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DEVELOPING A FLOW-BASED PLANNING AND CONTROL APPROACH FOR LINEAR INFRASTRUCTURE PROJECTS

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ABSTRACT

The Last Planner System (LPS) and Location Based Planning and Control (LBPC) have been successfully used in many projects, either separately or together. Despite previous studies that have discussed the role of each of them, the complementarity between LPS and LBPC still needs to be further explained by using core Lean Production concepts. Moreover, most implementations reported in the literature of those two planning models have been concerned with building projects. Only a few cases are related to infrastructure projects, which have different types of complexity in relation to conventional building projects. This paper reports the initial results of the development of a planning and control model for linear infrastructure projects. This investigation was based on a case study carried out in a construction company from Uruguay. The development of the model considers some specific complexity features of linear infrastructure projects, such as high uncertainty, and independent linear processes spread around large urban or rural areas. The main insights provided by this study are concerned with devising a flow-based planning and control tool for look-ahead planning, the definition of criteria for devising location-based systems, the emphasis of work-in-progress control, and the use of visual management.

KEYWORDS

Flow, production planning and control, linear projects, Last Planner, Location-based management, visual management.

INTRODUCTION

Major advancements in construction planning and control has been achieved by adapting and implementing core concepts and principles of the Lean Production Philosophy Ballard & Tommelein, 2020; Brady et al., 2018; Seppanen et al., 2015). In fact, changes

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in production planning and control have played a key role in the genesis of the Lean Construction movement, due the strong impact of the Last Planner System® (LPS), developed by Ballard and Howell (1998). This system is able to increase the reliability of short term planning by shielding planned work from upstream variation, and by seeking conscious and reliable commitment of labor resources by team leaders (Ballard, 2000). At the medium term level, constraints are systematically identified and removed, with the aim of making available the necessary resources, such as materials, information and equipment (Ballard 2000). Besides LPS, another important development of construction planning and control based on the Lean Production philosophy is the adoption of location-based planning and control (LBPC) systems, which can be regarded as a set of planning and control techniques that makes an explicit connection of construction activities to work locations, such as line of balance (Olivieri et al., 2019), location-based management (Seppanen et al., 2010), and takt-time planning (Frandson et al., 2013). Location-based planning seeks to reach simultaneously continuous product flow and uninterrupted use of labour (Olivieri et al, 2019). By using visual tools, production goals can be easily communicated, and issues related to the amount of work-in-progress (WIP), batch size, and lack of synchronization between crews are made explicit (Nut et al., 2020). LPS and LBPC have been successfully used in many projects from different countries, either separately or together, and sometimes combined with Critical Path Method (CPM) (Olivieri et al., 2019).

There are clear complementarities between LPS and LBPC. From one hand, LPS is a planning and control approach that is mostly focussed on medium and short-term planning level, which is capable of dealing with uncertainty and complexity by involving subcontractors and crew leaders in planning and control (Ballard 2000). Due to short feedback cycles and strong emphasis on collaboration, LPS is effective for managing commitments and support learning (Viana et al., 2017). On the other hand, LBPC is mostly used for long-term planning or phase scheduling and is primarily focussed on the technical perspective of planning and control (Seppanen et al., 2015). It deals explicitly with some core production management concepts, such as takt time and synchronization, cycle time, batch size, and product- and workflows. Moreover, LBPS can naturally contribute to improve process transparency in production management. However, two main research gaps can be pointed out in the literature. Firstly, despite the growing number of companies have been jointly adopted LPS and LBPC (Olivieri et al., 2019), and several contributions from research studies that have investigated the combination of these two approaches (Seppanen et al., 2010; Kalsaas et al., 2014; Seppanen et al., 2015; Nutt et al., 2020), the complementarity between LPS and LBPC still needs to be further explained by using some core Lean Production concepts. These are pull planning, continuous (product) flow, WIP control, standardized work, and synchronization of interdependent work, which can be considered as key elements of the Lean Production Philosophy (Arogyaswamy & Simmons, 1991).

