ES are algorithms similar to genetic algorithms that mimic the principles of natural evolution as a method to solve parameter optimisation problems (Carson and Maria, 1997). Minimisation of cost and schedule as well as maximisation of productivity were defined as the main optimisation goals for decision-makers, where the WIP buffer size was the decision variable (González *et al*, 2009).

5.2.1. Strategic level of buffer design: multiobjective analytic model. The MAM is a mathematical meta-model, which is in turn an output from the SO modelling to design the WIP buffers at strategic scheduling level (long-term period). The SO modelling uses a general simulation-architecture for repetitive construction processes based on the conceptual framework shown in Figure 2. 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 allow the generality and reliability of MAM to be assured as a mathematical approximation. Also, MAM uses Pareto Front principles (Figure 3) on the typical cost-time trade-off problem for the conceptual definition of simple and practical nomographs (as those used in hydraulic engineering) to design the WIP buffer 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. The whole Pareto Front line is bound in the cost-time trade-off problem for those solutions which minimise time and cost (Feng *et al*, 1997).

As the design of WIP buffers can be understood as an optimisation process, González *et al* (2009) experimentally demonstrated by using SO modelling that a Pareto Front line can be bounded by two optimisation goals: minimisation of schedule (time) and maximisation of productivity, where the solution space in which an optimum WIP buffer can be searched is: Min WIP buffer $\leqslant$ Optimum WIP buffer $\leqslant$ TP. The WIP buffer minimising time represents the minimum buffer size in the Pareto Front line, while the one maximising productivity represents the maximum buffer. In practice, the optimum WIP buffer cannot be lower than the minimum production units to perform work

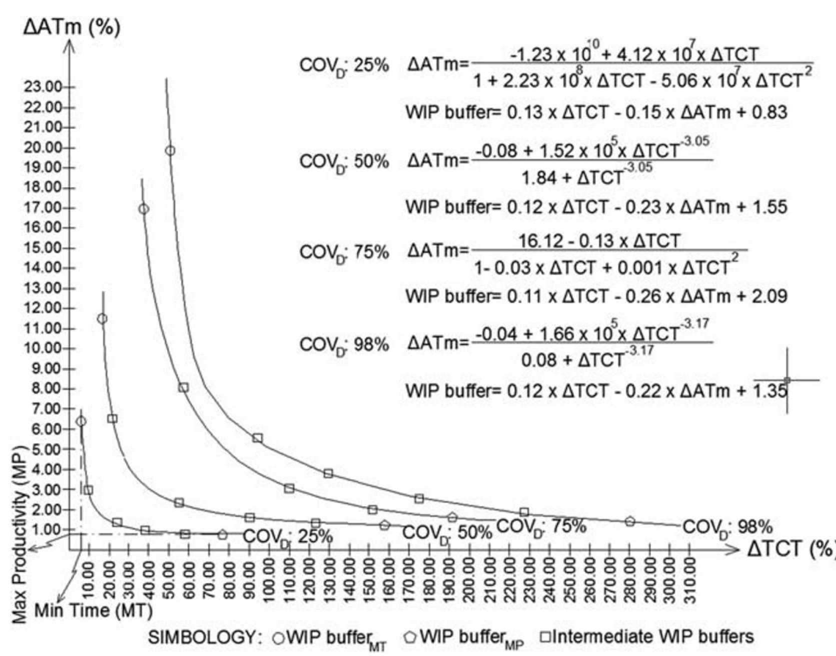


Figure 3 WIP buffer nomographs for 10 repetitive processes in the critical path with an expected duration of 2 days by production unit and for different variability levels (adapted from González *et al*, 2009).

(normally equal to one construction unit). Otherwise, there is a theoretical upper limit in terms of the total production in a project (see Figure 2). Once the extreme points of a Pareto Front line are defined, the following assumptions can be used to complete this line: (1) The Pareto Front Line is completed estimating the intermediate WIP buffer sizes (between the previous WIP buffers). As the extreme points of the Pareto Front line are known and they are represented by discrete values (buffer size), it is possible to easily determine these points. Note that the buffers size increase from the buffer that minimises time to the one that maximises productivity; and (2) The schedule and productivity responses for every WIP buffer size are calculated by simple simulation runs.

