KEY LAST PLANNER SYSTEM METRICS
TO ASSESS PROJECT PERFORMANCE IN
HIGH-RISE BUILDING AND INDUSTRIAL
PROJECT

DANIEL EDUARDO PÉREZ MARTÍNEZ

Thesis submitted to the Office of Research and Graduate Studies
in partial fulfillment of the requirements for the Degree of
Master of Science in Engineering

Advisor:
LUIS F. ALARCÓN CÁRDERNAS

Santiago de Chile, December, 2021

© 2021, DANIEL PÉREZ MARTÍNEZ
KEY LAST PLANNER SYSTEM METRICS TO ASSESS PROJECT PERFORMANCE IN HIGH-RISE BUILDING AND INDUSTRIAL PROJECT

DANIEL EDUARDO PÉREZ MARTÍNEZ

Members of Committee:

LUIS F. ALARCÓN CÁRDENAS
MANUEL CARPIO MARTÍNEZ
RODRIGO HERRERA VALENCIA
ÁVARO SOTO ARIAZA

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Santiago de Chile, December 2021
Keep pushin’
ACKNOWLEDGEMENTS

First at all, I want to thank to my family for its love, support and company in this long but very important journey. Sometimes life impacts your plans and put you in different situation with no other way than push forward and keep going. Thanks for been that voice who help you to be a strong person and give me reasons for not to quit.

Also, I want to thank the other half of my family: my friends. From them who still with me before this adventure to the last one who appears in my life such as a surprise. Thank guys for believing in me, for been the place which I can find support words, a drink or a shoulder where I can cry without feeling ashamed.

Today, I close one of the most important stages of my life. Thanks to all the professors who taught me different skills to prepare my professional career. Thanks to Sergio Vera, Hernán de Solminihac, Manuel Carpio, Álvaro González and, to my advisor, Luis Fernando Alarcón for let me be their teacher assistant in different courses. To Jorge Muñoz-Gama, who helped and pushed me to publish my first conference paper. And last, but not least, thanks to Camilo Lagos and GEPRO for been a continuous support in my research.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................ IV

TABLE OF CONTENTS .......................................................................................................... V

LIST OF FIGURES ................................................................................................................ VII

LIST OF TABLES ................................................................................................................... VIII

ABSTRACT .......................................................................................................................... IX

RESUMEN ........................................................................................................................... X

STRUCTURE OF THE THESIS ........................................................................................... XI

1. INTRODUCTION ............................................................................................................. 1

  1.1 GAPS IN TRADITIONAL CONSTRUCTION MANAGEMENT SYSTEMS ......................... 1

  1.2 THE LAST PLANNER SYSTEM ® .............................................................................. 4

  1.3 LIMITATIONS IN THE LAST PLANNER SYSTEM ® ADOPTION AND CURRENT RESEARCH ......................................................... 6

2. SUMMARY OF CONDUCTED WORK ............................................................................. 9

  2.1 RESEARCH OPPORTUNITIES .................................................................................. 9

  2.2 HYPOTHESIS ......................................................................................................... 10

  2.3 OBJECTIVES ......................................................................................................... 10

    2.3.1 General objective .............................................................................................. 10

    2.3.2 Specific objectives ............................................................................................ 10

  2.4 METHODOLOGY ..................................................................................................... 11

3. DATABASE DESCRIPTION ........................................................................................... 12

4. JOURNAL ARTICLE ........................................................................................................ 14

  4.1 ABSTRACT ............................................................................................................. 14

  4.2 INTRODUCTION ..................................................................................................... 15

  4.3 RESEARCH METHODOLOGY ............................................................................. 18

  4.4 LITERATURE RESEARCH METHODOLOGY ......................................................... 21
4.5 COLLECTION OF INFORMATION .................................................................................21
4.6 PROJECT TYPE COMPARISON ..................................................................................24
4.7 ASSESSMENT OF THE CORRELATIONS BETWEEN THE METRICS ......................25
4.8 ASSESSMENT OF THE DIFFERENCES BETWEEN THE HIGH AND LOW SCHEDULE PERFORMANCE PROJECTS......26
4.9 RESULTS AND DISCUSSION ..................................................................................28

4.9.1 Literature research findings.................................................................................28
4.9.2 Differences between high-rise and industrial construction projects ..................35
4.9.3 Assessment of correlations between LPS and performance metrics ....................36
4.9.4 Analyses of the differences between the projects with high and low schedule performance outcomes .................................................................................................................44

4.10 CONCLUSIONS .....................................................................................................49
4.11 DATA AVAILABILITY STATEMENT .......................................................................51
4.12 ACKNOWLEDGMENTS ..........................................................................................51
4.13 REFERENCES: ........................................................................................................52

5. CONCLUSIONS ......................................................................................................... 61
6. REFERENCES ............................................................................................................62
7. APPENDIX ..................................................................................................................71

7.1 DECISION ON MANUSCRIPT MS COENG-10840R2..............................................72
7.2 CONFERENCE PAPER SCCC 2018: “CONSTRAINT BAG PROCESS MODEL: A PROCESS MINING APPROACH TO LEAN CONSTRUCTION” ............................................................................................................73
LIST OF FIGURES

Figure 1.1 Earned Value Method curves example (Adapted from de Solminihac T. & Z., (2020)) .................................................................2
Figure 1.2 Summary of the Last Planner System (Adapted from Rodríguez Fernández et al., (2011)) ................................................................................................................................................5
Figure 4.1 Relationships between LPS components in high-rise sample ............37
Figure 4.2 Correlations between SPI Average, PPC Average, PCR Average with Final SPI..................................................................................................................................................38
Figure 4.3 Relationships between LPS metrics in Industrial sample .................40
Figure 4.4 Correlation between Constraints Per Week (CPW) and Short-term periods with Corrective Actions ..........................................................................................................................42
LIST OF TABLES

Table 3.1 Scope of use of LPS across execution........................................12
Table 3.2 Collection of minimum LPS required information .......................13
Table 4.1 Description of the LPS and performance metrics ........................20
Table 4.2 Differences between high-rise and industrial construction projects ......35
Table 4.3 Correlations between metrics in high-rise building projects ..............39
Table 4.4 Correlations between metrics in industrial construction projects .........43
Table 4.5 Differences between high-rise building performance groups ............45
Table 4.6 Differences between industrial construction performance groups .........48
ABSTRACT

The Last Planner System® (LPS) establishes short cycles of planning and control, comprising Lookahead Planning, the make-ready process, short-term planning commitments, identifying Reasons for Noncompletion and implementing corrective actions. Most LPS research has covered longitudinal case studies, but quantitative transversal research is needed to determine the impact of key LPS processes in performance. The researchers aimed to determine the relationships between LPS components and project performance. 23 metrics were established to evaluate 6 components and 253 possible correlations between them. The author assessed information from 255 projects and found 131 projects, in 5 categories, with sufficient information to construct the metrics. Two categories had sufficient sample sizes, which produced a sample of 71 high-rise building (HR) and 28 industrial construction (IC) projects. Each sample was assessed separately to test the correlations and the project categories were compared to determine statistically significant differences. Then, the projects were classified according to their schedule performance outcome, using a clustering algorithm, to find differences between high- and low-performance projects. Statistically significant correlations between the 6 components were found in both samples, 6 metrics presented statistically significant differences between high- and low-performance in HR projects and 1 in IC projects.

Keywords: Last Planner System, quantitative analysis, k-means, construction projects, lean construction, industrial projects, high-rise buildings projects, construction performance
RESUMEN

El Sistema del Último Planificador o Last Planner System (LPS) presenta una metodología de planificación y control de proyectos basado en la planificación del corto plazo, la preparación del trabajo ejecutable, el cumplimiento de compromisos, identificación de causas de no cumplimiento y la implementación de acciones correctivas. Investigaciones pasadas se basan principalmente en casos de estudios longitudinales, pero la realización de un análisis cuantitativo transversal es necesario con el objetivo de determinar el impacto de las principales métricas de la metodología. La investigación busca determinar relaciones entre los componentes de LPS y el éxito de los proyectos. 23 indicadores fueron construidos para evaluar 6 componentes consiguiendo más de 250 correlaciones diferentes. Para esto, se obtuvo información de 255 proyectos en donde 131 de ellos, clasificados en 5 categorías, contenían información suficiente para construir las métricas propuestas. Dos de las cinco categorías cumplieron con el tamaño muestral mínimo, lo que se redujo a la obtención de 71 proyectos de edificación en altura (HR) y 28 proyectos de construcción industrial (IC). Cada muestra fue estudiada de forma separada para testear las diferentes correlaciones, y fueron comparadas para encontrar diferencias estadísticamente significativas. Luego, los proyectos fueron clasificados de acorde a su desempeño respecto a la planificación original, usando un algoritmo de obtención de clústeres, para encontrar diferencias entre proyectos con alto y bajo desempeño. Se encontraron diferentes correlaciones estadísticamente significativas entre los 6 componentes en ambos tipos de proyectos, 6 indicadores presentaron diferencias significativas entre proyectos con un alto y bajo desempeño en proyectos de edificación en altura y 1 en proyectos industriales.

Palabras clave: Last Planner system, Sistema del último planificador, análisis cuantitativo, k-medias, proyectos de construcción, construcción sin pérdidas, proyectos industriales, edificación en altura, desempeño construcción
STRUCTURE OF THE THESIS

The thesis document is organized in the following chapters:

1. **Introduction:** This introductory chapter presents the gaps between the traditional construction management systems compared to the Last Planner System ®. Additionally, an extended literature review of the LPS’ state of art is presented.

2. **Summary of conducted work:** This chapter presents research opportunities identified from the state of the art. It also includes the proposed hypothesis, objectives, and methodology of the thesis.

3. **Database description:** This section contains a brief description of the database used in the journal article presented later.

4. **Journal Article:** Chapter 3 presents an article, submitted to the Journal of Construction Engineering and Management. The article presents a quantitative analysis for different construction projects and determine key metrics to assess the performance success. The article has already passed two rounds of reviews and is currently being prepared for an editor only review, very close to final acceptance.

5. **Conclusions and recommendations:** This chapter presents the conclusions of this research and recommendations for future research.

6. A conference paper is indexed at the end of this manuscript. This paper was developed during the initial exploratory stage of the research and reports the use of process mining to explore the data available for LPS in the database.
1. INTRODUCTION

1.1 Gaps in traditional construction management systems

Construction is a project-based industry where multiple stakeholders depend on the delivery of new or significantly improved infrastructure. Projects are unique complex endeavors which involve overlapping activities with long scopes, such as engineering and design, development, resource provisioning, building, management and commissioning (Taylor & Ford, 2006). Dynamic factors such as requirement or design changes, uncontrollable conditions and varying performance across the multiple stakeholders, cause uncertainty in the project plan and variability in execution, which can lead to schedule and budget deviations (Budi et al., 2019). Traditional analytic management (TAM) systems like the Critical Path Method (CPM) and Earned Value Management (EVM) have been used systematically since the 1970’s, to plan and control projects (Damnjanovic & Rispoli, 2014; Kelley & Walker, 1959; Y.-W. Kim & Ballard, 2010; Koskela et al., 2014; Olivieri et al., 2019). These traditional systems use sequential constraints between tasks to determine the most critical route for the project completion, employ result-oriented techniques to control the state of the project across execution, and establish corrective actions to prevent significant deviations in the critical route (Abdel Azeem et al., 2014; Kelley & Walker, 1959). Nonetheless, these methods have presented several limitations to prevent deviations that have been addressed by researchers over the past decades (Abdel Azeem et al., 2014; Williams, 2003).

TAM limitations include schedule rigidity, uncertainty induction, failing to prevent deviations before they significantly impact the schedule and failing to detect their source or origin from a process perspective (Y.-W. Kim & Ballard, 2010). At the planning stage, TAM systems divide work into detailed groups of activities, which are planned and optimized separately, often leading to suboptimal resource allocation and work
prioritization (Nikhil & Hedao, 2017). The use of time slacks allocated inside the planned duration of each task can affect the sequential links between activities and lead to misrepresentations of the critical route (Nikhil & Hedao, 2017). Also, authors have found that most projects use traditional bar-chart planning methods to develop their schedules and obtain the critical route as a result, rather than using systems such as CPM to determine the best possible path of execution based on activity dependencies (Abdul-Rahman et al., 2006). The use of highly detailed schedules with hidden slacks and multiple dependencies can hinder the systematic update of the plan and detriment proactive planning (Abdel Azeem et al., 2014). In addition, the time slacks incorporated into each task can hide subsequent deviations until a critical task is significantly affected.