Secondly, most implementations of LPS and LBPC reported in the literature have been concerned with residential, industrial, and commercial building projects. Only a few studies have reported the implementation of those planning and control approaches in infrastructure projects (Olivieri et al., 2019; Kassab et al., 2020). Many infrastructure projects, such as roads, railways, water supply, power transmission, are often linear in nature, have some degree of repetitiveness, and are usually spread across large geographic areas (Yabushi, 2010; Mattila and Abraham, 1998). Moreover, those projects are more affected by uncertainty that building projects (Dave et al., 2013), due to variations in underground conditions, open-air work, and long-distance travelling.

This paper reports the initial results of the development and improvement of a planning and control model for linear infrastructure projects, which combines elements of LPS and LBPC. That model has been developed in a construction company in Uruguay, which has carried out several linear infrastructure projects, such as sewage systems, telecommunications, and electricity distribution. The research question that guided this investigation was: how to plan and control linear infrastructure projects based on LPS and LBPC? The development of the model considers some specific complexity features of linear infrastructure projects, such as high uncertainty, and independent linear processes spread around large urban or rural areas. The name flow-based approach for planning and control comes from the key role played by the management of both product flows and workflows in this type of project. The results presented in this paper are limited by the fact that these are based on a single case study. Therefore, only some initial insights towards the development of the model are provided.

RESEARCH METHOD

DESCRIPTION OF THE COMPANY

Stiler is a construction company founded in Uruguay in 1959, with has more than 50 years of experience on a wide range of engineering and construction projects, including residential buildings, hospitals, industrial plants, bridges, water and sewage systems, electricity distribution, and telecommunication networks. This company operates not only in Uruguay, but also in other Latin American countries, such as Peru and Paraguay. In 2021, this company had more than 40 simultaneous contracts. The Lean journey of this company started around seven years ago by the implementation of LPS, similarly to many other companies. In 2021, the company decided to extend the Lean implementation program, by including production system design (PSD), and by combining LPS with LBPC. In the first year of the program training courses were carried out, and three new pilot studies were undertaken in different projects. The case study reported in this paper was carried out in one of the pilot projects, named Red Manga, an infrastructure project that had three main types of construction work: 45 km of sewage system (including underground pipes, connection to existing homes, and inspection boxes), 7 km of storm drainage (including macro-drainage pipes and inspection boxes), pumping stations and roadworks (including paving, curbs, and small bridges). This project was in a large urban area (40 hectares) in the outskirts of the city of Montevideo, Uruguay. The Lean implementation program is still going on in 2022, and other pilot studies on linear infrastructure projects have been developed.

RESEARCH DESIGN AND IMPLEMENTATION STEPS

The main outcome of the case study developed in this investigation was the initial version of a planning and control model for infrastructure projects. The development and refinement of the planning and control model was divided into three main phases: (i) assessment of existing situation; (ii) implementation in the pilot study; and (iii) evaluation of implementation results. Table 1 presents an overview of the lean implementation program carried out by the company in 2021, in which there were three pilot studies – Red Manga was one of them. For each phase, the multiple sources of evidence used in this investigation are presented. All authors of this paper have been involved in the implementation of the planning and control model in the Red Manga project. Therefore, they were able to carry out direct observation, participant observation in planning meetings, and took part in the Lean workshops, in which the proposed model was presented and discussed by a group of managers and technical staff of the company.

Table 1: Stages of the study

<table>
<tr><th>Phase/Year</th><th>Scope of analysis</th><th>Evaluation mechanisms/Sources of evidence</th></tr>
<tr><td>Phase 1
Assessment
March 2021</td><td>Whole company</td><td>1-day site visit per project: assessment of the current planning and control systems by using an evaluation protocol
Participant observation in 1 weekly planning session for each project
4 sets of interviews for each project: including top managers, engineers, and architects
1 interview with a board member
1 interview with the operations manager
Analysis of the current company's system for planning and control</td></tr>
<tr><td>Phase 2:
Implementation
April - October 2021</td><td rowspan="2">Number of Projects: 3
Infrastructure project: 160 km lines - 5000 connections
Medium Income Residential Building: 125 dwellings
Medium Income Residential Building: 40 dwellings</td><td>Participant observation in 8 PSD meetings (4h)
4 production design system feedback meetings (2h)
Participant observation in 8 lookahead meetings (2h)</td></tr>
<tr><td>Phase 3
Results
November 2021</td><td>Participant observation in 12 weekly planning session (1.5h each)
12 site visits
8 Lean workshops (5h) involving pilot project teams</td></tr>
</table>

Phase 1 – Assessment of existing situation

The focus of Phase 1 was to assess the existing planning and control model adopted in the company, particularly organizational aspects, and analyse data from a set of existing projects. Interviews and meetings were carried out with top managers, architects/engineers, site supervisors and subcontractors. Three construction projects were visited, and the existing plans and databases were analysed. The authors also carried out direct observation in construction sites and interviewed several project and production managers.

