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INTEGRATING TASK FRAGMENTATION AND EARNED VALUE METHOD INTO THE LAST PLANNER SYSTEM USING SPREADSHEETS

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ABSTRACT

Construction schedulers make use of several tools as project management software of general purpose and spreadsheets for applying the Last Planner System of Production Control. This widespread practice has the disadvantage of working with questionable algorithms and models difficult to adapt to the construction industry, besides having to work with disconnected and complex information to manage data. In this paper a new layout and computation of multidimensional non-cyclic directed graphs based on its adjacency matrices is presented. All the precedence relationships are considered, in addition to the optimal and discretionary fragmentation of task in real conditions with work and feeding restrictions. This approach has been implemented with Visual Basic for Excel. A new approach for the representation and computation of projects for the Last Planner System of Production Control is presented. This approach is integrated with the management of the Earned Value and ad-hoc complex optimization. LPS™, CPM, EVM and PPC are found to be complementary, and the Zaderenko´s algorithm modified and implemented in Excel can be used to integrate them.

KEYWORDS

Lean construction, Last Planner System, Construction Scheduling with spreadsheets.

INTRODUCTION

To improve the efficiency of the planning process of construction projects, practitioners schedule through a hierarchy of three levels from low to high level of detail. Ballard and Howell (1998) propose The Last Planner System of Production

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Control (LPS™) as a hierarchy of three levels from low to high level of detail: master plan and phase planning (long term), look-ahead planning (medium term), and commitment planning (short term). The long term planning is to obtain a general plan establishing the strategic targets (phase planning) aimed to developing more detailed work plans and identify all the work packages for the construction project, showing the main activities, their duration and sequences indexed at the top level of the work breakdown structure (WBS henceforth). In the middle term planning, the schedulers develop actions in the present to produce a desired future, preparing, analysing, and solving the conflicts and restrictions in a lower and more detailed level of the WBS. In the short term planning or Weekly Work Planning (WWP), collaborative agreement or commitment planning works at the lowest levels of the WBS making things happen, bearing in mind the work that is being done now and that is made-ready to be done (Koskela, Stratton and Koskenvesa, 2010).

Lean construction practitioners make use of custom spreadsheets and project management software of general purpose, which implements a group of mathematical algorithms known in a generic form as Critical Path Method (CPM henceforth). These tools are fluently used by practitioners and implemented in the commercial software designed to assist them in the scheduling process. However, many times practitioners are not aware of the implications about using these algorithms or they do not understand CPM software properly. Furthermore, even skilled technicians may have problems interpreting the implementing criteria of CPM algorithms as well as its relaxations (Wiest, 1981), not properly documented in the management commercial packages even those of the highest quality. In addition, the results obtained on the benchmarking tests indicates that not only they are hardly applicable or feasible in realistic environments, but that they are not currently competitive with the best state-of-the-art algorithms available in the literature (Mellentien and Trautmann, 2001; Trautman and Baumnn, 2009). This widespread practice has the disadvantage of working with questionable obsolete algorithms and models difficult to adapt to the construction industry, besides having to work with disconnected and complex information to manage data.

CPM has been widely criticized as inadequate to the task of controlling work in projects (Koskela, et al., 2014), and Earned Value Management (EVM) for managing task at the operational level, suggesting that LPSTM and Percentage of Promises Completed (PPC) are more appropriate to manage works when it is applied to the operation level (Kim and Ballard, 2010). LPSTM is a collaborative, commitment-based planning system, and CPM is a class of operations research algorithms for computing the times of the activities based on its precedence restrictions. PPC is the measure of promises completed on time and EVM is a tool for production control by a comparison between budgeted and scheduled with performed, obtaining different measures to report the progress of the project in terms of cost, production and time (Ponz-Tienda, Pellicer and Yepes, 2012). LPSTM, CPM, EVM and PPC are complementary rather than competitive, and the inadequacy is on the fitness of the implemented algorithms to the construction industry. Research is heading towards the establishment of alternative project control accounting systems not subject to the traditional limitations of EVM, such as unbalanced process flows and lack of predictability (Kim and Ballard, 2000), mainly in terms of workflow and value generation (Kim, Kim and Cho, 2015)

In this paper a new layout and computation of multidimensional non-cyclic directed graphs based on its adjacency matrices is presented with a realistic approach in construction production planning. All the precedence relationships are considered, in addition to the optimal and discretionary fragmentation of task in real conditions with time, work and feeding restrictions. This approach has been implemented with Visual Basic for Excel in a complete and adaptable application for the LPSTM integrated with the management of the EVM and ad-hoc complex optimization models.