By using the production responses for every WIP buffer previously calculated (simulation outputs), multiple non-linear regression equations can be fitted to model the relationship between the WIP buffer sizes and their production responses. Thus, the MAM nomographs were implemented. Figure 3 shows an example for the 10 repetitive processes, with an expected duration of 2 days and four different variability levels adapted from González *et al* (2009). 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; (3) variability levels defined by the Coefficient of Variation (COV) of process duration (ratio between σ_D and μ_D) and (4) number of total production units (TP).

The main SO outputs are: (1) The WIP buffer sizes; (2) Productivity for each WIP buffer characterised as the difference between expected and actual values of the average m for all the processes (ΔTm); (3) Schedule or time for each WIP buffer characterised as the difference between actual and planned project schedule considered for the processes in the critical path (ΔTCT); (4) The WIP buffer size that minimises ΔTCT or time, WIP buffer$_{MT}$; (5) The WIP buffer size that maximises ΔATm or productivity, WIP buffer$_{MP}$; and (6) Project cost for each WIP buffer as the difference between actual and planned budget (ΔTC), which is estimated as $\Delta TC = f(\Delta Tm, \Delta TCT,$ WIB buffer size, Direct Costs, Indirect Costs). Direct Costs are the labour, material and equipment costs. Indirect costs are the overhead and some fixed costs. Figure 3 also shows that $\Delta ATm = f(\Delta TCT)$ and WIP buffer $= f(\Delta ATm, \Delta TCT)$ are the multiple non-linear regression models that can be developed from the nomographs data. Note that the curves and mathematical relationships are built using discrete points, that is the WIP buffer sizes that are integer numbers representing discrete production units (see more details about the cost, schedule, and productivity models used in González *et al*, 2009).

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

5.2.2. Example of buffer design at strategic level. To illustrate the integrated methodology, a repetitive housing project of 10 sequential processes, with an μ_D of 2 days/unit (or a m_i of 0.5 units/day) and a CT_i of 200 days by process, and a total cumulative progress of 100 houses is portrayed in the linear scheduling diagram (Figure 4), which in turn represents the strategic scheduling level for the WIP buffer design (these processes are along the critical path and for the sake of simplicity non-critical processes are not considered).

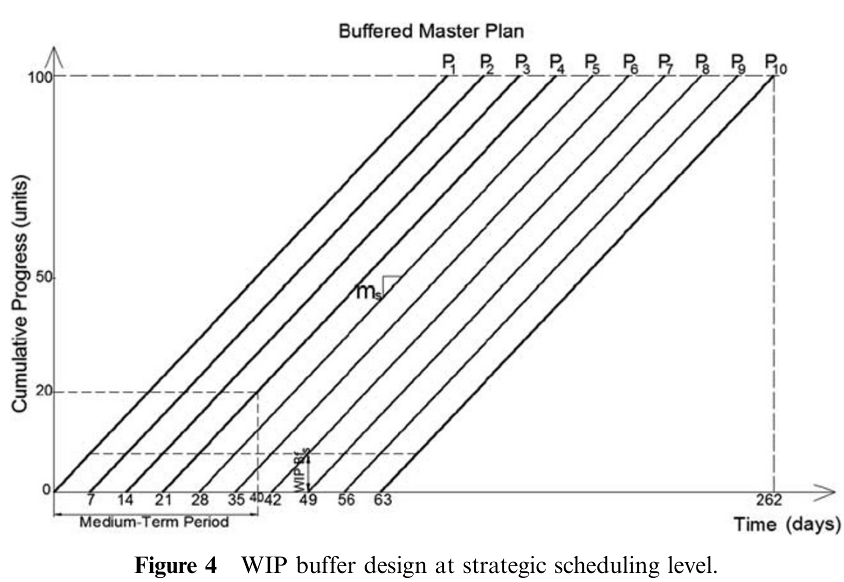


Figure 4 WIP buffer design at strategic scheduling level.

Table 1 Direct and indirect project costs (adapted from González *et al*, 2009)

*Direct costs**,†			*Indirect costs*†	
Material production unit cost ($/unit)	Labour daily cost ($/unit)	Equipment daily cost ($/unit)	Supervision‡ costs ($/unit)	Daily overhead costs§ ($/days)
$450.0	$45.0	$120.0	$700.0	$390.0

*The direct costs are directly proportional to the TP number.
†Costs in US dollars of 2009.
‡The supervision costs are directly proportional to the TP number.
§The daily overhead costs are directly proportional to the TCT.