![Figure 1.1 Earned Value Method curves example (Adapted from de Solminihac T. & Z., (2020))]({#})

TAM systems also present limitations in project control. First, they rely on accumulative result-oriented indicators, which add the value earned by multiple activities into a single result indicator, which is compared to the planned value to obtain an
accomplishment ratio, like the Schedule Performance Index (SPI) and Cost Performance Index (CPI), in addition to variance and deviation metrics. These metrics are used to estimate the project outcome based on the actual performance. Three control limitations have been discussed in literature: First, the use of accumulative metrics can hide variability since the variations are compensated when multiple tasks are aggregated (Abdul-Rahman et al., 2006). Second, accumulative indicators overestimate the impact of deviations at early stages of execution and underestimate variations at late stages since the relative weight of the work decreases as the metric represents a larger portion of the project scope (Hughes et al., 2004). Third, result-oriented metrics detect deviations after the fact and estimates made based on these performance measurements lack key information regarding processes such as planning, work preparation and continual improve (Sarhan & Fox, 2013b).

Authors have used multiple approaches to surpass the limitations of traditional management systems. Several studies have addressed the keys to project success, how to evaluate it and which metrics should be used to assess performance based on different success definitions (Abdel Azeem et al., 2014; Batselier & Vanhoucke, 2015; Chen et al., 2016). Also, researchers have proposed process-oriented and leading indicators to complement traditional management metrics, allow the detection of deviation sources and improve performance assessment (Ballesteros-Pérez et al., 2019; Chen, 2014; Hamzeh et al., 2019). In addition, multiple contributions have been made to traditional control methods such as EVM, to establish performance criteria (Y.-W. Kim & Ballard, 2010) and improve prediction accuracy (Abdel Azeem et al., 2014). Also, multiple efforts have allowed to determine critical causes of project deviation (Pajares & López-Paredes, 2011), key aspects for project success (Bryde et al., 2018) and develop predictive models which use them to estimate project outcome based on its characteristics, conditions and actual performance (Chen et al., 2016; Iyer & Banerjee, 2016; Votto et al., 2020). Although, recent research has found that projects rely mostly on basic means of planning and control, such as simple Gantt scheduling and basic result-oriented control metrics (Galloway,
2006; Olivieri et al., 2019; Sarhan & Fox, 2013b). These studies also have showed why projects only use basic metrics to control them. This underutilization in control methodologies is due to the project’s complexity, the lack of time and the lack of understanding of its value. These are some of the key reasons why projects have not adopted such contributions (Sarhan & Fox, 2013b).

The Lean Construction community has proposed an alternative approach to project management, called the Last Planner System, based on the implementation of a systematic planning and control process and the use of simple process-oriented metrics to trace project performance across execution (Ballard, 1993; Hamzeh et al., 2019). LPS relies on the assessment of work preparation efficiency, compliance in short-term execution and variability to evaluate the key processes involved in schedule and budget accomplishment (Ballard & Howell, 1994). Also, it proposes a systematic scheduling method in which the required work is pulled instead of following a static deterministic critical route and, hence, it promotes dynamic schedules which can adapt better to the changes in conditions, priorities or work requirements (Ballard, 2000; Ballard & Howell, 2003b).

1.2 The Last Planner System ®

The Last Planner System ® of production control (LPS) has been implemented in many countries since its proposal, over the past 27 years (Ballard & Howell, 2003a; Daniel et al., 2014). LPS is based on the Lean Construction philosophy and promotes workflow stabilization to reduce time and resource wastes and improve compliance during execution. It proposes the management of commitments at an operational level to ensure that work is planned and assigned properly, and the management of constraints to eliminate issues that could prevent compliance with the work committed (Ballard, 1994). Its implementation has allowed to improve short-term compliance, work productivity (Ballard & Howell, 1994), minimize workflow variability (Ballard & Howell, 1994; Nikhil & Hedaoo, 2017), improve schedule performance (Alarcón & Letelier, 2014;
Ballard & Tommelein, 2016; Indira & Jyothisna, 2017) and reduce cost deviations (Daniel et al., 2014; Fernandez-Solis et al., 2013). In addition, research has shown significant benefits in communication, teamwork, understanding of the project and workforce involvement in management (Castillo et al., 2018; Koskela et al., 2010; Tayeh et al., 2019).

![Figure 1.2 Summary of the Last Planner System (Adapted from Rodríguez Fernández et al., 2011)](image)

LPS is based on five principles (Ballard et al., 2009): First, the tasks should only be planned in increasing detail when its execution time approaches, to allow for schedule flexibility and avoid uncertainty induction. Second, tasks should be planned together with the direct responsible to ensure the correct assessment of resources and needs. Third, upcoming work should be pulled by removing constraints in advance to prepare work. Fourth, commitments should be reliable, and compliance should be continuously assessed. Finally, the project team should focus on continuous improvement by systematically implementing corrective actions to remove sources of non-compliances. Following these principles is secured by the implementation of the five LPS components: (1) phase planning, (2) lookahead planning, (3) managing a workable backlog of tasks, (4) managing short-term commitments of execution and (5) taking corrective actions to remove RNCs (Ballard, 2000; Ballard & Tommelein, 2016). The systematic use of these
components establishes a virtuous cycle of sound work preparation, pulling work in advance, improving short-term compliance and removing barriers which detriment productivity and schedule performance (AlSehaimi et al., 2014; Y.-W. Kim, 2019; Tayeh et al., 2019).

For this purpose, several metrics have been developed as the Percent of Constraint Removed (PCR) which measures the proportion of the effectiveness in the constraints removal process in the work preparation (Y.-W. Kim, 2019). Also, metrics such as the Percent Plan Complete (PPC) are used to control the ratio of effectively completed tasks. The problems detected are reported as Reasons for Non-Compliance (RNC) to measure the potential impact in the project schedule and to take Corrective Actions (CA) for the future (Ballard & Tommelein, 2016)

1.3 Limitations in the Last Planner System ® adoption and current research

Despite the multiple benefits before implementing the LPS, several barriers in the adoption of the methodology such incomplete measurement in the PPC index and underutilization of lookahead plans have been discovered (Perez & Ghosh, 2018). Also, the underutilization of different data collected in the whole life of the projects (Fernandez-Solis et al., 2013), the lack in the search of RNC (Ballard & Tommelein, 2016) or the deficiency of lookaheads plans implementation (Gao & Low, 2014) do not allow to assess the benefits of LPS accomplishment.

These barriers are mainly caused by the partial adoption of the methodology and include limitations such as the exclusive focus on improving short-term execution metrics such as the PPC (Perez & Ghosh, 2018), underutilization of lookahead plans to identify new constraints and plan their removal (Gao & Low, 2014), lack of assessment of the state of the WB and the availability of work that should be committed in the short-term plan (Lagos et al., 2017), lack of emphasis on identifying and registering the root causes of RNCs for the purpose of obtaining valuable information on the most recurring problems
(Dave, Hämäläinen, Kemmer, et al., 2015) and the underutilization of different data collected across the project execution scope to detect trends that can lead to failure and opportunities to revert them (Fernandez-Solis et al., 2013). Additionally, deficiencies in the registration of the detailed information from key elements such as constraints and RNCs prevent the use of these sources of information to assess their impact on the propagation of variability and deviations and use process-oriented metrics to control them (Ballard & Tommelein, 2016). Hence, partial LPS implementations not only reduce performance improvements but also prevent more thorough assessments of the benefits of LPS and the relationship between the LPS components and the key project management processes (Ballard & Tommelein, 2016).

In addition, even though research has shown that the use of IT support can lead to improvements in the collection and use of critical LPS information (Lagos et al., 2016), in-depth analyses of LPS implementations in projects using IT support systems have still found grounds for improvement in elements such as constraint management for work preparation and implementation of CAs to prevent recurring sources of RNCs (Lagos et al., 2019). In fact, Cisternas (2013) discovered that projects that used a specific IT support system based on LPS used less than half of its capabilities, with diminished use of components such as the management of the WB obtained from the lookahead plan, controlling the work preparation by assessing the constraints management metrics such as the PCR, and implementing and registering CAs linked to specific types of RNCs, among others. These limitations have been attributed to excessive focus on the short-term scope, difficulty in registering information due to time restrictions, lack of widely known metrics to assess such components and difficulty in observing quantitative evidence of their impacts on performance and continual improvement (Alarcón et al., 2008; Dave et al., 2015). Therefore, the proposition, thorough understanding and wide adoption of process-oriented LPS metrics aligned with the basic concepts of the Lean Construction and components of the LPS methodology are needed to improve the LPS implementation and
to attain its benefits in project management and execution (Alarcón et al., 2005; Lagos et al., 2016, Dave et al., 2015).
2. SUMMARY OF CONDUCTED WORK

2.1 Research Opportunities

Researchers have found that the partial adoption of LPS has been caused by (1) the difficulty of assessing the effectiveness and efficiency of components, such as work preparation or learning from recurrent Reasons for Noncompletion (RNCs) to prevent sources of deviation, (2) the lack of understanding of the impact of processes such as lookahead planning to improve performance, and (3) the lack of quantitative metrics to assess the performance in key LPS processes, such as work preparation and the management of Corrective Actions (Bajjou & Chafi, 2018; Sarhan & Fox, 2013). The recent development of information technology systems to support LPS implementation (Lagos et al., 2019) has allowed the collection and use of more quantitative data to assess work preparation and RNC removal. However, some authors have argued that more quantitative analysis is required to demonstrate the impact on project performance (Dave, Hämäläinen, Kemmer, et al., 2015), determine the relationships to traditional and LPS management metrics (Alarcón et al., 2014), and propose quantitative standards to assess performance with regard to the implementation of these components (Lagos & Alarcón, 2020).
2.2 Hypothesis

Several process oriented LPS metrics can be related with the outcome results in project performance.

2.3 Objectives

2.3.1 General objective

This study aims to understand the relationship between LPS process-oriented metrics and the schedule performance metrics for construction projects.

2.3.2 Specific objectives

1. Analyze the main differences in LPS process-oriented performance between two kind of construction projects (high-rise building and industrial construction)
2. Determine the relationships between process oriented LPS metrics and performance metrics in high-rise buildings and industrial projects
3. Analyze the key differences in the LPS process-oriented metrics between projects with high and low schedule performance outcomes
4. Analyze the relationships between the 6 LPS components
2.4 Methodology

The methodology is divided in five sequential phases with the purpose to address the objectives of this investigation

i. Literature Review: in this phase, the principal objective was to determine gaps in transversal quantitative studies and different results from quantitative and case studies.

ii. Data Collection: then, a standardized quantitative information from GEPRO’s software development IMPERA was obtained. The database includes more than 400 projects, with different use of the software’s features. The projects were classified based on the information recorded on the software to obtain a clean database with 256 projects. All of them were analyzed to obtain a final database of 99 projects with a complete use of the software in its entire lifetime. With this information, a 23 metrics guideline was constructed for all the projects obtained.

iii. Data Analysis: in this stage, with the data collected, all the characteristics for each project was analyzed to determine type of project, the 23 metrics average and standard deviations, and principal differences of this metrics between the project’s categories.

iv. Correlations: for all the projects, a linear regression analysis was performed to find statically differences between he 23 metrics in each sample (type of project).

v. Performance Analysis: and finally, each kind of project was analyzed used k-means to determine two groups based on their final schedule performance. Then, a complete statistically significant different analysis was made between the groups to characterize each sub sample.
3. DATABASE DESCRIPTION

The database includes a sample of 255 construction projects with a minimum planned duration of 12 weeks, an average planned duration of 52 weeks and a standard deviation of 26 weeks. They registered information, in average, from 7.1% planned progress and 8.4% actual progress, until 85.9% planned progress and 80.6% actual progress, which means that, in average, the projects registered approximately 72% of the actual execution scope and 79% of the planned scope.

Additionally, the number of projects which started registering data from earlier than 1%, 5% and 10% progress, and until at least 90%, 95% and 99% progress, measured by the (1) planned baseline and (2) actual progress were calculated to understand consistency in the use of the software. Table 3.1 presents the results, which indicate that only 69% of the projects register LPS information until at least the point of planned completion, just 51% of the sample registered actual completion, 41% registered the entire planned scope and only 16% of the sample registered the entire execution scope. In addition, 39% to 65% of projects start registering LPS information after the project had already started and reached an overall progress greater than 1%. In fact, between 21% and 33% of the projects started registering LPS data after surpassing 10% execution progress.