The reminder of this paper is structured as follows: Section 2 provides a literature review of the Project Scheduling Problem with GPRs and feeding precedence relationships. Section 3 details the proposed algorithms for multidimensional non-cyclic directed graphs based on its adjacency matrices. In section 4, the proposal implemented for spreadsheets is shown. Finally, conclusions are drawn.

LITERATURE REVIEW

Projects are usually represented as acyclic directed graph without cycles and circuits in two ways, considering the activities on the arrows of the graphs know as *Activity-on-Arrow* (*AoA*) (Kelley and Walker, 1959; Malcolm, et al., 1959), and considering the activities on the nodes of the graph, know as *Activity-on-Node* (*AoN*). The *AoN* model was introduced by Roy (1962 cited in Kerbosch and Schell, 1975) and later improved with the well-known Precedence Diagramming Method (*PDM*) (IBM, 1968).

The *PDM* graphs considered the activities as non-splitting allowed and contemplated four kinds of *Generalized Precedence Relationships* (*GPRs*): *finish-to-start (FS(z_{ij}))*, *start-to-start (SS(z_{ij}))*, *finish-to-finish (FF(z_{ij}))* and *start-to-finish (SF(z_{ij}))*. The *PDM* graphs with *GPRs* present an anomalous effect, called *reverse criticality*, that grates against one´s natural feelings about the consequences of lengthening or shortening a job (Wiest, 1981), changing the concept of a critical path itself. Crandall (1973) proposed the first splitting allowed algorithm that partially avoids the reverse criticality. This algorithm considers that "*disallowing the splitting of activities was an excessive relaxation of the real problem"*, presenting a heuristic algorithm to compute the times and the minimum duration of the project.

The Crandall´s algorithm was improved by Moder, Philips and Davis (1983), including the start-to-finish relationship. More recently, Valls, Martí and Lino (1996) analyse the Crandall's algorithm, proposing a new computation and more realistic treatment of the *start-to-finish* relationship. Other relaxed algorithm have been proposed by Hajdu (1996), but it provides infeasible solutions to the problem in some cases.

An important and not well-known feature of graphs, especially project graphs, is that they can be represented by indexed matrices, based on its precedence relationships and represented by adjacency matrices. This characteristic is regardless of its nature, no matter if it is an *AoA* graph or an *AoN* graph.

The first algorithm to compute the times of the activities of a project based on its matrix representation was proposed by Zaderenko (1968). The Zaderenko´s algorithm only considered the *finish-to-start* relationships, computing the early start and finish of the activities. The Zaderenko´s proposal was improved by Ponz-Tienda (2011), proposing a new representation and computation of multidimensional non-cyclic directed graphs based on its adjacency matrices considering all the *GPRs* for the non-splitting allowed case and feeding precedence relationships.

INDEXING CRITERIA WITH SPREADSHEETS

The indexing criterion is based on the Zaderenko´s proposal, in which each $a_{j,j}$ element of the adjacency matrix correspond to the lead/lag of the relationship between an activity *j* and its predecessor ones (*i*) (*Figure*).

			Predecesor activities					
		duration	*1*	*2*	*…*	*i*	*…*	*n*
Activities	*1*	d_1	$a_{1,1}$	$a_{1,2}$	$a_{1,\dots}$	$a_{1,i}$	$a_{1,\dots}$	$a_{1,n}$
	2	d_2	$a_{2,1}$	$a_{2,2}$	$a_{2,\dots}$	$a_{2,i}$	$a_{2,\dots}$	$a_{2,n}$
	…	$d_{\dots}$	$a_{\dots,1}$	$a_{\dots,2}$	$a_{\dots,\dots}$	$a_{\dots,i}$	$a_{\dots,\dots}$	$a_{\dots,n}$
	j	d_j	$a_{j,1}$	$a_{j,2}$	$a_{j,\dots}$	$a_{j,i}$	$a_{j,\dots}$	$a_{j,n}$
	…	$d_{\dots}$	$a_{\dots,1}$	$a_{\dots,2}$	$a_{\dots,\dots}$	$a_{\dots,i}$	$a_{\dots,\dots}$	$a_{\dots,n}$
	n	d_n	$a_{n,1}$	$a_{n,2}$	$a_{n,\dots}$	$a_{n,i}$	$a_{n,\dots}$	$a_{n,n}$