Phase 2 – Implementation

The main activities developed in Phase 2 were: (i) development of a 40-hour training course on Lean Construction for the pilot project teams; (ii) development of a production system design model for the company, and implementation in one pilot project; (iii) development of the planning and control model, by combining LPS and LBPC, and implementation in the three pilot projects; and (iv) definition of standard practices for production system design (PSD), and production planning and control. PSD can be described as collaborative and systemic pre-construction planning exercise, as described by Barth et al. (2020). The proposed model for planning and control was built on what the company had developed in previous years and kept several existing good practices.

Phase 3 – Analysis of results

Phase 3 consisted of: (i) production of manuals containing the set of practices to be widely adopted in the company; (ii) refinement of the PSD model; and (iii) evaluation of results of the partial implementation of the proposed planning and control model.

Along the development of this Lean Implementation Program, the company decided to extend the Management and Control Department by including a team of technical staff to be directly involved in training activities, development of standardized tools, and pilot studies. Besides the pilot studies, other projects were encouraged to implement the proposed PSD and planning and control models after the end of the first year of the Lean Implementation Program, with the support of the technical staff of the Management and Control Department.

Based on the reflection on the results achieved in the Red Manga project, some initial insights were produced towards the development of the flow-based planning and control model developed for linear infrastructure projects.

RESULTS

CHARACTERISTICS OF LINEAR INFRASTRUCTURE PROJECTS

The definition of the planning and control model for linear infrastructure projects was strongly based on the type of project complexity faced in those projects, both in terms of structural complexity and uncertainty. These are:

(i) Projects are spread in large urban (e.g., sewage systems, optical fibre installation) or rural (e.g., electricity distribution) areas. Moving crews and equipment from one workplace to another is often time-consuming;

(ii) There is some degree of repetition, as processes are linear and have similar sequences of operations, but there are variations in some parameters, such as depth of excavation, position of inspection boxes, and diameter of pipes.

(iii) A high degree of uncertainty exists, mostly concerned with the lack of knowledge about underground (e.g., existing utilities, soil conditions) and neighbourhood (e.g. criminality, access) conditions, as well as with the possibility of inclement weather affecting open-air work;

(iv) Some tasks depend on the permission of client organization or local community, such as connection of public utilities to existing buildings;

(v) The number of different processes is relatively small, compared to a building project. The work of different crews can be decoupled, provided no resources are shared between them. Therefore, although uncertainty is high, the propagation of variability can be limited by dividing the work of crews in different zones and by having dedicated resources for each one; and

(vi) The reduction of WIP is mandatory for some tasks (e.g., sewage systems, stormwater drainage) as holes on the ground cannot be left open for a long time due to safety issues and possibility of rain.

All these characteristics were found in the Red Manga project. In some other linear infrastructure projects of the company, concerned with electricity and telecommunications utilities, there was an additional uncertainty related to the scope of work defined in the contract. In some of those contracts, the company plays the role of a service provider for several months: orders are placed by the client organization a short term in advance (e.g., between two and four weeks) and the company needs to plan tasks in a relatively short horizon, demanding flexibility to manage capacity as new orders arrive. By contrast, building projects are usually concentrated in a single construction site, being less affected by permits to carry out tasks, as these are usually obtained before starting the construction stage. Repetition is high, especially in residential projects, although most of them have some non-repetitive work. Many different crews are involved, and there are several sources of uncertainty, especially related to the large supply chain involved. However, several processes (e.g. internal finishings) are not affected by inclement weather. Finally, increasing work-in-progress is a major type of waste in many building projects.