<table>
<thead>
<tr>
<th>Single criteria</th>
<th>Planned progress (Baseline)</th>
<th>Actual progress (Masterplan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earlier than 1%</td>
<td>61%</td>
<td>35%</td>
</tr>
<tr>
<td>Earlier than 5%</td>
<td>76%</td>
<td>65%</td>
</tr>
<tr>
<td>Earlier than 10%</td>
<td>81%</td>
<td>75%</td>
</tr>
<tr>
<td>At least 99%</td>
<td>69%</td>
<td>51%</td>
</tr>
<tr>
<td>At least 95%</td>
<td>76%</td>
<td>58%</td>
</tr>
<tr>
<td>At least 90%</td>
<td>79%</td>
<td>67%</td>
</tr>
<tr>
<td>Combined criteria</td>
<td>Planned progress (Baseline)</td>
<td>Actual progress (Masterplan)</td>
</tr>
</tbody>
</table>

Table 3.1 Scope of use of LPS across execution
Finally, the percent of short-term periods in which the projects had registered schedule accomplishment, short-term compliance, and constraint management information – represented by the number of SPI, PPC and PCR registrations, respectively –, compared to the number of short-term periods in each project were calculated. The Table 3.2 presents the results and is possible to observe that most of the projects registered at least the required information to assess schedule accomplishment, while only 70.6% registered short-term commitments in 90% or more of their short-term periods and only 48.2% managed constraints in more than half of the short-term periods registered. The results were almost equivalent when only the projects which registered the complete planned scope were assessed.

<table>
<thead>
<tr>
<th>% Short-term periods</th>
<th>% Projects with SPI</th>
<th>% Projects with PPC</th>
<th>% Projects with PCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% or more</td>
<td>100,0%</td>
<td>94,5%</td>
<td>48,2%</td>
</tr>
<tr>
<td>70% or more</td>
<td>98,8%</td>
<td>89,8%</td>
<td>31,4%</td>
</tr>
<tr>
<td>80% or more</td>
<td>98,4%</td>
<td>82,4%</td>
<td>22,0%</td>
</tr>
<tr>
<td>90% or more</td>
<td>98,0%</td>
<td>70,6%</td>
<td>9,8%</td>
</tr>
<tr>
<td>95% or more</td>
<td>97,6%</td>
<td>54,1%</td>
<td>5,5%</td>
</tr>
<tr>
<td>99% or more</td>
<td>96,9%</td>
<td>31,4%</td>
<td>2,4%</td>
</tr>
</tbody>
</table>
4. JOURNAL ARTICLE

KEY LAST PLANNER SYSTEM METRICS TO ASSESS PROJECT PERFORMANCE IN HIGH-RISE BUILDING AND INDUSTRIAL PROJECT

Daniel Pérez¹, Camilo Lagos² and Luis Fernando Alarcón³

¹Master of Science student, Dept. of Construction Engineering and Management, Pontificia Universidad Católica de Chile
²Corresponding author, Ph.D. student, Dept. of Construction Engineering and Management, Pontificia Universidad Católica de Chile
³Professor, Dept. of Construction Engineering and Management, Pontificia Universidad Católica de Chile

4.1 Abstract

The Last Planner System® (LPS) establishes short cycles of planning and control, comprising Lookahead Planning, the make-ready process, short-term planning commitments, identifying Reasons for Noncompletion and implementing corrective actions. Most LPS research has covered longitudinal case studies, but quantitative transversal research is needed to determine the impact of key LPS processes in performance. The researchers aimed to determine the relationships between LPS components and project performance. 23 metrics were established to evaluate 6 components and 253 possible correlations between them. The authors assessed information from 255 projects and found 131 projects, in 5 categories, with sufficient information to construct the metrics. Two categories had sufficient sample sizes, which produced a sample of 71 high-rise building (HR) and 28 industrial construction (IC) projects. Each sample was assessed separately to test the correlations and the project
categories were compared to determine statistically significant differences. Then, the projects were classified according to their schedule performance outcome, using a clustering algorithm, to find differences between high- and low-performance projects. Statistically significant correlations between the 6 components were found in both samples, 6 metrics presented statistically significant differences between high- and low-performance in HR projects and 1 in IC projects.

4.2 Introduction

Construction is a project-based industry in which multiple stakeholders depend on the delivery of new or significantly improved infrastructure (Yang et al., 2018; Yang & Shen, 2015). Projects are unique complex endeavors that involve overlapping activities, long scopes and dynamic factors, which can lead to schedule and budget deviations (Budi et al., 2019; Taylor & Ford, 2006). Traditional result-oriented management systems, such as the Critical Path Method (CPM) and Earned Value Management (EVM), have been used since the 1950s to plan and control projects (Damnjanovic & Rispoli, 2014; Kelley & Walker, 1959; Y. Kim & Ballard, 2010; Koskela et al., 2014; Olivieri et al., 2019), but they present several limitations in preventing project deviations. These limitations include schedule rigidity caused by inappropriate use of sequential constraints, uncertainty induction due to detailed planning for long scopes and the incorporation of hidden time slacks between tasks, as well as failure to detect sources of deviation before they impact the schedule or budget due to the use of result-oriented metrics (Abdel Azeem et al., 2014; Y. Kim & Ballard, 2010; Nikhil & Hedao, 2017; Williams, 2003). Although several contributions have been made to surpass the limitations of traditional management systems, most projects rely on basic, result-oriented means of planning and control, and these improvements have not been adopted into common practice due to complexity, lack of understanding or the effort required to implement them (Galloway, 2006; Olivieri et al., 2019; Sarhan & Fox, 2013b).
The Lean Construction community has proposed an alternative approach to project management, called the Last Planner System® of Production Control (LPS), which is based on the implementation of a systematic planning and control process and the use of simple process-oriented metrics to trace the project performance across execution (Ballard, 1993; Hamzeh et al., 2019). LPS relies on the assessment of work preparation efficiency, compliance in short-term execution and variability to evaluate the key processes that are involved in schedule and budget accomplishment (Ballard & Howell, 1994). Additionally, it proposes a systematic scheduling method in which the required work is pulled instead of following a static deterministic critical route, and hence, it promotes dynamic schedules that can adapt better to changes in conditions, priorities or work requirements (Ballard, 2000; Ballard & Howell, 2003b).

The benefits of LPS implementation have been covered by multiple researchers over the past 27 years (Ballard & Howell, 2003a; Daniel et al., 2014; Lerche et al., 2020). They include improvements in short-term compliance (Ballard & Tommelein, 2016), work productivity (Ballard & Howell, 1994), minimizing workflow variability (Ballard & Howell, 1994; Nikhil & Hedaoo, 2017), improving schedule performance (Alarcón et al., 2014; Ballard & Tommelein, 2016; Indira & Jyothsna, 2017) and reducing cost deviations (Daniel et al., 2014; Fernandez-Solis et al., 2013). In addition, research has shown significant benefits in communication, teamwork, understanding of the project and workforce involvement in the management (Castillo et al., 2018; Koskela et al., 2010; Tayeh et al., 2019). Despite the multiple LPS benefits, recent research has shown that most projects exhibit partial implementations, which focus mostly on the short-term management component of the methodology and disregard critical elements, such as constraint management for work preparation and registering Corrective Actions (CAs) to remove recurrent problems (Daniel et al., 2017; Hamzeh et al., 2012).

Researchers have found that the partial adoption of LPS has been caused by (1) the difficulty of assessing the effectiveness and efficiency of components, such as work
preparation or learning from recurrent Reasons for Noncompletion (RNCs) to prevent sources of deviation, (2) the lack of understanding of the impact of processes such as lookahead planning to improve performance, and (3) the lack of quantitative metrics to assess the performance in key LPS processes, such as work preparation and the management of Corrective Actions (Bajjou & Chafi, 2018; Sarhan & Fox, 2013).

Researchers have found that LPS implementation barriers also depend on the type of projects where it is applied and the conditions under which the project is being carried out (Balkhy et al., 2021). Differences in incentives, involvement, training, procedures and communication can impose barriers to obtain its benefits (Daniel et al., 2017). Hence, understanding the differences and similarities between LPS adoption, performance levels and outcomes is highly relevant to help industry improvements and securing LPS benefits.

The recent development of information technology systems to support LPS implementation (Lagos et al., 2019) has allowed the collection and use of more quantitative data to assess work preparation and RNC removal. However, some authors have argued that more quantitative analysis is required to demonstrate the impact on project performance (Dave, Hämäläinen, Kemmer, et al., 2015), determine the relationships to traditional and LPS management metrics (Alarcón et al., 2014), and propose quantitative standards to assess performance with regard to the implementation of these components (Lagos & Alarcón, 2020).

Therefore, the authors aim to (1) determine the relationships between process-oriented LPS metrics and project performance and (2) determine key differences in process-oriented LPS metrics between projects with high and low schedule performance. A database composed of 71 high-rise buildings and 28 industrial construction projects, with weekly information regarding the management of constraints, short-term execution commitments, progress, schedule accomplishment, Reasons for Noncompletion and Corrective Actions, in addition to the final Schedule Performance Index (SPI), measured
at the point of planned completion and the final Schedule Deviation (SD) measured at the actual project completion was used to carry out the research. The projects were categorized based on the type of construction (high-rise or industrial) to determine whether different project types exhibited differences in LPS and performance metrics, and then, each construction type category was separately assessed to determine the correlations between the process oriented LPS metrics and project performance metrics. Finally, the projects in each category were categorized into high- and low-performance groups based on their final schedule accomplishment to determine the key differences in the LPS metrics associated with high performance in each construction type category.

4.3 Research methodology

This research combined analytic and quantitative approaches to assess the relationships between the LPS process-oriented metrics and the project performance in high-rise and industrial construction projects. The following research questions were established:

1. Which are the main differences in LPS process-oriented performance between high-rise building and industrial construction projects?
2. What are the relationships between process oriented LPS metrics and performance metrics in high-rise building and industrial construction projects?
3. What are the key differences in the process oriented LPS metrics between projects with high and low schedule performance outcomes?

The research was structured into five stages to address the research questions. First, an in-depth literature research was carried out to determine gaps in transversal quantitative studies and results from qualitative and case studies that could be assessed during the research. Second, standardized quantitative information, obtained from the database of LPS support software developed by the Pontificia Universidad Católica de Chile, was used to construct 23 process oriented LPS and performance metrics, which are presented in Table 4.1, for each of the 99 construction projects. Third, the project database was divided into a high-rise building (HR) sample and an industrial construction (IC) sample to search
for statistically significant differences between the project type categories in each of the 23 metrics. Fourth, the correlations between the 23 metrics in the projects within each sample were assessed. Finally, the projects within each sample were classified into two groups based on their final schedule accomplishment to determine the key differences between the projects that had high and low schedule performance, using the 23 metrics.
Table 4.1 Description of the LPS and performance metrics