Figure 1: Indexing criterion of the adjacency matrix

If the activities of the project are ordered in a topological way, then $\forall i \le j \;\Rightarrow\; a_{ij} = NULL$, obtaining the simplified matrix shown in *Figure* .

			Predecesor activities					
		duration	*1*	*2*	*…*	*i*	*…*	*n*
Activities	*1*	d_1						
	2	d_2	$a_{2,1}$					
	…	$d_{\dots}$	$a_{\dots,1}$	$a_{\dots,2}$				
	j	d_j	$a_{j,1}$	$a_{j,2}$	$a_{j,\dots}$			
	…	$d_{\dots}$	$a_{\dots,1}$	$a_{\dots,2}$	$a_{\dots,\dots}$	$a_{\dots,i}$		
	n	d_n	$a_{n,1}$	$a_{n,2}$	$a_{n,\dots}$	$a_{n,i}$	$a_{n,\dots}$	

Figure 2: Simplified adjacency matrix

And the algorithm for computing the times of the activities is shown in pseudo-code 1:

Table 1: Pseudo-code 1 Conceptual algorithm

Forward Pass	**Backward Pass**
FOR $(j = 1, n, +1)$	**FOR** $(i = n, 1, -1)$
FOR $(i = 1, j-1, +1)$	$LF_i = makespan$
IF $a(i,j) \ne NULL$ **THEN**	**FOR** $(j = i+1, n, +1)$
$ES_j = \max(SS_j, EF_i + a(i,j))$	**IF** $a(i,j) \ne NULL$ **THEN**
ENDIF	$LF_i = \min(LF_i, LS_j - a(i,j))$
$EF_j = ES_j + d_j$	**ENDIF**
$makespan = \max(makespan, EF_j)$	$LS_i = LF_i + d_i$

The previous algorithm can be improved including all the *GPRs* precedence relationships applying a multidimensional adjacency matrix with two rows and columns for each activity (Figure).

Furthermore, can be included the different nature of relationships as work and feeding precedence relationships applying equation 1, and the discretional fragmentation of activities applying the criterion exposed in Figure and equation 2.

$$\forall a_{ij} = z \mid z \neq NULL \Rightarrow \begin{cases} 0 \leq z < 1 & a_{ij} \text{ is a feeding relationship} \\ |z| \geq 1 & a_{ij} \text{ is a work relationship} \end{cases} \quad (1)$$

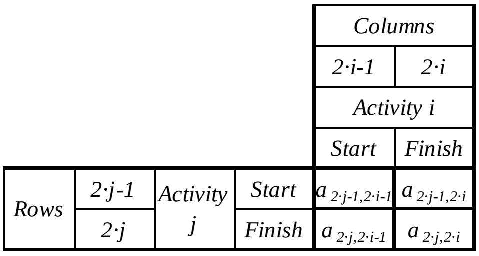

Figure 3: Multidimensional adjacency matrix

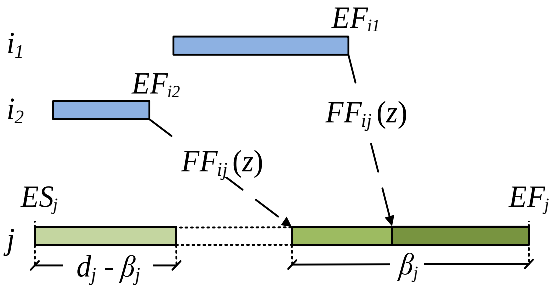

Figure 4: Splitting criterion of activities

$$\beta_j = \max\left(FF(z_{ij}),\ SF(z_{ij}) \right),\ \forall i \text{ predecessor of } j \quad (2)$$

And the algorithm for computing the times of the activities with feeding/work *GPRs* is shown in Table 2*: Pseudo-code 2* and Table 3*: Pseudo-code 3*:

Table 2: Pseudo-code 2 Forward pass algorithm with feeding/work GPRs

$\mathbf{FOR}\ (j = 1, n, +1)$

$ES_j = SS_j;$

$\mathbf{FOR}\ (i = 1, j-1, +1)$

$SSLag_{ij} = a(2\cdot j-1,\ 2\cdot i-1): \mathbf{IF}\ SSLag_{ij} < 1\ \mathbf{THEN}\ SSLag_{ij} = SSLag_{ij}\cdot d_i;$

$FSLag_{ij} = a(2\cdot j-1,\ 2\cdot i);$

$SFLag_{ij} = a(2\cdot j,\ 2\cdot i-1): \mathbf{IF}\ SFLag_{ij} < 1\ \mathbf{THEN}\ SFLag_{ij} = SFLag_{ij}\cdot d_i;$

$FFLag_{ij} = a(2\cdot j,\ 2\cdot i): \mathbf{IF}\ FFLag_{ij} < 1\ \mathbf{THEN}\ FFLag_{ij} = FFLag_{ij}\cdot d_j;$

$\beta_j = \max(\beta_j, FFlag_{ij}, SFlag_{ij});$

$SSlag_{ij} \left[\begin{array}{l} \mathbf{IF}\ \beta_j - d_j < SSlag_{ij}\ \mathbf{THEN}\ k_{ij} = EF_i - d_i + SSlag_{ij} - ES_i\ \mathbf{ELSE}\ k_{ij} = SSlag_{ij} \\ ES_j = \max(ES_j, ES_i + k_{ij}); \end{array} \right.$

$FSlag_{ij} \left[ES_j = \max(ES_j, EF_i + FSlag_{ij}) : \right.$

$FFlag_{ij} \left[EF_j = \max(EF_j, EF_i + FFlag_{ij}); \right.$

$SFlag_{ij} \left[\begin{array}{l} \mathbf{IF}\ \beta_j - d_j < SFlag_{ij}\ \mathbf{THEN}\ k_{ij} = EF_i - d_i + SFlag_{ij} - ES_i\ \mathbf{ELSE}\ k_{ij} = SFlag_{ij} \\ EF_j = \max(EF_j, ES_i + k_{ij}); \end{array} \right.$

$EF_j = \max(EF_j, ES_j + d_j);$

$\mathbf{IF}\ j\ \textit{is not fragmentable}\ \mathbf{THEN}\ ES_j = EF_j - d_j;$

Table 3: Pseudo-code 3 Backward pass algorithm with feeding/work GPRs

$$\textbf{FOR}\ (i = n, 1, -1)$$
$$\quad \textbf{FOR}\ (j = i+1, n, +1)$$
$$\quad\quad LS_i = \min i\left(LS_i, LS_j - k_{ij}\right) : LF_i = \min\left(LF_i, LS_j - FSlag_{ij}\right);$$
$$\quad\quad LF_i = \min\left(LF_i, LF_j - FFlag_{ij}\right) : LS_i = \min\left(LS_i, LF_i - d_i\right);$$
$$\quad\quad \textbf{IF}\ i\ \textit{is not fragmentable}\ \textbf{THEN}\ LF_i = LS_i + d_i;$$

IMPLEMENTATION IN AN HOLISTIC PULL SYSTEM

The previously exposed algorithms have been implemented in an Excel add-in that can be downloaded from http://goo.gl/a7G3L3 (Figure). This app includes the matrix algorithm exposed in pseudo-code 1 called *Matrix Pro*, the pseudo-code 2 and pseudo-code 3 for multidimensional adjacency matrices for *GPRs* called *Matrix GPRs*, and a suite of utilities for managing called *Matrix Commitments*.

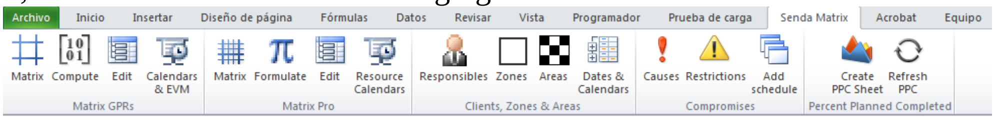

Figure 5: Senda Matrix Ribbon for Excel

The software completely supports the pull system of the LPS™, including location and responsibilities definition, making use of Excel's features, especially the unlimited possibilities of exchange of information between books and sheets (Figure 6).