EXISTING PLANNING SYSTEM

Before the beginning of the Lean Implementation Program, the Red Manga project had adopted a version of LPS devised for linear infrastructure projects. The main element of this planning system was a weekly meeting, in which both a one-week short-term plan and a three-week look ahead plan were produced. Those plans were prepared in movable boards in which sticking notes were used to plan work-packages, as shown in Figure 1. Only the most important processes were included in the plan, i.e., the ones that effectively had a linear character. Each line represents a crew, and each column defines a working-day. Most packages had durations longer than a week, and often had to be divided into sub-batches to fit the one-week horizon of the short-term plan. In each weekly meeting, the first panel is removed, and a new one is added at the end of the four-week planning horizon. This visual device clearly allows the planning meeting participants to see plans as a set of parallel workflows, so that an effort is made to keep the crews working uninterruptedly in the same processes and locations. This flow-based approach for production planning and control contrasts with the traditional activity-based approach adopted in LPS. This meeting is highly collaborative, and had the participation of the site manager, planning engineer, foreman and the supervisors of the main crews. Some small non-repetitive activities, which had low interdependence with linear processes were managed separately.

Due to the high degree of variability, and emerging information about the work zones, the sequence of batches is often changed. According to the managerial team, this does not cause much disruption in the workflow, because crews can work independently from each other, and there is usually many work-zones available to be tackled. However, a major concern of the site manager is to avoid spreading crews in workstations that are far from each other, as this can increase logistic costs and cause postponement in the delivery of completed batches. Therefore, constraint analysis was limited to the one-month horizon of lookahead planning. Most constraints considered in that plan were the ones that did not involve external stakeholders, such as design details produced by the company detail design team, demolitions and set up activities that could only be undertaken immediately before the beginning of a new work package. Colourful (orange or blue) cards, i.e. *kanbans*, were used to represent constraints of different nature in the visual plan, allowing a quick identification of the nature of the existing constraints. Long-term constraints, such as material supply, acquisition of equipment, and changes in existing working utilities, were managed separately, mostly based on the long-term plan. Traditional LPS metrics were used, such as PPC (percentage of plans completed), PPC for different crews, causes for the non-completion of work packages, overall number of constraints, and percentage of constraints removed. Productivity rates were available for different process, considering different parameters (e.g., depth of excavation, and diameter of the pipes). Those rates were used for estimating the duration of each batch of linear processes. Location-based planning was not explicit used, as the long-term plan was represented by a Gantt bar chart. However, there was some visual devices in which the project was divided by two categories of zones: (i) macro-zones, defined as delivery stages of the project by contract; and (ii) micro-zones, defined by the minimum batches for short term-plans, e.g., pipe segments that were separated by inspection boxes.

Figure 1: Movable boards used for look-ahead and weekly planning.

Contract management was strongly based on a spreadsheet in which the status of the execution of each activity was monitored (e.g., started, completed, inspected, certified by the client). Although the LPS metrics were systematically analysed in planning meetings, project progress was monitored by using the earned-value method approach. Due to the high uncertainty involved in the project, many changes in the sequence of batches had to be made.

IMPROVEMENT OPPORTUNITIES

In Phase 2 several improvement opportunities, mostly related to the explicit use of LBPC and its integration to LPS, were identified in the existing planning system. These were:

(i) Establish two levels for constraint analysis and removal. The existing one was kept for constraints that needed less than one month for removal, and a constraint control tool was proposed for long lead-time items;

(ii) Introduce visual tools for controlling rhythm, similar to flowline schedules. This is a key control related to takt-time planning (Frandson et al., 2013), enabling project progress to be assessed by the pace of each linear process;

(iii) Devise a location-based system that had four hierarchical levels, instead of only two. The criteria for defining work-zones were: (a) stages of the project defined by the contract, i.e. large batches that represent deliverables demanded by the client; (b) batches that are related to the existence of topographic features of the area, including water basins, natural barriers (e.g. roads, built facilities, slopes, etc.), which might affect the work sequence; (c) batches that are flow-oriented, i.e. define a zone that need to be delivered together for efficiency purposes; and (d) minimum short-term plan batches (which were fully listed in the spreadsheet of contract deliverables). Table 2 summarizes the description of each type of work-zone;

(iv) For each hierarchical level, a matrix for controlling the production status, like the one proposed by Sacks et al. (2009), was created. This matrix allows priorities to be made in terms of batches to be finished first, prioritize processes, including those that appear as critical, as well as to control each task status - whether the task is completed, in progress, stopped or not released (not started). Then, more emphasis could be given to the analysis and control of WIP, uncompleted batches, and distances between workstations. Therefore, the production status matrix can be considered as a tool for pulling production, considering the concept of pull proposed by Hop and Spearman (2004): work is released according to system status rather than based on customer demand;

(v) Create check-in and check-out control in each work zone, based on the minimum batch defined in the short-term plan. The database of project deliverables can be adapted and used for that purpose, enabling not only a control of project progress that is consistent with PPC, but also the easy calculation of metrics on cycle time variation and WIP; and

(vi) Based on the control of WIP, two project progress curves can be produced, one that considers all tasks completed and another that only considers completed batches.