Table 2 Strategic WIP buffer production responses (González *et al*, 2009)

WIP buffer (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

Note: Values in bold represent the optimum WIP buffer size and its production responses.
*These values are only indicative amounts used to undertake the sensitivity analysis given the approximations caused from the non-linear models (Figure 3), which should be refined in the planning process when a decision is made.

So Figure 4 shows a Buffered Master Plan with 10 processes (P1 ... P10). The project schedule, TCT, for the Buffered Master Plan in this example is 262 days. Table 1 shows a detail of the projects costs based on the González *et al*'s (2009) illustration. At this level, the following steps can be followed:

(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. In this case, the nomograph available in Figure 3 is used to develop this illustration.

(2) *Selection of a specific Pareto Front line*: The decision-maker should choose a variability or COV_D level for the project according to his or her preferences and knowledge available (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 WIP buffer. In this example, a COV_D of 50% is selected following the illustration developed by González *et al* (2009).

(3) *Estimation of WIP buffer responses*: By using the specific MAM nomograph and its specific relationships for cost, schedule and productivity, the different production responses for different WIP buffer sizes can be computed (based on the data available in Table 1 and Figure 4). Table 2 shows the calculation of different WIP buffer sizes based on González *et al* (2009).

(4) *WIP buffer selection*: In this illustration, it is assumed (that the preference of the decision-maker is to minimise costs, and accordingly, an optimum WIP buffer is defined. So, the decision-maker can choose the different buffer sizes in the selected Pareto Front line. Thus, he or she can estimate the production responses on time and productivity for every single buffer size graphically or mathematically using the Pareto Front line as shown in Figure 3 for a COV_D of 50%. By using these production responses, the cost response can be calculated for every buffer regarding the cost model addressed in Section 3.2.1 and the available cost data in Table 1. Table 2 shows hypothetical buffer sizes and their time and productivity response, as well as the cost response. Thus, a WIP buffer size of 4 units is shown in Table 2 as the optimum buffer minimising the project costs (values in bold).

(5) *Development of Buffered Master Plan*: The selected WIP buffer size is inserted in the Master Plan, producing the totally buffered plan shown in Figure 4 with a constant WIP buffer size for all processes, considering the real production rate, number of processes, cumulative progress and the corresponding Time buffer. Subscripts 's', 't' and 'o' are used to refer the strategic, tactical and operational scheduling levels, respectively.

Note that the Buffered Master Plan is the initial plan to execute the processes, being deterministic in nature. The project due date and the main milestones can be estimated from this plan. The most important characteristic of the Buffered Master Plan is the higher probability of achieving the project due date, as this explicitly involves production uncertainty through the buffers.

5.2.3. Tactical level of buffer design: SO modelling. At tactical scheduling level, the design of WIP buffers is more dynamic where the SO models are directly used. This scheduling level considers a smaller time window (medium-term period) and is closer to the work front where a greater degree of production detail is found. Therefore, the latter allows a permanent feedback from the workplace to constantly update a Lookahead plan that holds the designed WIP buffers. Likewise, the WIP buffer sizes are simultaneously updated within the Lookahead plan, with this process being necessarily performed by the SO models. Similarly, the theoretical and practical SO modelling framework was previously tested by González *et al* (2009).

As mentioned earlier, the SO modelling uses a general simulation-architecture based on the conceptual framework shown in Figure 2, which is suitable to repetitive building projects. Its main inputs are the processes duration PDF that can be subjective (use of expert judgment) or objective (use of historical information), the number of processes, the expected duration by production unit, μ_D, the minimum WIP buffers size the crews need to perform work, and the number of production units. At this level, the main output is the optimum WIP buffer size that either minimises cost and time or maximises productivity (more details in González *et al*, 2009).