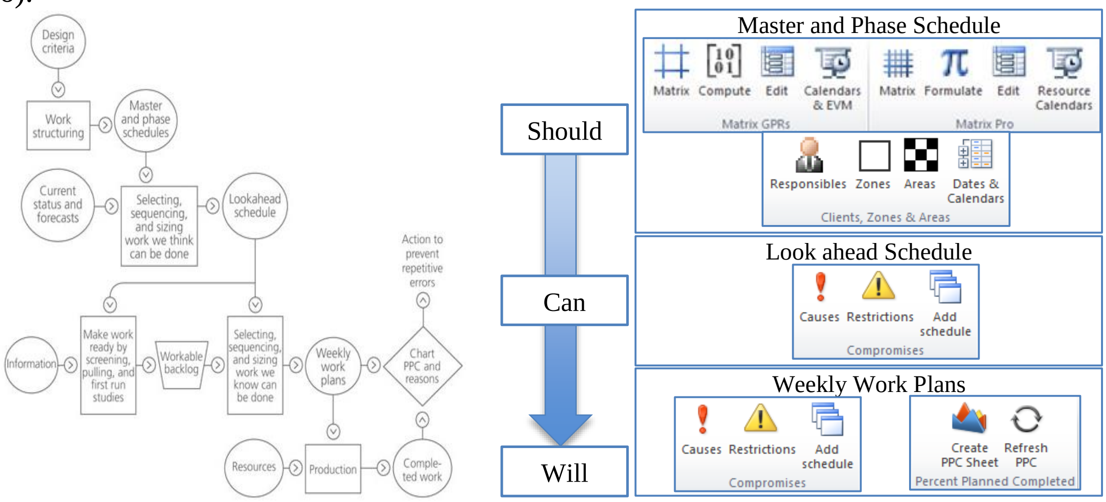

Figure 6: LPS™ (Ballard, 2000) Pull System with Senda Matrix

For a better understanding of the pull process with *Senda Matrix*, a practical example of application that supports the *LPS™* has been included. The example of application is the construction of a five floors building for classrooms and offices.

MASTER AND PHASE SCHEDULE

The main program has been scheduled with *Matrix GPRs* and contemplates seventeen activities (Figure 7), each one with different continuity conditions and feeding and work precedence relationships.

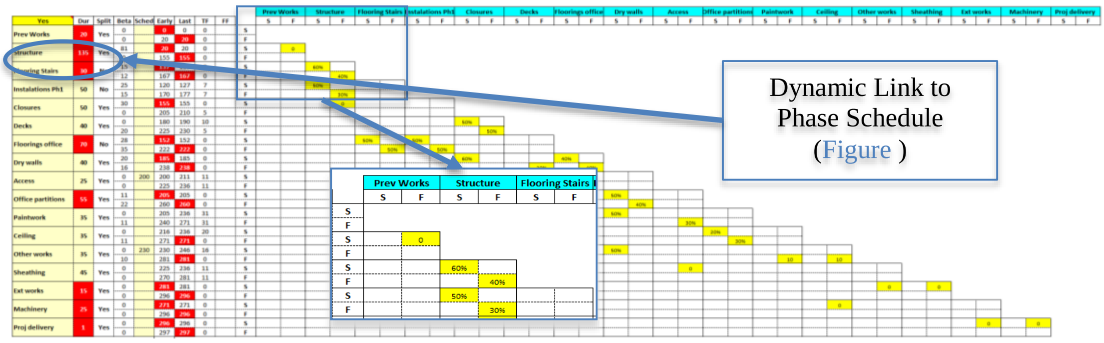

Figure 7: Main Program representation with Matrix GPRs

The Structure activity of the Main Program was analysed in depth with twenty detailed activities, as a Phase Schedule. The structure phase was scheduled using *Matrix Pro* (Figure) in a different book, applying a dynamic link from the main program. A RCPSP (Resource Constrained Project Scheduling Problem) optimization model was applied considering an availability of five workers. An optimal makespan for the structure of 135 days was obtained against the initial makespan of 166 days (Figure) (Ponz-Tienda, 2011; Ponz-Tienda, Pellicer and Yepes, 2012; Ponz-Tienda et al, 2013).