Moreover, some minor improvements related to the implementation were made, including: (i) making explicit in the plan a backlog of made-ready tasks, (ii) emphasize learning opportunities in planning meetings by discussing the causes for the non-completion of packages and deviations in relation to the planned rhythm.

Complementing Table 2, Figure 2 presents work-zones for the four levels of the location-based system: the work-zones of a lower hierarchical level are always a subdivision of a higher level. At level 1, there were 5 work-zones, while at Level 2 there were 12. At Level 3, the number of work-zones was 38 – these should play a key role in the planning decisions regarding WIP and logistics. Each Level 3 work-zones had typically 60 to 80 sewage pipe stretches. Altogether there were 1150 batches for short-term planning. Figure 3 presents some additional details on the production status matrix for levels 3 and 4. It illustrates how this tool allows a visual representation of the production units where crews are working. It also provides an overview of the project progress, pointing out problems related to the excessive amount of WIP or unfinished work. Based on the development of tools for managing LBPC, a model for long-term planning was also proposed for the company. In this model, the main elements for long-term plans are the location-based system, a graph for controlling the pace of linear processes, and the sequence of work-zones at the Level 3. No detailed sequence for Level 4 work-zones should be produced due to the high uncertainty involved in sequence of minimum work batches.

Table 2: Hierarchical structure of the location-based system

Level	Base-Unit	Amount	Types	Variables considered
Level 1	UN-L1	Total of 5 UB-L1	Contract small projects	Contracting conditions
Level 2	UB-L2	Total of 12 UB-L2	Physical mapping	Topography, basins
Level 3	UB-L3	Total of 38 UB-L3	Completed batch	Workflow, sections
Level 4	Section	40-60 sections per UB-L3. Total 1150 sections	Work batch	Pipe section