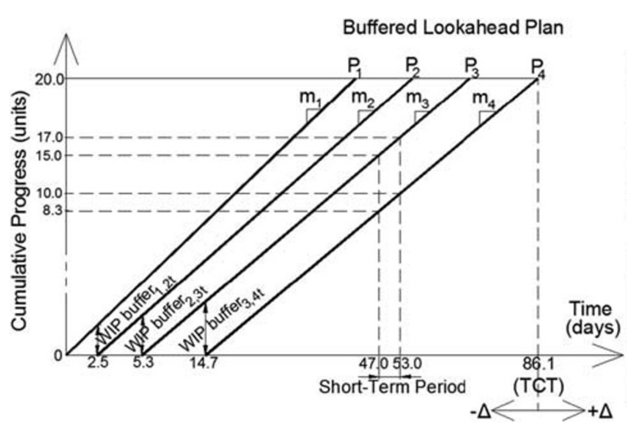
5.2.4. Example of buffer design at tactical level. Figure 5 presents the Buffered Lookahead Plan that includes a set of different WIP buffers$_{i,jt}$ as well as the average production rates (m_i) for the P_1, P_2, P_3, and P_4 processes. As shown in Figure 4, the schedule for the Buffered Lookahead Plan should be 40 days (5 workdays for 8 weeks) considering 20 production units. In practice, the duration of this plan should be higher given the effect of variability. Furthermore, Figure 5 shows two tables with information on the individual m_i, cycle times, CT_i, and the optimum sizes of the Time buffers and WIP buffers after the SO process. In this case the medium-term period contains four processes that account the 20 production units (note that the medium-term period shown in Figure 4 holds the P1, P2, P3, P4, P5 and P6 processes; however, for the sake of simplicity only those processes considering all the 20 production units were used). This is an approach suggested by the authors to manage the production processes in the medium-term period. However, other criteria can be used to define a different number of processes and amount of production units to be analysed, which should be part of further research. At this stage, the following methodological steps can be followed:

(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 for the given production are chosen.

(2) *Capture inputs for simulation models*: In this stage the following basic information to the run simulation model should be captured:

(2.1) The actual construction costs, number of actual workers by process and minimum WIP buffer size. In addition, planned process duration should be considered.

(2.2) Definition of process duration PDF by process, using historical data or expert judgement. Estimates from expert judgement may be codified by using Beta PDFs and the Visual Interactive Beta Estimation (VIBES) algorithm proposed by AbouRizk *et al* (1991). In this case, it is assumed that historical data are available to fit duration PDFs for every process. Table 3 shows their statistical details. It is also assumed that higher levels of variability (>COV = 50%) and expected



Production Characteristics		
Process P_i	m_i (units/ day)*	CT_i (days)
1	0.40±0.003	50.0
2	0,36±0.002	55.5
3	0.32±0.003	62.5
4	0.28±0.002	71.4

*A 95% confidence interval is provided as m_i is an stochastic output from SO models.

WIP Bf Characteristics			
T buffer$_{i,jt}$	Duration (days)	WIP buffer$_{i,jt}$	Cum. Progress (units)
1,2t	2,5	1,2t	1.0
2,3t	2.8	2,3t	1.0
3,4t	9.4	3,4t	3.0

Figure 5 WIP buffer design at tactical scheduling level.

Table 3 Characteristics and parameters of the duration PDFs (adapted from González *et al*, 2009)

Process	*Type of PDF*	*Shape and/or scale parameters*	μ_D *(days)*	*COV (%)*
P1	Beta	$a=0.7$; $b=1.01$; $L=0.5$; $U=5.0$	2.34	57.39
P2	Uniform	$a=0$; $b=4.3$	2.15	57.74
P3	Gamma	$\alpha=3.17$; $\beta=0.694$	2.20	56.36
P4	Beta	$a=0.7$; $b=1.01$; $L=0.5$; $U=5.0$	2.18	61.86

duration by production unit ($>\mu_D=2$days) is found onsite, which provides a more realistic production scenario than planned (González *et al*, 2009).

(3) *Model validation and SO process*: The validation process basically analyses the robustness of simulation inputs and outputs (being the simulation architecture previously validated). Also, the SO process to design the WIP buffers is carried out in this stage. The sub-steps are the following:

(3.1) Validation of simulation model with the minimum WIP buffers, which allows the intermediate and final model outputs to be analysed after a reliable statistical number of simulation runs are performed using historical data or expert judgement. In this case, the production parameters previously mentioned and the duration PDFs from Table 3 are used. This model can represent the base case as an unbuffered construction schedule.