<table>
<thead>
<tr>
<th>Process</th>
<th>KPI</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schedule Outcome</td>
<td>Final Schedule Performance Index (SPI)</td>
<td>The final SPI is measured at the point of planned completion. A final SPI &lt; 100% indicates a delay. If the projects finish ahead of schedule, the final SPI equals the inverse of the planned progress at that point.</td>
</tr>
<tr>
<td></td>
<td>Final Schedule Deviation (SD)</td>
<td>The schedule deviation measured at the point of completion. SD = (Actual completion – Planned completion)/Planned Duration. SD &gt; 0% indicates delay.</td>
</tr>
<tr>
<td>Schedule performance</td>
<td>Average Schedule Performance Index (SPI)</td>
<td>Average of the actual progress over the planned progress across all of the project’s weeks</td>
</tr>
<tr>
<td></td>
<td>Variability of the Schedule Performance Index (SPI Var)</td>
<td>Standard deviation of the SPI values registered at each week across all of the project’s weeks</td>
</tr>
<tr>
<td>Short-term execution</td>
<td>Average Percent Plan Complete (PPC)</td>
<td>Average of the percent of the execution commitments made at each week that were effectively accomplished</td>
</tr>
<tr>
<td></td>
<td>Variability of Percent Plan Complete (PPC Var)</td>
<td>Standard deviation of the Percent Plan Complete across execution</td>
</tr>
<tr>
<td>Work preparation</td>
<td>Number of Reasons for Noncompletion (Nº RNC)</td>
<td>Total number of RNCs registered by the project</td>
</tr>
<tr>
<td></td>
<td>Reasons for Noncompletion per Week (RPW)</td>
<td>Average number of RNCs registered per week</td>
</tr>
<tr>
<td></td>
<td>Number of Reasons per Week, corrected by Impact (RNC x Impact)</td>
<td>Multiplication of the RPW by the average impact of the RNCs. The impact is the difference between the committed and actual progress, over the committed progress.</td>
</tr>
<tr>
<td></td>
<td>Percent of Short-term Periods with RNC (STP w/R)</td>
<td>Percent of weeks in which, at least, one execution commitment was unaccomplished</td>
</tr>
<tr>
<td>Constraint management</td>
<td>Number of constraints (Nº Const.)</td>
<td>Total number of constraints registered by the project</td>
</tr>
<tr>
<td></td>
<td>Constraints Per Week (CPW)</td>
<td>Average number of constraints managed per week</td>
</tr>
<tr>
<td></td>
<td>Percent of Short-term Periods with Constraint Identification (STP w/CI)</td>
<td>Percent of weeks in which, at least, one new constraint was registered</td>
</tr>
<tr>
<td></td>
<td>Average Constraint Identification Time (CIT)</td>
<td>Average difference between the date of registration of a constraint and the required date of removal</td>
</tr>
<tr>
<td></td>
<td>Average Constraint Planning Time (CPT)</td>
<td>Average difference between the date of registration of a constraint and the planned date of removal</td>
</tr>
<tr>
<td></td>
<td>Average Constraint Removal Time (CPT)</td>
<td>Average difference between the date of registration of a constraint and the actual date of removal</td>
</tr>
<tr>
<td>Corrective Actions</td>
<td>Number of Corrective Actions (Nº CA)</td>
<td>Total number of corrective actions registered by the project</td>
</tr>
<tr>
<td>management</td>
<td>Corrective Actions per Week (APW)</td>
<td>Average number of corrective actions registered per week</td>
</tr>
<tr>
<td></td>
<td>Percent of Short-term Periods with Corrective Actions (STP w/CA)</td>
<td>Percent of weeks in which, at least, one corrective action was registered</td>
</tr>
<tr>
<td></td>
<td>Number of Corrective Actions per RNC (APR)</td>
<td>Total number of corrective actions over the total number of Reasons for Noncompletion</td>
</tr>
</tbody>
</table>
4.4 Literature research methodology

The authors conducted an in-depth literature review process, comprised of two stages. First, the authors focused on investigations about LPS methodology and components, analysis of impacts in construction, and the analysis and introduction of new metrics. Then, all the case-study and empirical articles were analyzed to seize the gap between the past and current investigation. The authors started by searching articles indexed in the Web of Science and Scopus databases between 2015 and 2021, using the following combinations of keywords in the titles, abstracts or keywords: (“Last Planner System”; “LPS”; “Last Planner”) AND [ (“case”; “cases”; or “case-study”) OR (“quantitative”; “perception”; “qualitative”; “transversal”; or “longitudinal”) OR (“comparison”; “differences”; “correlation”; “relationship”; “assessment” or “evolution”)]. The search resulted in 75 journal articles and 46 conference proceedings papers. 43% of the articles assessed corresponded to longitudinal cases of study, or single case study research, while only 10% of them corresponded to transversal research publications. 25% of the studies addressed either perceptions or empirical data regarding the impact of LPS implementation on project performance, while only 13 papers used quantitative information to evaluate the impacts. Also, just 15 articles assessed quantitative information across transversal samples, but none of them assessed empirical relationships between LPS components and performance, using quantitative management metrics. The literature review did not provide evidence of a transversal study carried out to empirically correlate the five components of LPS, including constraint management, work-preparation, short-term planning, schedule performance assessment and corrective actions implementation, despite two transversal studies regarding the impact of constraint management on performance (Y. Kim, 2019; Lagos & Alarcón, 2021).

4.5 Collection of information

The authors assessed a database comprised of 489 projects which used the same software to implement LPS. The projects belonged to 54 construction companies and 12
type categories, including engineering and design, high-rise building, residential densification, industrial construction, health-infrastructure, transportation-infrastructure, mining development, among others. These projects also belonged to different life-cycle stages, including feasibility studies, engineering, design, procurement, contracting, construction, commissioning, or operational updates, among others. All the projects which belonged to stages different than execution, or which represented minor construction efforts with durations shorter than 12 weeks were removed to focus on the construction execution scope. Filtering allowed to obtain 255 construction projects, although, many implemented the software during late stages or execution or dropped its use prior to reaching the end of the project’s planned and actual scope. Also, some projects made partial use of the software and, therefore, did not register relevant elements for the research such as constraint information. 90 projects were removed because they did not register key information to assess the LPS component’s implementation, such as constraints and the initially planned progress scope (Baseline plan).

The research methodology also required to obtain representative metrics to assess the LPS components across execution, therefore, 34 projects were removed because they started information registration after 1% actual progress or dropped the use of the software before reaching 99% planned or actual progress. Finally, the 131 projects belonged to 5 project categories: high-rise buildings, industrial projects, civil engineering works, hospitals construction and other minors’ projects, although only two of these categories (High-rise Building and Industrial Construction) had the minimum of 15 projects required to obtain representative means and medians (Cohed, 1977). Hence, the final study sample was composed of 99 projects, belonging to two categories: Industrial Construction (IC) and High-rise building (HR). The first category included 28 projects, with a mean of 31 weeks and a maximum of 73 weeks of execution. These projects contain civil, and electromechanical assemblies, such as pumping systems installations, industrial equipment installations, plant developments and improvements, among others. The HR category consisted in 71 projects, with an average of 60 weeks and a maximum of 116
weeks of duration. It included mainly residential developments projects and, to a lesser extent, the construction of buildings for commercial and enterprise use. These buildings had 10 to 20 floors and were constructed mainly with reinforced concrete, with the exception of a few buildings with reinforced masonry.

Each project category was analyzed separately to assess the differences between the project types, the correlations between the metrics and the differences between the projects that had high schedule accomplishment and those that failed to meet the planned schedule. Four logs of data were obtained from each project to represent their: progress evolution, historical constraints, RNCs and CAs registered. The progress log contained weekly information regarding the accumulated planned and actual progress of the project, the SPI, PPC and PCR, measured at the end of each short-term period. This log was used to calculate the average and standard deviation of the PPC, PCR and SPI over the entire project’s planned scope. The final schedule accomplishment indicators were also obtained from the progress log.

The final Schedule Deviation (SD) measured the time deviation of the project over the project’s planned scope, while the final SPI was calculated separately for high- and low-performance projects. If a project failed to meet the schedule, the final SPI was calculated as the actual progress achieved at the point of planned completion. For projects that finished ahead of schedule, the final SPI was calculated as the inverse of the planned progress at the point of actual completion. Hence, a final SPI of over 100% indicated that the project finished early, while a final SPI of under 100% indicated delay. Similarly, a final SD of larger than 0% indicates delay.

The constraints log contained detailed information for each constraint registered by the project. First, the total Number of Constraints (NC) and the Number of Constraints Per Week (CPW) were calculated in each project. Second, the detailed constraint information was used to construct three constraint management indicators: the Constraint Identification Time (CIT), which measured the difference between the date of registration
of each constraint and the latest required time of removal; the \textit{Constraint Planning Time} (CPT), which measured the difference between the date of registration of each constraint and the planned time of removal; and the \textit{Constraint Removal Time} (CRT), which measured the difference between the identification date and the actual date of removal. Finally, the average CIT, CPT, and CRT across all the project’s constraints were calculated in each project.

The RNCs log contained detailed information on each RNC registered by the project for each unaccomplished execution commitment in each week. The impact of each RNC was calculated as the difference between the committed and actual progress of the affected task and dividing it by the committed progress. Four RNC metrics were calculated using this log: the total \textit{Number of RNCs} per project (Nº RNC), the average \textit{Number of Reasons for Noncompletion Per Week} (RPW) and \textit{Average RNC Impact per Week} (ARI), which was obtained by multiplying the RPW by the average RNC impact of the project. Additionally, the Corrective Actions log was used to calculate the total \textit{Number of CAs} (Nº CA) per project, the average \textit{Number of Corrective Actions per Week} (APW) and the \textit{Number of Corrective Actions per Reason for Noncompletion} (APR). Finally, the four logs were combined to calculate the percent of \textit{Short-term Periods with Constraint Identification} (STP w/CI), with \textit{Constraint Management} (STP w/CM), with \textit{Reasons for Noncompletion} (STP w/R) and with \textit{Corrective Actions} (STP w/CA). The 23 metrics used in this study are described in Table 4.1.

\subsection*{4.6 Project type comparison}

Since researchers have covered several implementation barriers which are dependent on the type of project and the conditions under which it is being performed (Perez & Ghosh, 2018), the authors chose to assess industrial and high-rise building construction projects separately to assess if these factors influenced the relationship between LPS processes and performance.
The twenty-three metrics, in addition to the average Number of Short-term Periods (Nº STP) in each sample, were used to compare the subsample of 71 high-rise building projects against the subsample of 28 industrial construction projects. First, the normality of the subsamples was assessed using the Shapiro-Wilk test for the industrial construction subsample and the Kolmogorov-Smirnov test for the high-rise building sample. The tests were selected since Shapiro-Wilk is better suited for samples under 50 subjects and Kolmogorov-Smirnov is preferred for larger samples (Razali & Wah, 2011). In both cases, the null hypothesis H0, “the sample follows a normal distribution”, was established using a 95% confidence level and it could be accepted if the p-value obtained from the test was larger than 0.05.

If both subsamples exhibited a normal distribution for a specific metric, the T test was used to evaluate the statistical significance of the mean differences between two independent samples. If any of the subsamples did not exhibit a normal distribution, the Mann-Whitney U test was used to evaluate the statistically significant differences between two independent samples (Zimmerman, 1987). Since at least one of the two subsamples did not follow a normal distribution for each of the 22 metrics, the Mann-Whitney U test was used to evaluate the differences in all the metrics. The null hypothesis H0, “There is no significant difference between the subsamples”, was established using a 95% confidence level, which means that H0 could be rejected if the p-value obtained from the test was lower than 0.05. This finding would mean that the subsamples exhibited statistically significant differences.

4.7 Assessment of the correlations between the metrics

The 253 possible relationships between the 23 metrics were assessed separately in each subsample (HR and IC projects) of the study. Hence, a specific pair of metrics could exhibit different relationships in high-rise building projects than in industrial projects. First, a two-dimensional outlier detection analysis between the pairs of metrics in each subsample was performed using the interquartile range (IQR) method (Rousseeuw &
Hubert, 2011) to eliminate abnormal data that could influence the results of the correlation analyses. A limit of 5% outliers was established to avoid a significant decrease in the sample sizes. This approach meant that at most 1 and 3 projects could be treated as outliers when analyzing the relationship between a specific pair of metrics in the industrial construction and high-rise building samples, respectively. The relationships were assessed using the correlation coefficients $R$ calculated between each pair of metrics in each subsample of complete construction projects. The strength of the relationship was considered to be weak if the absolute value of $R$ was equal to or greater than 0.3, moderate if it was equal to or greater than 0.5 and strong if it was equal to or greater than 0.7 (Cohed, 1977). The $p$-values of these relationships were calculated using the $R$ values and the number of projects assessed in each analysis. The metrics must have exhibited at least a weak strength and a $p$-value equal to or lower than 0.05 to be considered in the following analyses and discussion. Given the subsample sizes, the correlations were statistically significant if $R$ was equal to or greater than 0.38 in the industrial construction projects and 0.3 in the high-rise building projects.

4.8 Assessment of the differences between the high and low schedule performance projects

The IC and HR projects were treated as independent samples for the assessment of the project performances. Since quantitative outcome information was available, the researchers decided to develop quantitative rules to classify projects based on performance similarities, instead of using expert criterion or previously defined performance categorization roles. Therefore, it was decided to apply a clustering algorithm to determine a group of high-performance projects with similar outcomes. The use of a two-dimensional recursive K-Means clustering algorithm based on the final SPI and final SD of each project was selected, because it allowed to determine the optimal number of clusters that sufficed two conditions: Minimizing the average distance from any project to the center of its cluster; and maximizing the distance between cluster centers. The K-
means algorithm was used to classify the projects binarily into high or low schedule performance outcome groups, separately, in each category (IC and HR projects).