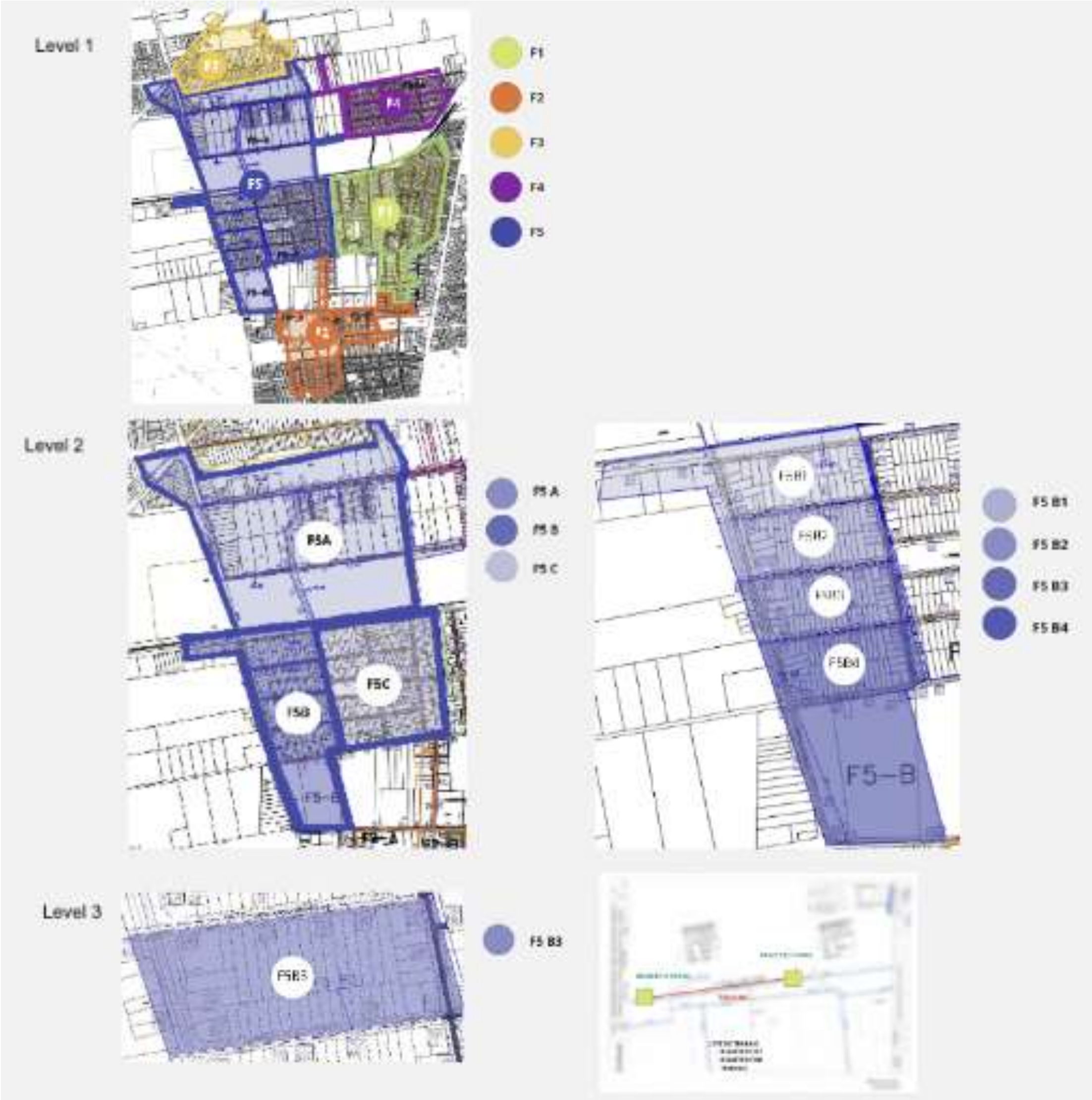

Figure 2: Hierarchical structure of location-based control levels

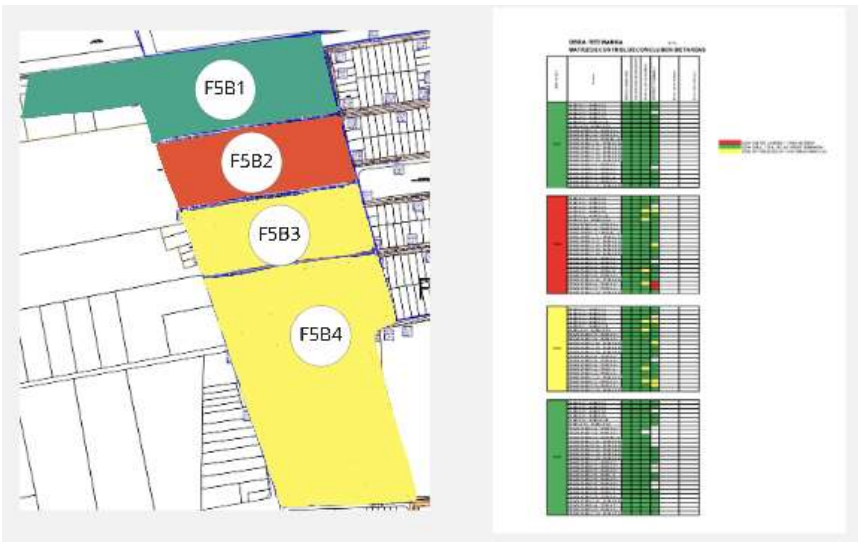

Figure 3: Transition from Level 3 to Level 4 location-based control

Some of the improvement opportunities identified in the case study have resulted in changes in the project planning and control system (e.g. graph for rhythm control, backlog of made-ready tasks), while others will be only implemented in future projects (e.g. the production status matrix, check-in and check-out control, long-term systematic constraint analysis). Figures 4 present a location-based metric that have been developed for future projects, named project progress considering only complete batches. Despite those limitations, some of the production metrics adopted have provided evidence of improvements in project performance: (i) reduction in PPC variability, (ii) increase in project progress (18% above target), increase in profit margin (0,4%).