(3.2) An SO process search is developed to state the optimum WIP buffer sizes in order to minimise the project costs. A cost model for a production of 20 units is proposed based on the suggestions as stated in Section 3.2.1 and cost data from Table 1 (see more details about the cost model used in González *et al*, 2009). The SO process performed 33 660 simulation runs, which reaches a convergence level of 99.52% (optimum solution) and a minimum project cost of \$104 267.9. The WIP buffer sizes and the production responses are shown in Figure 5. Note that the estimates in Figure 4 such as CT_i and TCT are based on the average value of m_i.

(4) *Development of Buffered Lookahead Plan*: At this stage, the designed WIP buffers are incorporated into a buffered plan at a medium-term period. As shown in Figure 5, the WIP buffers sizes can be different due to the stochastic nature of processes, with different average production rates and variability levels. It is also shown that the new medium-term period is 86.1 days higher than the planned one. However, this period could be lower or higher ($\pm\Delta$) with other simulation inputs (ie different production scenarios).

Note that the example in Figure 5 shows a Buffered Lookahead Plan with more realistic information; therefore, the planning periods can be more accurate. Owinf to the lack of production information (historical or expert opinion) at the beginning of project execution, it could be necessary to wait a reasonable timeframe for the generation of project production data and the subsequent development of the Buffered Lookahead Plan.

5.3. Buffer management function

At operational scheduling level, the WIP buffer management is focused on a short-term period. The work is performed and production involves even more sensitive variations and dynamic conditions; therefore, a different modelling strategy was selected. MLR models based on those factors affecting project planning performance such as lack of labour, lack of buffer and poor planning were used. Thus, a modelling framework that allows the progress of weekly work to be predicted by using historical site information is developed. This allows the weekly management of the WIP buffers, which can modify their size according to the site information such as planned progress, variability/reliability of commitment planning and labour productivity (González *et al*, 2010, 2011).

5.3.1. Operational level of buffer management: reliable commitment model.

The RCM (González *et al*, 2010), which is a novel decision-making tool for construction based on lean production principles (Womack and Jones, 1996), allows a more reliable prediction of work progress at operational scheduling level. The RCM's basic hypothesis is that the progress of a repetitive construction process can be predicted, for a short-term period, using a linear model with at least three variables: labour (workers), WIP buffer, and planned progress. So, MLR models are used to implement the RCM, which relate predicted progress (PRP) of an individual process as dependent variable to their independent variables: worker-weeks available over the whole planned week (W), buffer available at the beginning of the planned week (WIP buffer), and planned progress estimated for the week (PP). In other words, a general expression, $\mathrm{PRP}=\beta_0+\beta_2\mathrm{W}+\beta_1\mathrm{WIPbuffer}+\beta_3\mathrm{PP}$, for the RCM is defined. RCM replaces the notion of duration variability used at the WIP buffer design stage by the variability of the planning process or 'planning reliability' for the WIP buffer management stage. To achieve this, the Process Reliability Index (PRI) is proposed, which is defined

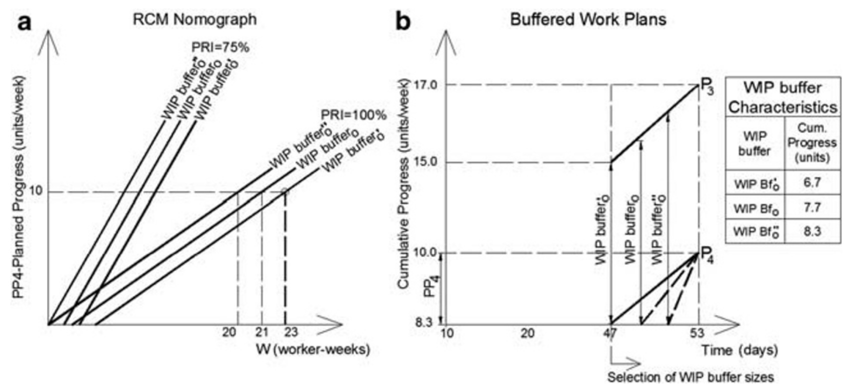


Figure 6 WIP buffer management—operational scheduling level: (a) RCM nomograph; (b) Buffered Work Plans (adapted from González *et al*, 2011).

as the ratio between actual and planned progress of a process, varying between 0 and 100%. In addition, the mathematical RCM framework has been tested and validated in a number of repetitive building projects (González *et al*, 2010).