The algorithm classified each sample into 2 to 5 clusters, recursively, and selected the number of clusters that minimized the within-cluster sum of square (WSS) distance to their centroid. Then, if 2 clusters were obtained, each cluster would represent a performance group, while if 4 clusters were obtained, the vectors that separated the clusters in the middle would be used to classify the projects. If 3 or 5 clusters were obtained, two sets of vectors, which consisted of the segregation between clusters Nº2 and Nº3 or between clusters Nº4 and Nº5, would be assessed. In that case, the set of vectors that maximized the distance between clusters would be selected. This allowed to classify projects using an exclusion rule: The highest performance clusters determined the success group, and, by default, the rest of the clusters represented low-performance projects.

A set of two vectors was obtained for each subsample, which represented quantitative rules to segregate the projects based on a minimum final SPI and maximum final SD. In essence, the entire sample was analyzed to find a group of projects who had high-performance outcomes, measured by their final SPI and SD, and one or multiple clusters of projects which obtained significantly different results, which were considered as low-performance projects. These groups were used to assess the statistical significance of the differences between the high- and low-performance projects in each type of construction. The same process described in the previous sections was used to assess the normality of each group and to assess the statistical significance of the mean differences using the T test or the Mann-Whitney U test accordingly. At least one group did not follow a normal distribution in every comparison, and thus, the Mann-Whitney U test was used to evaluate the differences in the 23 metrics in the HR and IC samples.
4.9 Results and discussion

4.9.1 Literature research findings

The Last Planner System® has been implemented in many countries over the past 27 years (Ballard & Howell, 2003a; Daniel et al., 2014). LPS is based on the Lean Construction philosophy and promotes workflow stabilization to reduce time and resource waste and to improve compliance during execution (Ballard & Tommelein, 2016). LPS proposes the management of commitments at an operational level to ensure that work is planned and assigned properly and the management of constraints to eliminate issues that could prevent compliance with the work committed (Ballard, 1994).

LPS is based on five principles (Ballard et al., 2009): First, the tasks should only be planned in increasing detail when its execution time approaches, to allow for schedule flexibility and avoid uncertainty induction. Second, tasks should be planned together with direct responsibility to ensure the correct assessment of the resources and needs. Third, upcoming work should be pulled by removing constraints in advance to prepare for the work. Fourth, commitments should be reliable, and compliance should be continuously assessed. Finally, the project team should focus on continuous improvement by systematically implementing Corrective Actions to remove sources of noncompletion. Following these principles is secured by the implementation of the five LPS components: (1) phase planning, (2) lookahead planning, (3) managing a Workable Backlog of Tasks (WB), (4) managing short-term commitments of execution and (5) taking Corrective Actions to remove RNCs (Ballard, 2000; Ballard & Tommelein, 2016). The systematic use of these components establishes a virtuous cycle of sound work preparation, pulling work in advance, improving short-term compliance and removing barriers that detriment productivity and schedule performance (AlSehaimi et al., 2014; Y. Kim, 2019; Tayeh et al., 2019).

Several metrics have been developed to assess performance using the Last Planner System®. The basic metrics that measure work preparation and short-term compliance at
a task level are the *Tasks Made Ready* (TMR), which measures the number of constraint-free tasks that enter the short-term plan over the number of tasks planned for that week, and the *Percent Plan Complete* (PPC), which measures the percent of short-term execution commitments accomplished over the number of commitments made for each week (Ballard, 2000). Practitioners have also adopted metrics that were derived from the Earned Value Method to assess the schedule and budget compliance, such as the *Schedule Performance Index* (SPI), which measures the actual accumulated progress over the planned progress at a certain point of execution, and the *Cost Performance Index* (CPI), which measures the planned budget over the actual expenditure, to assess the rate of accomplishment of the planned cost at a certain execution point (Y. Kim, 2019). Additionally, researchers have proposed the adoption of additional metrics to assess work preparation at the constraint level, committing to critical tasks and matching load to capacity (Hamzeh et al., 2019).

The *Percent of Constraints Removed* (PCR) has been proposed to be a complement to the TMR, to assess the work preparation at the constraint level. Hence, while the TMR measures the effectiveness of the work preparation, the PCR represents its efficiency by assessing the percent of constraints that were removed prior to the date on which a set of tasks is required to enter the short-term plan (Y. Kim, 2019). Since LPS proposes that each constraint identified should be assigned a committed time of removal, the PCR can be calculated each week at the constraint level by assessing the percent of constraints successfully removed before or at their committed date over the number of constraints committed to be removed at a certain week (Lagos et al., 2019). Additionally, authors have argued that measuring the PCR at the constraint level is more suitable for assessing the constraint management efficacy and work preparation efficiency since it reflects how many constraints present delays in removal that lead to reductions in the executable backlog of tasks that will enter the short-term plan (Emdanat & Azambuja, 2016; Hamzeh et al., 2015).
Other LPS metrics have been proposed to assess the capability for planning short-term execution in advance, assess deviation from the short-term plans and determine how much of the work planned is critical to sustain the project plan (Hamzeh et al., 2019). These metrics include (1) the percent of Tasks Anticipated (TA), which measures the percent of the short-term plan activities from a specific short-term period that were planned to be executed in that specific short-term period at least two weeks in advance; (2) The Required Level (RL), which measures the number of critical tasks planned at each short-term period over the total number of tasks planned; (3) the percent of Work Completed Uncommitted (CU), which assesses the percent of tasks that were executed during a short-term period but were not part of the initial short-term plan over the number of tasks originally committed; and (4) Percent Complete New (PCN), which is calculated similar to the PPC but also considers the total number of uncommitted tasks completed in the numerator and divisor to measure the total number of tasks completed over the total number of activities executed in the short-term period.

Thus, there is still a need to assess their relationships with the most widely adopted LPS metrics and traditional project performance metrics, such as the SPI or CPI (Y. Kim, 2019; Novinsky et al., 2018). Researchers who have focused on the quantitative assessment of LPS have used metrics such as TA, RL, CU and TMR to successfully assess performance and determine the need for specific actions for improvement in the cases studied, but their efforts have been limited mostly to longitudinal studies due to the lack of comparable data among the larger samples of the projects (Hamzeh et al., 2019). Quantitative transversal studies with larger data samples have been published with regard to some of the LPS metrics measured at the task level, such as the TMR and PPC, and have found that such metrics correlate with traditional performance and outcome indicators, such as the SPI and CPI, and can help differentiate projects according to their expected outcome (Y. Kim, 2019; Lagos et al., 2019). Nevertheless, similar studies regarding metrics measured at the constraint level or using RNCs and CAs information have yet to be conducted. Additionally, most quantitative studies have used small data
samples or focused on a small number of metrics (Alarcón et al., 2014; Lagos & Alarcón, 2020); hence, transversal research that involves a larger number of projects and a wider spectrum of metrics is needed to better understand the relationships between the LPS components and the project performance.

Some exploratory efforts using transversal approaches have shown encouraging results. Using semiquantitative metrics derived from the weekly registration of RNCs and CAs, the authors obtained information that allowed us to assess performance and differentiate the projects according to their outcomes (Lagos & Alarcón, 2020). Similarly, semiquantitative assessments of the level of implementation of LPS have served to determine the relationships between specific LPS components, such as work preparation, constraint management, and short-term execution, and performance indicators, such as the SPI and productivity (Gonzalez et al., 2008; S. Kim et al., 2015; Min et al., 2011).

Other efforts to improve the LPS implementation include the use of information technology (IT) support systems such as Impera and vPlanner, among others (Emdanat et al., 2016; Lagos & Alarcón, 2020). These software programs have been developed to facilitate LPS adoption, and their benefits include standardization of the planning and control processes, incorporation and use of new indicators to assess compliance with project planning and systematic analysis of constraint detection and removal (Lagos et al., 2017). Exploratory research using such systems has shown that measurements of the average and variability of the PPC, PCR and SPI obtained from IT tools can help to predict the expected outcome of the projects and allow the identification of success criteria at early stages of project execution (Alarcón & Letelier, 2014; Lagos & Alarcón, 2020). Additionally, recent investigations have presented how new IT tools, such as process mining, can learn from past LPS implementation and predict deviations in the programmed schedule associated with constraint management (Pérez et al., 2018).
Despite the multiple benefits attributed to implementing LPS, several barriers have limited its impact on project performance and prevented a more thorough understanding of the relationship between the implementation of LPS components, improvements in key management and execution processes and their effects on performance indicators (Dave, Hämäläinen, Kemmer, et al., 2015). These barriers are mainly caused by the partial adoption of the methodology and include limitations such as the exclusive focus on improving short-term execution metrics such as the PPC (Perez & Ghosh, 2018), underutilization of lookahead plans to identify new constraints and plan their removal (Gao & Low, 2014), lack of assessment of the state of the WB and the availability of work that should be committed in the short-term plan (Lagos et al., 2017), lack of emphasis on identifying and registering the root causes of RNCs for the purpose of obtaining valuable information on the most recurring problems (Dave, Hämäläinen, Kemmer, et al., 2015) and the underutilization of different data collected across the project execution scope to detect trends that can lead to failure and opportunities to revert them (Fernandez-Solis et al., 2013). Additionally, deficiencies in the registration of the detailed information from key elements such as constraints and RNCs prevent the use of these sources of information to assess their impact on the propagation of variability and deviations and use process-oriented metrics to control them (Ballard & Tommelein, 2016). Hence, partial LPS implementations not only reduce performance improvements but also prevent more thorough assessments of the benefits of LPS and the relationship between the LPS components and the key project management processes (Ballard & Tommelein, 2016).

The involvement of key roles such as the client, main contractor and subcontractors depends on the characteristics of the projects and conditions under which it is being managed. Factors such as contractual relationships, communication and incentives have been found to influence LPS management factors like work preparation effectiveness and short-term commitments alignment (Castillo et al., 2018). If parties work without shared goals, their plans might differ significantly and negatively impact the chain of commitments (Rincón et al., 2019).
For example, the complexity, budget and scope of Industrial Construction projects require better alignment between actors, which is often incentivized by the client. Hence, they can demand higher process control standards and accountability to both the main contractor and subcontractors directly (Balkhy et al., 2021; Nieto-Morote & Ruz-Vila, 2012). The close involvement of the subcontractors in planning, onsite coordination and control, also facilitates their active participation in LPS (Nieto-Morote & Ruz-Vila, 2012). In contrast, in High-rise building projects, subcontractor incentives and requirements are more traditional and, commonly, involve payments directly related to the quantity of work executed or completed (Castillo et al., 2018). Therefore, subcontractors have less incentives to align their work plans to the main contractor’s, especially when schedule variance causes a misalignment constraint-free tasks and the Lookahead Plan (Priven & Sacks, 2015). This phenomenon has been described as the tendency of subcontractors to act as autonomous agents under no shared incentives to systematically coordinate work through LPS (Rincón et al., 2019). Training and shared understanding of the Lookahead Plan are critical to promote subcontractor involvement (Rincón et al., 2019).

On the other hand, Industrial and Civil construction projects are commonly carried out while the client continues operations, hence, the participation of the client on work preparation and close coordination to secure the short-term plan is critical to facilitate short- and mid-term compliance (Daniel et al., 2019). If the client is not aware of the Lookahead Plan or is not able to ensure worksite availability, it will directly impact short-term compliance, limiting the capability of the main contractor and its subcontractors to sustain a reliable continuous workflow (Tezel et al., 2018). As to High-rise Building and Residential projects, they take place away from the direct client operations and, therefore, are less limited by the client’s capability to secure onsite conditions, but, the tendency of the subcontractors to act as autonomous agents can cause that the short-term execution plans are not properly aligned with the Lookahead Plan’s best interests (Fernandez-Solis et al., 2013).
The closer involvement of subcontractors in the planning and control process and the higher dependency on the client for constraint removal could cause clients to pay a more relevant role than subcontractors in Industrial Construction (Nieto-Morote & Ruz-Vila, 2012). As to High-rise Building, less dependency on the client and less involvement of subcontractors could invert their relevance in LPS management (Fernandez-Solis et al., 2013). The existence of differences in management and execution conditions makes assessing the comparison of LPS implementation metrics in HR and IC projects a relevant gap in the current scientific literature.