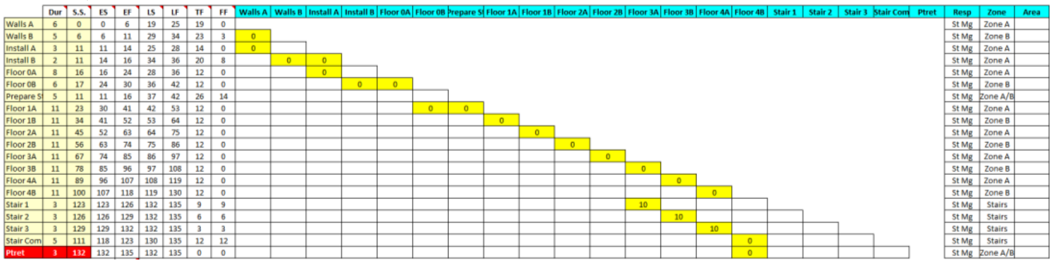

Figure 8: Phase schedule representation, Responsibles and Zones with Matrix Pro

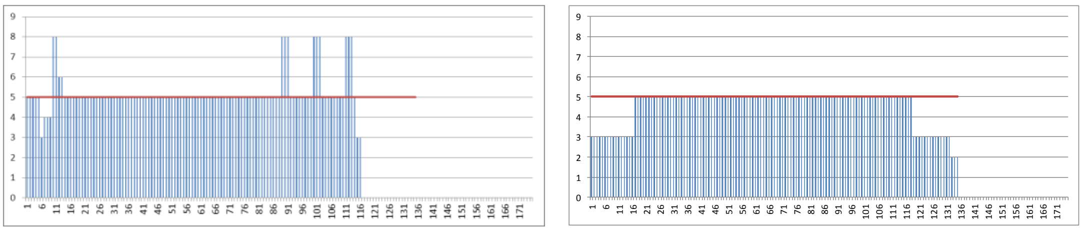

Figure 9:Optimization Model for the Phase Structure with Matrix Pro

All of Excel's features can be used, even allowing to create different reports as temporal diagrams or Line of Balance (LBM) charts (Figure).

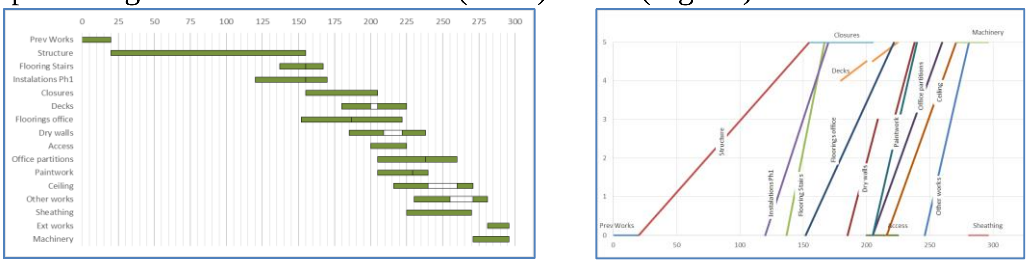

Figure 10: Main Program representation with temporal and LBM diagrams

LOOK AHEAD SCHEDULE AND WEEKLY WORK PLAN

To manage the pre-requisites, restrictions, look-ahead programs and weekly work plans, *Matrix Commitments* was used. For the look-ahead programs, temporal charts of 5 weeks (4+1) was selected in the WWP sheet manager, and 2 weeks (1+1) for the weekly work plans (*Figure*).

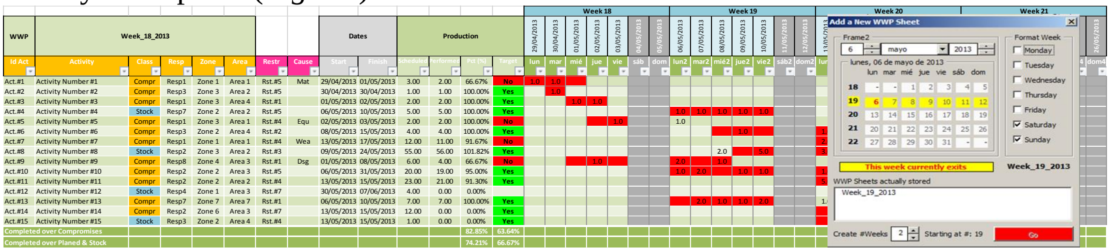

Figure 11: Look Ahead Program with Matrix Commitments

MEASUREMENT, LEARNING AND CONTINUAL IMPROVEMENT

The control and continual improvement process is developed in two levels with different goals: the schedule level and the commitments level (Figure 3).