MLR models can be parameterised to develop RCM nomographs that relate AP (actual progress of an individual process) to *W*, WIP buffers and PRI as shown in Figure 6(a) for every short-term period. RCM allows the optimum WIP buffer sizes to be defined, bearing in mind the maximisation of labour productivity. In other words, one could analyse how the size of the WIP buffer size can increase the labour productivity decreasing the *W* level given a defined PP and PRI levels. As a result, weekly sensitivity analysis can be carried out to estimate the impact of the WIP buffers size over the process labour productivity (more details about buffer management with the RCM in González *et al*, 2011).

5.3.2. Example of buffer management at operational level. Figure 6(b) shows an example of Buffered Work Plans. Figure 5 provides the short-term period of 1 week approximately (days 47 to 53) for the Buffered Work Plans. In this period, the P3 and P4 processes are analysed, both processes are performing activities over this week. Figure 6(b) shows the planned progress for both processes. P3 process starts the work at unit 15 and finishes at unit 17, having a planned progress of two units for the short-term period. P4 process starts the work at unit 8.3 and finishes at unit 10 with a planned progress of 1.7 units approximately (referred as PP4 in Figure 6).

Furthermore, a table in Figure 6 is shown with the hypothetical WIP buffer sizes analysed at this level. In this case, the analysis begins with the WIP buffer created in the short-term period between P3 and P4 (Figure 5 refers), which is denoted as WIP buffer$'_o$ in Figure 6. The analysis is focused on those processes for which the WIP buffer size (as construction units) has been produced and there is available information. These processes should be sensitive to the sizes of the WIP buffer available according to the information provided by 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 buffer is a key construction precondition.

(2) *MLR model definition*: By using historical production data from the project one could fit an equation such as $\text{PRP} = 0.3 + 0.25\text{W} + 0.45\text{WIPbuffer} + 0.1\text{PP}$ (for illustration purposes, a hypothetical equation has been proposed). This equation could be parameterised to $\text{PP} = (0.3 + 0.25\text{W} + 0.45\text{WIPbuffer})/(\text{PRI-}0.1)$ applying the guidelines provided by González *et al* (2011). By using the last equation, the nomograph shown in Figure 6(a) can be developed.

(3) *Definition of PRI levels*: The planned progress (PP4), worker-weeks (W) and available WIP buffers should be defined for each process. Therefore, a decision-maker can estimate the planning reliability (PRI) for his/her estimates. Figure 6(a) illustrates this procedure for a PP4 of 10 units and a hypothetical PRI level of 100% with 23 planned worker-weeks and the given WIP buffer$'_o$. Figure 6(b) shows a required progress of 1.7 units to achieve the PP4. The above-mentioned scenario represents the buffering base case. Note that different PRI levels and production scenarios could be defined by a decision-maker.

(4) *Selection of the WIP buffer and labour levels*: Figure 6(a) and (b) shows an example of the different WIP buffer sizes that could be estimated at this level. These buffer sizes are WIP buffer$'_o \leqslant$ WIP buffer$_o \leqslant$ WIP buffer$''_o$ (a detail of the buffer sizes is in Figure 6(b)). The lowest buffer size, WIP buffer$'_o$, has the highest number of worker-weeks (23) for the given PP4 and PRI (Figure 6(a)), and accordingly, Figure 6(b) shows that has the lowest production rate (lower slope of the straight line) to perform PP4 in a week,

which in turn means the worst labour productivity. In contrast, Figure 6(a) shows that the highest buffer size, WIP buffer$''_o$, requires the lowest number of worker-weeks (20) for the given PP4 and PRI, while Figure 6(b) shows that has the highest production rate. In other words, the labour performance is improved by applying higher buffer sizes. In fact, the latter buffer strategy would improve the labour productivity from the buffering base case, WIP buffer$_o$, by 15% (from 0.074 units/worker-weeks to 0.085 units/worker-weeks given a net progress of 1.7 units). Finally, the decision-maker according to his/her preferences should choose the WIP buffer size that he/she considers the best.