In addition, even though research has shown that the use of IT support can lead to improvements in the collection and use of critical LPS information (Lagos et al., 2016), in-depth analyses of LPS implementations in projects using IT support systems have still found grounds for improvement in elements such as constraint management for work preparation and implementation of CAs to prevent recurring sources of RNCs (Lagos et al., 2019). In fact, Cisternas (2013) discovered that projects that used a specific IT support system based on LPS used less than half of its capabilities, with diminished use of components such as the management of the WB obtained from the lookahead plan, controlling the work preparation by assessing the constraints management metrics such as the PCR, and implementing and registering CAs linked to specific types of RNCs, among others. These limitations have been attributed to excessive focus on the short-term scope, difficulty in registering information due to time restrictions, lack of widely known metrics to assess such components and difficulty in observing quantitative evidence of their impacts on performance and continual improvement (Alarcón et al., 2008; Dave et al., 2015). Therefore, the proposition, thorough understanding and wide adoption of process-oriented LPS metrics aligned with the basic concepts of the Lean Construction and components of the LPS methodology are needed to improve the LPS implementation and to attain its benefits in project management and execution (Alarcón et al., 2005; Lagos et al., 2016, Dave et al., 2015).
4.9.2 Differences between high-rise and industrial construction projects

Statistically significant differences were found in metrics from 5 of the 6 components assessed, which are presented in Table 4.2. Hence, it was considered that the project type categories should be treated as independent samples in the study. The twenty-three process and outcome metrics were assessed, in addition to the average Number of Short-term Periods in each group, by comparing the means of the 71 high-rise buildings and 28 industrial construction projects. The results showed that the samples exhibited statistically significant differences in the No STP and 11 other metrics, including their final SPI and SD, their PPC and PCR average, and the variability of the SPI and PPC, among others. The HR sample exhibited lower final SPI and greater final SD values, which indicated that HR projects were more prone to delays. Additionally, their average duration was greater, which meant that the variability and uncertainty could propagate across a longer scope. The later could explain why they exhibited a tendency toward delayed completion.

Table 4.2 Differences between high-rise and industrial construction projects

<table>
<thead>
<tr>
<th>Component</th>
<th>KPI</th>
<th>High-rise building (AVG)</th>
<th>Industrial construction (AVG)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Nº STP</td>
<td>60</td>
<td>31</td>
<td>0.00</td>
</tr>
<tr>
<td>Outcome</td>
<td>SPI Final</td>
<td>92%</td>
<td>100%</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>SD Final</td>
<td>23%</td>
<td>0%</td>
<td>0.00</td>
</tr>
<tr>
<td>Schedule performance</td>
<td>SPI Average</td>
<td>96%</td>
<td>94%</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>SPI Var</td>
<td>41%</td>
<td>47%</td>
<td>0.00</td>
</tr>
<tr>
<td>Short-term execution</td>
<td>PPC Average</td>
<td>82%</td>
<td>73%</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>PPC Var</td>
<td>14%</td>
<td>19%</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Nº RNC</td>
<td>387</td>
<td>215</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>RPW</td>
<td>7.1</td>
<td>6.5</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>RNC x Impact</td>
<td>4.2</td>
<td>3.6</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>STP w/R</td>
<td>58%</td>
<td>66%</td>
<td>0.19</td>
</tr>
<tr>
<td>Work preparation</td>
<td>PCR Average</td>
<td>73%</td>
<td>63%</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>PCR Var</td>
<td>25%</td>
<td>24%</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>STP w/WP</td>
<td>41%</td>
<td>76%</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>Nº Const.</td>
<td>146</td>
<td>351</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Nevertheless, the PPC and PCR averages of the HR sample were greater than those of the IC projects, while the variability of the PPC in the HR projects was lower. These results indicate that HR projects exhibited better work preparation and short-term execution and, despite the significant difference in the total number of RNCs between the samples, there was no significant difference in the average number of RNCs per week, which indicates that HR projects presented more RNCs only because they registered more short-term periods. In contrast, HR projects registered fewer constraints per week and in total, which accounted for a significantly lower percent of short-term periods with work preparation and constraint identification. The lack of focus on constraint management could be one of the causes of the lower empirical outcome found in the HR projects.

4.9.3 Assessment of correlations between LPS and performance metrics

The correlations between LPS and performance metrics were assessed separately for the high-rise building and industrial construction samples. The metrics represent 6 LPS components: (1) final schedule outcome, (2) schedule performance across execution, (3) short-term work execution, (4) work preparation, (5) constraint management and (6) management of CAs to remove RNCs sources. Given the sample sizes, the minimum statistically significant correlation coefficient was $R = 0.3$ in the high-rise building sample and $R = 0.38$ in the industrial construction sample. Eighty-nine correlations (35.2%) were identified in the high-rise building sample out of the 253 possible relationships. Sixty-two metrics were weakly correlated, 14 of which were moderately correlated, and 13 were

<table>
<thead>
<tr>
<th>Constraint management</th>
<th>CPW</th>
<th>2.4</th>
<th>10.9</th>
<th>0.00</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STP w/CI</td>
<td>28%</td>
<td>57%</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>CIT</td>
<td>30.7</td>
<td>25.8</td>
<td>0.45</td>
</tr>
<tr>
<td></td>
<td>CPT</td>
<td>8.5</td>
<td>14.7</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>CRT</td>
<td>18.7</td>
<td>19.1</td>
<td>0.68</td>
</tr>
<tr>
<td>Corrective actions</td>
<td>Nº CA</td>
<td>129</td>
<td>76</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>APW</td>
<td>2.2</td>
<td>3.1</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>APR</td>
<td>0.60</td>
<td>0.67</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>STP w/CA</td>
<td>32%</td>
<td>33%</td>
<td>0.93</td>
</tr>
</tbody>
</table>
strongly correlated. Additionally, 56 correlations (22.1%) represented relationships between the metrics from different components.

![Diagram of LPS components](image)

**Figure 4.1 Relationships between LPS components in high-rise sample**

The HR correlation results are presented in Table 4.3, and Figure 4.1 shows the 13 relationships found between the 6 LPS components assessed in the HR sample. The results from the HR analyses show that the final SPI is positively correlated with the SPI, PPC and PCR averages and negatively correlated with the variability of the PPC. Although these correlations were weak, they show that HR projects that achieved greater long- and short-term compliance in addition to better work preparation could expect better schedule accomplishment outcomes. Additionally, the final SD was weakly correlated with the average constraint removal time, which means that the HR projects that require more time to remove the constraints to prepare tasks for execution tend to obtain greater schedule deviations. This inference is also supported by the relationships found between the PPC and PCR, which indicate that higher PCR averages correlate with higher PPC averages,
while lower PCR variability also correlates with lower PPC variability. Similarly, a greater PCR average correlates with a lower number of RNCs, and a lower number of RNCs per week corrected by impact also correlates with a greater final SPI. Hence, these relationships allowed to infer that better work preparation contributes to better short-term execution and that both contribute to better schedule accomplishment outcomes.

![Figure 4.2 Correlations between SPI Average, PPC Average, PCR Average with Final SPI](image)

In addition, HR projects that registered new constraints in a larger percent of their short-term periods exhibited lower PCR variability, and a lower constraint removal time exhibited a moderate positive correlation with the PCR average. Hence, identifying constraints systematically and removing them efficiently can improve the work preparation. Finally, the positive correlation between the Nº CAs and percent of STP w/R allowed to infer that projects that are systematically affected by compliance issues tend to implement more Corrective Actions.
Table 4.3 Correlations between metrics in high-rise building projects

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPI Final</td>
<td>SPI Average</td>
<td>PPC Average</td>
<td>PPC Var</td>
<td>Nº RNC</td>
<td>RNC x Impact</td>
</tr>
<tr>
<td>1</td>
<td>SPI Final</td>
<td>-</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>SD Final</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>SPI Average</td>
<td>0.9</td>
<td>0.9</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>SPI Var</td>
<td>-</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>PPC Average</td>
<td>0.7</td>
<td>0.7</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>PPC Var</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Nº RNC</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>0.6</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>RPW</td>
<td>0.9</td>
<td>0.6</td>
<td>0.4</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>RNC x Impact</td>
<td>0.4</td>
<td>0.3</td>
<td>0.4</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>STP w/R</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>4</td>
<td>PCR Average</td>
<td>0.6</td>
<td>0.6</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>PCR Var</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>STP w/WP</td>
<td>0.8</td>
<td>0.8</td>
<td>0.9</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>5</td>
<td>Nº Const.</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>CPW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>STP w/CI</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>CIT</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>CPT</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>CRT</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
</tr>
<tr>
<td>6</td>
<td>Nº CA</td>
<td>0.9</td>
<td>0.9</td>
<td>0.5</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>APW</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>APR</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
</tbody>
</table>
After performing the same analyses in the IC sample, 50 statistically significant correlations (19.8%) were found, distributed in 11 weak correlations, 22 moderate correlations and 17 strong relationships from the 253 pairs of metrics assessed. Twenty-four of these correlations represented relationships between metrics that assessed different LPS components and allowed to determine the existence of relationships that connect all 6 of the components addressed. The results of the correlation analyses in the IC sample are presented in Table 4.4, and Figure 4.2 represents the 11 relationships found between the LPS components.

![Figure 4.3 Relationships between LPS metrics in Industrial sample](image)

The relationships found between short-term execution, schedule performance and outcome in industrial construction are similar to the findings from high-rise building projects. The final SPI was positively correlated with the SPI and PPC averages, while the
final SD was negatively correlated with the variability of the SPI and PPC. In a similar manner, lower PPC variability was correlated with lower SPI variability across executions. Hence, it could be inferred that improving short-term execution compliance can help to obtain greater schedule accomplishment rates across execution, which correlate to better schedule performance outcomes. Additionally, PCR variability was positively correlated with SPI variability and negatively correlated with the SPI average, which allowed to infer that greater stability in work preparation contributed to better schedule accomplishment across execution.

An interesting relationship was found between the management of the constraints and the management of the Corrective Actions. The IC projects that registered more Corrective Actions Per Week also obtained higher PCR averages, and the Number of Constraints Per Week was positively and strongly correlated with the Percent of Short-term periods with Corrective Actions. These results showed that IC projects that had better performance in either constraint management, work preparation or Corrective Actions management also tended to have better performance in the other two components. Hence, it could be inferred that these types of projects employed more thorough LPS implementations since their performance in different LPS components was aligned. Finally, moderate, and strong positive relationships were found between the Nº RNCs and the Nº CAs managed by the projects, which shows that IC projects that experienced more short-term compliance issues also took more Corrective Actions to manage and remove those issues.
Figure 4.4 Correlation between Constraints Per Week (CPW) and Short-term periods with Corrective Actions
Table 4.4 Correlations between metrics in industrial construction projects

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SD final</td>
<td>SPI Final</td>
<td>SD final</td>
<td>SPI Final</td>
<td>SD final</td>
<td>SPI Final</td>
</tr>
<tr>
<td>1</td>
<td>SPI Final</td>
<td>1.0</td>
<td>0.6</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>SPI Var</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>2</td>
<td>PPC Average</td>
<td>0.8</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>PPC Var</td>
<td>0.4</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>PPC Average</td>
<td>0.6</td>
<td>0.6</td>
<td>0.8</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>RNC x Impact</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>RNC x Impact</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>STP w/R</td>
<td>0.6</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>PCR Average</td>
<td>-</td>
<td>0.4</td>
<td>-</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>STP w/WP</td>
<td>0.5</td>
<td>0.6</td>
<td>0.8</td>
<td>0.6</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>Nº Const.</td>
<td>0.6</td>
<td>0.6</td>
<td>0.5</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>CPW</td>
<td>0.6</td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>CIT</td>
<td>0.8</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>CPT</td>
<td>1.0</td>
<td>1.0</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>6</td>
<td>Nº CA</td>
<td>0.9</td>
<td>0.9</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>APW</td>
<td>0.5</td>
<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>APR</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>
4.9.4 Analyses of the differences between the projects with high and low schedule performance outcomes

After applying the clustering algorithm in the HR sample, the following segregation rule was obtained: high-performance projects must have a minimum SPI of 95% and a maximum SD of 17%; otherwise, they are categorized as low-performance projects. Using this rule, the high schedule performance outcome group was composed of 26 projects and the remaining 45 projects were classified in the low schedule performance outcome group. Then, given the difference in the group sizes and that at least one group did not exhibit a normal distribution in each metric, the Mann-Whitney U was used test to evaluate the statistical significance of the differences. Additionally, since the final SPI and final SD were used to classify the projects, the remaining 21 process oriented LPS metrics were used to assess the differences. Six statistically significant differences were found regarding the SPI average across execution, the PPC average and its standard deviation, RNC x Impact, the PCR average, and the average Constraint Removal Time. These results are presented in Table 4.5.