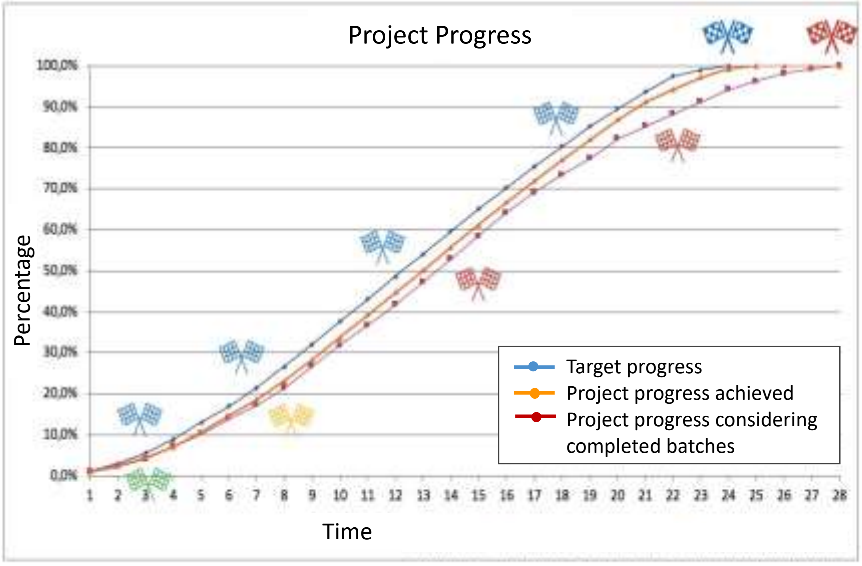

Figure 5: Example of graph for project progress control for complete batches.

DISCUSSION AND CONCLUSIONS

The flow-based planning and control model proposed for linear underground infrastructure projects has some innovations, when compared to other models devised for building projects:

(i) There is a good integration of LPS and LBPC. From one hand, LPS plays a key role in dealing with uncertainty and structural complexity by establishing hierarchical planning levels, using collaborative decision making, and creating a backlog of made-ready activities. This can be understood as a hybrid (pull-push) planning and control model, as there is clearly a mechanism for pulling production by triggering work based on the status of the system, as suggested by Hopp & Spearman (2004). On the other hand, LBPC explicitly deals with several concepts that play a key role in the Lean philosophy, such a batch size, cycle time, synchronization, and work-in-progress control.

(ii) Based on the production status control tool and on other visual control devices, the status of the system can be monitored, and this information can be used in LPS collaborative planning meetings for pull production;

(iii) Similarly to LPS, LBPC is also hierarchically organized in order to deal with the high uncertainty involved in the sequence of batches. Moreover, the proposed model strongly emphasizes to location-based control, by using several location-based metrics, such as batch adherence, cycle time variation, project progress considering complete batches, and unnecessary work-in-progress. Based on the maps of the urban or rural areas where those projects are being built, other metrics could be devised, such as average distance between workstations, which could be used as indirect measurement of logistic costs.

(iv) Dividing constraints into categories also seems to be an important mechanism for making lookahead planning more effective. Some of the constraints should be dealt clearly by site managers, e.g. by using kanban cards, while other require improvements in the integration with other sectors of the organization or external supply chain members. This type of approach for medium-term planning level has already been suggested by Brady et al. (2019).

(v) Visual management plays a key role in the implementation of the model, as a mechanism for copying with the type of complexity that exist in linear underground infrastructure projects. It is very important to visualize workflows that are longer that the short-term planning horizon, operational constraints that need to be removed within the 4-week window, deviation in the rhythm of linear processes, and the zones that must be prioritised in terms of completing batches at different hierarchical levels.

In the following steps of this investigation, other improvement opportunities will be explored, including the implementation of the standardized work approach for synchronizing processes and increasing efficiency, and the use of digital technologies for status control, including the use of performance dashboards. There are also some future opportunities that can be explored in the development of planning and control for infrastructure projects. Those projects are much more diverse than building projects. They might combine linear and non-linear work, underground, and surface activities, highly mechanised and manual work, etc. Therefore, companies that operate in that segment of the construction industry need planning and control models that are flexible to cope of those differences but based on the same fundamental core Lean concepts and principles.

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