The commitments level control with PPC measures helps the team to work on the basis of learning the continual improvement process. The PPC index does not measure production rates; it teaches the team to improve the production rates from what was "effectively done" to what "can be done" from now into the future.

The schedule level control with the EVM, provides cost and schedule deviations values on productivity and economic terms from what was "really done" of the Weekly work plans.

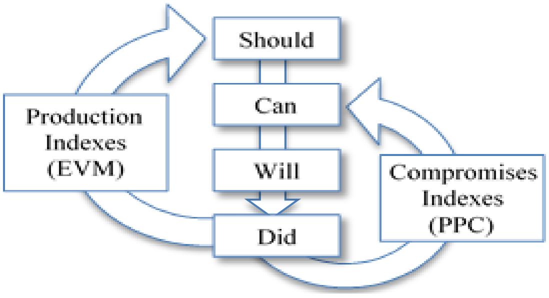

Figure 3: Integrated EVM and PPC for continual improvement

Both methods work together efficiently to reduce variability and to make the work more predictable, closing the total improvement process (Figure 4). From the "done" to the "can be done", up to the "should be done" in terms of production through the continual learning process.

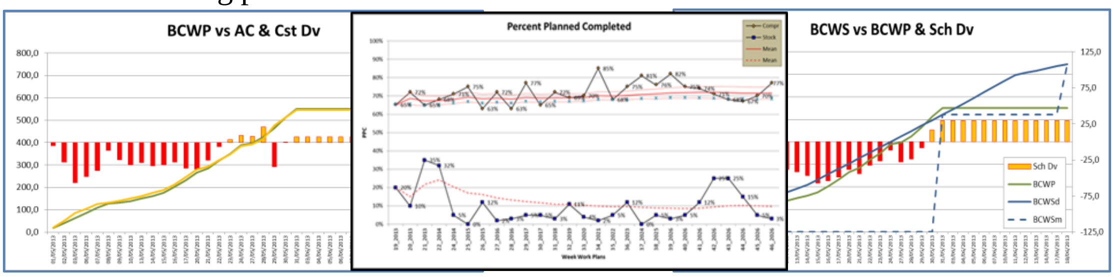

Figure 4: Cost Deviation, Schedule Deviation, PPC and Pareto Chart

Kim and Ballard (2000) found that EVM method's validity is compromised in account for "unbalanced process flows and lack of predictability". Advances are needed in order to validate and integrate new production control approaches in terms of workflow and value generation, with current practices (Kim, Kim and Cho, 2015).

Nevertheless, EVM, together with the commitments level control, allows to effectively recognizing the root causes of deviations, contributing to the reliability of workflow.

CONCLUSIONS

In this paper, a new approach for the representation and computation of projects for the Last Planner System of Production Control is presented. This approach is integrated with the management of the Earned Value and ad-hoc complex optimization models. The proposal has been implemented in an add-in for Excel called *Senda Matrix*. This add-in takes into consideration the feeding and work GPRs, allowing the splitting of activities in a discretionary way, avoiding the interruption of the critical path and the reverse criticality issue, as well as including the balance of process flows by integrating EVM with PPC calculations.

Senda Matrix is a Free and Open-Source Software (FOSS) under License Creative Commons–CY (Attribution), and is used in different undergraduate and postgraduate courses at Universidad de Los Andes at Bogotá, Colombia, and Universitat Politècnica de València, Spain (Pellicer and Ponz-Tienda, 2014; Pellicer, et al., 2015). It allows to effectively implementing advances. A base model for the integration of metrics is developed to serve as a basis for future developments.

This add-in for Excel has been developed from academia to support AEC industry and Lean practitioners that can use it in order to overcome some of the problems of the current commercial applications and help them make better decisions.

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