It was observed that high-performance projects exhibited higher SPI, PPC and PCR averages across execution than the low-performance projects. Additionally, the relative difference was larger in the PCR (20.9%) than in the PPC (14.1%) and SPI (6.4%), which allowed to conclude that even though the SPI average measures the direct ratio between the actual and planned progress across execution, the PCR and PPC present more significant differences, which could facilitate the assessment of the expected outcome across executions. In addition, the variability of the PPC, measured by its standard deviation, was 41.2% lower in the high-performance projects, which means that they reached significantly greater stability in the short-term execution across the project scope. The increase in the PPC average and its stability across execution also explains the
significant reduction (-63%) in the average number of RNCs per week, corrected by the impact (RNC x Impact) observed in the high-performance group compared to the low schedule performance projects. Finally, it was observed that while it took 22.7 days on average to remove the constraints in the low-performance projects, it took only 11.8 days, on average, in the high-performance group. The CRT difference allowed to infer that improving the constraint removal efficiency allowed for better work preparation, which increased the reliability of the short-term plans, increasing the PPC and SPI across the scope of execution.

Table 4.5 Differences between high-rise building performance groups

<table>
<thead>
<tr>
<th>KPI</th>
<th>High performance (AVG)</th>
<th>Low performance (AVG)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcome</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPI Final</td>
<td>99%</td>
<td>88%</td>
<td>0.00</td>
</tr>
<tr>
<td>SD Final</td>
<td>6%</td>
<td>32%</td>
<td>0.00</td>
</tr>
<tr>
<td>Schedule performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPI Average</td>
<td>100%</td>
<td>94%</td>
<td>0.00</td>
</tr>
<tr>
<td>SPI Var</td>
<td>18%</td>
<td>54%</td>
<td>0.07</td>
</tr>
<tr>
<td>Short-term execution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPC Average</td>
<td>89%</td>
<td>78%</td>
<td>0.00</td>
</tr>
<tr>
<td>PPC Var</td>
<td>10%</td>
<td>17%</td>
<td>0.00</td>
</tr>
<tr>
<td>Nº RNC</td>
<td>254</td>
<td>458</td>
<td>0.22</td>
</tr>
<tr>
<td>RPW</td>
<td>4.2</td>
<td>8.6</td>
<td>0.10</td>
</tr>
<tr>
<td>RNC x Impact</td>
<td>2.0</td>
<td>5.4</td>
<td>0.05</td>
</tr>
<tr>
<td>STP w/R</td>
<td>57%</td>
<td>58%</td>
<td>0.90</td>
</tr>
<tr>
<td>Work preparation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCR Average</td>
<td>81%</td>
<td>67%</td>
<td>0.01</td>
</tr>
<tr>
<td>PCR Var</td>
<td>24%</td>
<td>26%</td>
<td>0.22</td>
</tr>
<tr>
<td>STP w/WP</td>
<td>38%</td>
<td>43%</td>
<td>0.41</td>
</tr>
<tr>
<td>Constraint management</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nº Const.</td>
<td>130</td>
<td>155</td>
<td>0.74</td>
</tr>
<tr>
<td>CPW</td>
<td>2.0</td>
<td>2.6</td>
<td>0.61</td>
</tr>
<tr>
<td>STP w/CI</td>
<td>27%</td>
<td>28%</td>
<td>0.64</td>
</tr>
<tr>
<td>CIT</td>
<td>26.2</td>
<td>33.4</td>
<td>0.09</td>
</tr>
<tr>
<td>CPT</td>
<td>7.8</td>
<td>9.0</td>
<td>0.47</td>
</tr>
<tr>
<td>CRT</td>
<td>11.8</td>
<td>22.7</td>
<td>0.01</td>
</tr>
<tr>
<td>Corrective actions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nº CA</td>
<td>95</td>
<td>150</td>
<td>0.36</td>
</tr>
<tr>
<td>APW</td>
<td>1.6</td>
<td>2.6</td>
<td>0.28</td>
</tr>
</tbody>
</table>
The same analyses were performed in the IC sample, and the results are presented in Table 4.6. The use of the clustering algorithm allowed to formulate the following segregation rule: high-performance projects must have a minimum final SPI of 98% and a maximum SD of 2%; otherwise, they are categorized as low-performance projects. Using this rule, 19 high-performance and 9 low-performance projects were observed. After applying the normality tests, it was found that the Mann-Whitney U test was needed to assess all the possible differences between the groups. The possible differences in the 21-process oriented LPS metrics were addressed using the same techniques described in previous sections. However, only one statistically significant difference was found between the groups regarding PCR variability, measured by its standard deviation across execution, which was 23.8% greater in the high-performance group.

The lack of statistically significant differences between the groups could be attributed to the small sample sizes and the large differences between the number of projects in each group. Nevertheless, despite the failure to demonstrate the statistical significance of the differences, it is necessary to mention that 7 metrics exhibit relative differences that are equal to or greater than 20%, and 7 additional metrics exhibit differences greater than 40%. The most noticeable are a reduction of 60% in the total number of RNCs, a reduction of 44% in the average number of RNCs per week, an increase of 107% in the average 

<table>
<thead>
<tr>
<th>APR</th>
<th>0.73</th>
<th>0.53</th>
<th>0.16</th>
</tr>
</thead>
<tbody>
<tr>
<td>STP w/CA</td>
<td>30%</td>
<td>33%</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Number of Corrective Actions per Week and an increase of 42% in the Number of Constraints per Week in the high-performance group compared to the low-performance projects. Finally, similar to the HR results, the PPC and SPI averages of the high-performance group from the IC sample were slightly greater than those of the low-performance group.
The results of the mean difference analyses are consistent with the relationships that were found between the constraint management, work preparation, short-term execution, schedule accomplishment and outcome in the high-rise building and industrial construction samples. Hence, it was possible to conclude that improving performance in the LPS components can contribute positively to improving the schedule performance outcomes. In addition, based on the LPS principles, it was inferred that improving the constraint management and work preparation has a positive effect on short-term compliance and can help to reduce the recurrence of the RNCs. Similarly, improving the short-term compliance can allow to sustain a higher schedule performance across execution rates, which allows to obtain better schedule accomplishment outcomes. Finally, although the sample size of the industrial construction projects did not allow to determine the same number of statistically significant differences between the performance groups as in the HR sample, similar relationships were found, which allowed to infer that work preparation also had a positive effect on short-term execution, which helped to improve the schedule performance outcomes.
Table 4.6 Differences between industrial construction performance groups

<table>
<thead>
<tr>
<th>KPI</th>
<th>High performance (AVG)</th>
<th>Low performance (AVG)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcome</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPI Final</td>
<td>107%</td>
<td>82%</td>
<td>0.00</td>
</tr>
<tr>
<td>SD final</td>
<td>-7%</td>
<td>18%</td>
<td>0.00</td>
</tr>
<tr>
<td>Schedule performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SPI Average</td>
<td>99%</td>
<td>82%</td>
<td>0.26</td>
</tr>
<tr>
<td>SPI Var</td>
<td>52%</td>
<td>33%</td>
<td>0.68</td>
</tr>
<tr>
<td>Short-term execution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PPC Average</td>
<td>76%</td>
<td>66%</td>
<td>0.24</td>
</tr>
<tr>
<td>PPC Var</td>
<td>19%</td>
<td>19%</td>
<td>0.88</td>
</tr>
<tr>
<td>Nº RNC</td>
<td>151</td>
<td>376</td>
<td>0.18</td>
</tr>
<tr>
<td>RPW</td>
<td>5.3</td>
<td>9.5</td>
<td>0.22</td>
</tr>
<tr>
<td>RNC x Impact</td>
<td>3.1</td>
<td>4.8</td>
<td>0.31</td>
</tr>
<tr>
<td>STP w/R</td>
<td>61%</td>
<td>77%</td>
<td>0.10</td>
</tr>
<tr>
<td>Work preparation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCR Average</td>
<td>62%</td>
<td>66%</td>
<td>0.37</td>
</tr>
<tr>
<td>PCR Var</td>
<td>26%</td>
<td>21%</td>
<td>0.02</td>
</tr>
<tr>
<td>STP w/WP</td>
<td>79%</td>
<td>70%</td>
<td>0.18</td>
</tr>
<tr>
<td>Constraint management</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nº Const.</td>
<td>301</td>
<td>457</td>
<td>0.56</td>
</tr>
<tr>
<td>CPW</td>
<td>12.1</td>
<td>8.5</td>
<td>0.32</td>
</tr>
<tr>
<td>STP w/CI</td>
<td>58%</td>
<td>54%</td>
<td>0.64</td>
</tr>
<tr>
<td>CIT</td>
<td>27.4</td>
<td>22.6</td>
<td>0.52</td>
</tr>
<tr>
<td>CPT</td>
<td>17.6</td>
<td>8.4</td>
<td>0.20</td>
</tr>
<tr>
<td>CRT</td>
<td>21.9</td>
<td>13.0</td>
<td>0.38</td>
</tr>
<tr>
<td>Corrective actions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nº CA</td>
<td>70</td>
<td>100</td>
<td>0.13</td>
</tr>
<tr>
<td>APW</td>
<td>3.5</td>
<td>1.7</td>
<td>0.64</td>
</tr>
<tr>
<td>APR</td>
<td>0.65</td>
<td>0.75</td>
<td>0.48</td>
</tr>
<tr>
<td>STP w/CA</td>
<td>31%</td>
<td>38%</td>
<td>0.50</td>
</tr>
</tbody>
</table>
4.10 Conclusions

The Last Planner System® of production control has been implemented for over 27 years in multiple countries, and its positive effects on the project management and performance have been well documented. However, most quantitative research in LPS has focused on small data samples, performance improvements in cases of study or the relationship between the task-oriented metrics, such as the PPC and TMR, and the performance metrics, such as the productivity, budget and schedule accomplishment. Hence, the authors have argued the need to study the relationships between the key LPS components, such as the constraint management, work preparation, short-term compliance and management of Corrective Actions, with the schedule performance. Quantitative and analytic approaches were combined to assess these relationships and the impact that improving performance in these components could have on the project schedule accomplishment outcomes.

Therefore, the authors aimed to (1) determine the relationships between the process-oriented LPS metrics and the project performance and (2) determine the key differences in process-oriented LPS metrics between projects with high and low schedule performance. In addition, high-rise and industrial construction projects were compared to determine the differences in their process and outcome metrics. A database that comprised 71 high-rise building and 28 industrial construction projects, with weekly information regarding the management of constraints, short-term execution commitments, progress, schedule accomplishment, Reasons for Noncompletion and Corrective Actions, in addition to their final Schedule Performance Index (SPI), measured at the point of planned completion, and the final Schedule Deviation (SD), measured at the actual project completion, was used to conduct the research. Twenty-three metrics were established to represent the performance in 6 LPS dimensions, statistical correlation analyses were used to assess their relationships, and then, the projects were classifying according to their
schedule accomplishment outcomes and compared to assess the existence of statically significant differences in these metrics.

The correlation results obtained in the high-rise building and industrial construction samples allowed to conclude that constraint management, work preparation, short-term execution, the management of Corrective Actions, the schedule performance across execution and the schedule accomplishment outcome are significantly correlated. Additionally, the differences found between high- and low-performance projects in the high-rise building samples showed that projects with better outcomes in terms of the schedule accomplishment sustain more efficient constraint management, better work preparation, and higher short-term compliance and schedule performance across execution. Even though only one statistically significant difference was found between the performance groups in the industrial construction sample, similar trends were found in the relative differences between groups, such as greater SPI and PPC averages, in addition to a lower number of RNCs in the high-performance group.

These results allowed to conclude that improving constraint management and work preparation has a positive effect on short-term execution compliance and schedule performance, which helps avoid schedule deviations across execution and improve project outcome. Based on the relationships between the six LPS phases, researchers can gain understanding of the propagation of impact from the Lookahead Planning stage through short-term planning and execution, learning from RNCs to implement corrective actions and up to schedule performance and outcome. Gaining a better understanding of these relationships and key differences between high- and low-performance projects is key to develop new LPS implementation standards and assessment methods.

This research not only aids to demonstrate the importance of having a thorough LPS implementation and the use of process-oriented metrics to continuously assess
performance, but it shows the value of the LPS information being generated weekly from projects around the world. Collecting this data to develop larger transversal samples could allow the use of more complex Machine Learning Algorithms to develop prospective regression and classification models.