(5) *Development of Buffered Work Plans and labour planning*: Once the WIP buffer size and the number of worker-weeks are defined, the WIP size is included in the Buffered Work Plans, as well as the labour is allocated over the work-days of the week. As the selection of WIP buffer sizes can imply time-delays for the processes starting the work during the intended week (see Figure 6(b)), special attention should be given to the allocation of workers during the weekly work-days (González *et al*, 2011).

(6) *Onsite implementation of the WIP buffer*: The onsite use of the WIP buffer 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 buffer strategies at operational level.

6. Discussion

The findings of this research demonstrate the potential of applying the integrated methodology for scheduling repetitive building projects using WIP buffers, which applied specifically to housing projects. The integrated methodology considers models for each scheduling level of a repetitive building project. Each model is a reliable representation of the production itself in each scheduling level, capturing those essential parameters and characteristic for executing a repetitive building project (for naming a few: repetitiveness of processes and production units, modelling of discrete and identifiable production units, processes sequence and interdependence, processes duration and variability, modelling of WIP buffers). Furthermore, each model has been separately tested and validated for both theoretical and real construction scenarios (González *et al*, 2009, 2010, 2011). As such we argue that the generalisation ability of the integrated methodology for modelling any kind of repetitive building project, in the context of housing projects, is highly feasible. Even more, empirical data from González *et al* (2009, 2010, 2011) have demonstrated that other kind of repetitive projects is suitable to be represented by the individual models (MAM, SO and RCM) such as multi-storey buildings and industrial buildings (ie its repetitive construction components). Therefore, it is suggested that any kind of repetitive building project could be modelled and scheduled by the integrated methodology.

On the other hand, repetitive projects such as road or tunnelling projects could be potentially modelled by making slight changes in the modelling approaches and considering different levels of abstraction (for instance, when describing the production units in a road construction). However, future perspective to generalise the integrated methodology to a wider range of repetitive projects is part of the further research.

7. Conclusions

This paper proposed a general methodology to design and manage WIP buffers in repetitive building projects at a conceptual level. This methodology integrates different approaches to deal with the WIP buffer problem, combining the MAM, the SO modelling, and the RCM. This integration is performed associating these models to the three hierarchical levels for construction scheduling: strategic, tactical and operational. Thus, the MAM, the SO modelling and the RCM are adapted to the strategic, tactical and operational levels, respectively.

This paper tested three hypotheses that show the theoretical and practical implications of this research. Hypotheses H1 and H2 tested the theoretical implications of the integrated methodology, demonstrating the robustness and generalisation ability of this methodology given by its modelling framework. Although this methodology analysed a repetitive housing project, the authors suggest that this does not necessarily reduce its modelling capabilities and applicability to any kind of repetitive building project. Hypothesis H3 tested the practical implications of the integrated methodology. The assumption stated by H3 was only partially supported as the integrated methodology at strategic and operational scheduling levels only offers a practical framework to the project personnel by using nomographs (MAM and RCM). The tactical level based on SO modelling does not essentially represent a practical approach suitable to any construction project (and adaptable to the common decision practices in construction considering its complexity in terms of modelling skills required by project personnel). On the other hand, the integrated methodology presents logical and rational procedures based on analytical tools, which provides a more consistent and accurate buffer design and management framework for construction practitioners, which explicitly shows the impact of determined buffering strategies over project performance. This implies the explicit recognition of variability in a construction schedule and a lower risk of overruns, exceeding the planned schedule and wasted productivity.

The main limitation of this research is the conceptual nature of the integrated methodology that limits the opportunity that a full implementation of the integrated methodology takes place at this point. The different modelling components of the methodology were separately tested and validated in previous research. So the integration and interaction of these modelling components in the 'integrated methodology' remain conceptual at this point. Further research should be developed to test the application of the integrated methodology to other repetitive building projects (eg, multi-storey buildings and industrial buildings) and other repetitive projects in general (eg, road or tunnelling projects), to get a better understanding of interfaces, interactions and feedback among the different levels of the methodology and to validate the methodology as a whole.

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