4.11 Data Availability Statement

Some or all data, models, or code used during the study were provided by a third party.

- Access to the repository of the LPS support software was provided by Gestión de la Producción Asesorías SpA.
- Access to the project database was provided by the Production Management Centre from the Pontificia Universidad Católica de Chile.

Direct request for these materials may be made to the provider as indicated in the Acknowledgments.

4.12 Acknowledgments

The authors would like to acknowledge ANID for financial support for this study through projects FONDECYT Nº1181648 and Nº1210769 C. Lagos would like to acknowledge financial support from CONICYT Beca Doctorado Nacional Nº21181603. In addition, they would like to thank the Production Management Centre from the Pontificia Universidad Católica de Chile and Gestión de la Producción Asesorías SpA for allowing the use of the software IMPERA and access to the project database used in the research.
4.13 References:


5. CONCLUSIONS

The Last Planner System ® had improved construction projects for more than 25 years in different countries such USA, India, China, Chile, Colombia, among others. Different research had shown the impact in the production using surveys or a single project case of use to validate the methodology.

Nevertheless, this investigation tried to make a quantitative analysis between more than 90 projects, classified in two main categories, for a better understand of LPS impact. This study aimed to determine the relationships between the process-oriented LPS metrics and the project performance and determine the key differences in process-oriented LPS metrics between projects with high and low schedule performance.

The correlation results obtained in high-rise building and industrial construction samples allowed to confirm that a correct constraint management, work preparation, short-term execution, Corrective Actions management, schedule performance and schedule accomplishment are significantly correlated. Additionally, the differences between high and low performance projects showed that projects with better schedule performance had a more efficient constraint management, better work preparation and a higher short-term compliance.

And last, but not least, this investigation shown the relationship between the six components of LPS such (1) final schedule outcome, (2) schedule performance across execution, (3) short-term work execution, (4) work preparation, (5) constraint management and (6) management of Cas to remove RNCs sources.
REFERENCES


Engineering and Management, 145(10), 04019055. https://doi.org/10.1061/(asce)co.1943-7862.0001691


7. APPENDIX
7.1 DECISION ON MANUSCRIPT MS COENG-10840R2

You are being carbon copied ("to cc") on an e-mail from "Camilo Lagos Orza" colagorc@gmail.com
CC: "Daniel Pérez" dtperez@uc.cl, "Luis Fernando Alarcón" larcon@ing.puc.cl

ACCEPT FINAL

Ref.: Ms. No. COENG-10840R2

Key Last Planner System metrics to assess project performance in high-rise building and industrial construction projects

Daniel Pérez, Camilo Lagos, Luis Fernando Alarcón

Dear Mr. Lagos Orza,

Your Technical Paper, listed above, has been accepted for publication in ASCE’s Journal of Construction Engineering and Management.

Thank you for your contribution to the journal of Journal of Construction Engineering and Management. You will now be listed as a reviewer in the journals database. We ask that you review two papers within a year within your field of studies.

Your manuscript will now be forwarded to a Production Editor who will prepare it for publication. You will be notified of a publication date once your paper has been scheduled for an issue.

Thank you for submitting your work to ASCE’s Journal of Construction Engineering and Management.

Sincerely,

Tricia Kendiaw
Editorial Coordinator

In compliance with data protection regulations, you may request that we remove your personal registration details at any time. (Use the following URL: https://www.editorialmanager.com/coeng/login.asp?farr). Please contact the publication office if you have any questions.
7.2 CONFERENCE PAPER SCCC 2018: “CONSTRAINT BAG PROCESS MODEL: A PROCESS MINING APPROACH TO LEAN CONSTRUCTION”

The following conference paper was presented in the 27th International Conference of the Chilean Computer Science Society realized in Universidad Andrés Bello. The manuscript is presented in its original language and is available in IEEE Xplore webpage.
La industria de la construcción en Chile representa cerca del 6,4% de la economía nacional y su alza tiene estrecha relación con el crecimiento y calidad de vida del país [1]. El control y administración de su producción resulta ser de suma importancia en el proceso constructivo con el fin de aumentar la productividad en la industria. Así, es posible disminuir riesgos y costos al consumidor y la sociedad [2]. Dentro de los múltiples mecanismos de control y planificación es posible encontrar Last Planner System (LPS), basado en la filosofía Lean Construction (i.e., Construcción Sin Pérdidas, práctica que busca minimizar pérdidas en materiales, tiempo y esfuerzo aplicado con el fin de aumentar la producción y generación de valor [3]). Esta metodología ha permitido mejorar índices de producción en hasta un 30%, mejorando retornos económicos y estabilizando flujos de trabajo [4].

El uso de técnicas computacionales para la mejora en los procesos de control y seguimiento de proyectos de construcción se ha centrado principalmente en un análisis orientado a datos con una perspectiva clave-valor (e.g., ¿Qué número de compromisos se han incumplido en la planificación inicial de esta semana?, ¿Qué equipo se demora más en el cumplimiento de plazos?). Un buen ejemplo de esta perspectiva de análisis es el uso de técnicas de Big Data para la toma de decisiones en proyectos con gran cantidad de datos disponibles [5]. El auge del uso de sistemas de información ha permitido que disciplinas como la ciencia orientada a los datos (Data Science) lideren un enfoque más orientado a los datos en busca de obtener valor a partir del análisis de esa gran cantidad de datos disponibles [6]. Sin embargo, existe una perspectiva orientada a procesos [7] que no ha sido tan considerada y sistematizada con el objetivo de mejorar los procesos desde que inician hasta que terminan. La detección y análisis de patrones de procesos (e.g., la trayectoria seguida de cumplimiento, o incumplimiento, de los compromisos adquiridos inicialmente a lo largo de un mes de proyecto), pueden enriquecer y proporcionar un valor agregado a los análisis actuales enfocados en los procesos. En los últimos años, Process Mining [6], [8] ha emergido como una disciplina dentro de la ciencia orientada a los procesos (Process Science) y la computación capaz de analizar los datos desde esta perspectiva de procesos [9]. En concreto, Process Mining incluye técnicas y algoritmos para descubrir de forma automática modelos de proceso a partir de los datos, verificar la conformidad entre un modelo de procesos dato y los datos, o extender un modelo dado con información detectada en los datos [6].

El presente artículo propone el uso de Process Mining para...
el análisis de la perspectiva de procesos en proyectos de construcción. Sin ir más lejos, el artículo define un nuevo modelo llamado Constraint Bag Process Model (CBPM), el cual permite realizar de forma intuitiva un análisis de las trayectorias de cumplimiento de un conjunto de compromisos (i.e., restricciones) planificadas en proyectos de construcción, condicionadas a atributos como responsable, prioridad, tipo de restricción, entre otros. Finalmente, el modelo permite detectar trayectorias específicas dentro de una implementación de metodología Last Planner System (LPS).

El resto del artículo se estructura de la siguiente manera: la Sección II presenta una breve introducción a los conceptos de Last Planner Systems (LPS). Luego, la Sección III presenta la conceptualización del modelo Constraint Bag Process Model, y la Sección IV muestra su aplicación en un contexto concreto de LPS llamado IMPERA. Finalmente, se presenta el trabajo relacionado en la Sección V, y las conclusiones y el trabajo futuro en la Sección VI.

II. Last Planner System (LPS)


Figura 1. Etapas de LPS

Las etapas ilustradas en la Figura 1 corresponden a [11]:

- **Plan Maestro**: tiene como propósito establecer los principales hitos del programa a realizar. Se detallan las fechas más importantes del proyecto.
- **Planificación de Fases**: contempla un mayor nivel de detalle. Se especifican fechas de traspaso de actividades. Su realización tiene un fuerte énfasis en el trabajo colaborativo.
- **Lookahead**: una de las principales etapas de la metodología. Consiste en, de forma colaborativa, encontrar restricciones y factibilidad para las tareas a realizar en un periodo $t$ de tiempo futuro (i.e., típicamente un Lookahead comprende un periodo entre 4-6 semanas). En esta etapa, se establecen compromisos y fechas de liberación de restricciones. Entenderemos por restricción a un elemento o requisito que evita el comienzo, avance o término de una actividad según lo planeado. Una vez que esta esté liberada, significa que la actividad puede comenzar, continuar o terminar correctamente.
- **Programación Semanal**: concentra el mayor nivel de detalle de planificación. Establece el Inventario de Trabajo Ejecutable (ITE) para la semana. Además, se establecen indicadores que permitan conocer el estado actual del programa y/o proyecto.

En concreto, el modelo propuesto en este artículo se centra en la etapa lookahead. El modelo permitirá analizar de forma intuitiva las trayectorias de cumplimiento de las restricciones dentro de los periodos de lookahead.

Por simplicidad el modelo presentado en este artículo se basa en la metodología LPS. Sin embargo, los concepts definiados en este trabajo pueden ser fácilmente adaptados y aplicados a otras metodologías Lean Construction basadas en restricciones, e incluso, en otros contextos.

III. Constraint Bag Process Model (CBPM)

En esta sección se define el modelo Constraint Bag Process Model (CBPM). Este modelo se inspira en el concepto de una mochila de restricciones, i.e., una carga de trabajo que, de no cumplirse, se va acumulando en un actor determinado del proyecto.

Nótese, que el concepto de definir un modelo de proceso es un abuso del lenguaje. En concreto, esta sección propone una instancia específica de la estructura de datos requerida por los algoritmos de Process Mining para el contexto de proyectos de construcción [6]. En concreto, los elementos necesarios a definir son: 1) el concepto de caso o instancia del proceso (Sección A), 2) la definición de actividades del proceso (Sección B), y 3) el orden relativo entre actividades (Sección C). Adicionalmente, tanto los casos como las actividades son enriquecidas con atributos adicionales para su análisis (Sección D).

Según la definición CBPM, el resultado de aplicar algoritmos de descubrimiento de procesos sobre los datos estructurados, da como resultado el modelo del proceso a ser analizado. Dado el carácter interdisciplinario del método, y el sesgo representativo del modelo CBPM (e.g., por definición no puede existir paralelismo entre actividades), la recomendación es aplicar algoritmos con bajo nivel de complejidad, y con una salida fácilmente interpretable. En ese caso, buenos ejemplos de algoritmos a utilizar son Heuristic Miner [12], Inductive Miner [13], o alternativas comerciales similares como las proporcionadas por Disco [14] y Celonis [15, 16].

A. Definición de Caso

Entenderemos como caso a la ejecución de un conjunto de restricciones por una persona (o responsable, según LPS) en el periodo de tiempo comprendido en un Lookahead. A su vez, cada Lookahead comprende un periodo entre 4 y 6 semanas, dependiendo de la complejidad y decisión propia de cada proyecto en particular.

En otras palabras, un identificador de caso se define como una tupla $(l, r)$ donde $l$ indica el lookahead concreto del caso, y $r$ corresponde al $id$ del responsable del caso. Formalmente, definimos el conjunto de identificadores de caso $C$ como:

$$ C = \{(l, r) \mid l \in L \land r \in R\} $$

donde $L$ y $R$ corresponde al conjunto de lookahead y responsables considerados, respectivamente.
B. Definición de Actividades

Luego de definir los casos, es necesario definir las activid-

dades. Las actividades permitirán representar la criticidad de la

semana en función de los estados actuales de las restricciones,
y de la importancia con que se encuentren tipificadas (ALTA,

MEDIA, BAJA).

Con los estados actuales de las restricciones, semana a

semana, y su relación con su importancia, es posible definir un

color que representará el estado de la mochila de restricciones

para cada caso. Por lo tanto, las actividades o estados para
cada caso son: GREEN, YELLOW y RED. Donde GREEN

es el estado de menor criticidad, YELLOW el de mediana

criticidad y RED el de mayor criticidad. Estas actividades son
calculadas en base al estado e importancia de las restricciones
en la semana i de cada Lookahead.

B1. Estado de las Restricciones: Los estados de las

restricciones vienen definidos según la metodología LPS. Estos
son:

- Pendiente en Plazo (PP): una restricción está Pendiente

en Plazo cuando no ha sido liberada y aun no cumple su
plazo máximo de liberación comprometido.

- Atrasada (ATR): una restricción está Atrasada cuando

el plazo máximo de liberación comprometido se ha
cumplido y la restricción aún no ha sido liberada.

- Liberada a Tiempo (LAT): cuando la restricción fue li-
berada antes de cumplirse el plazo máximo de liberación
comprometido.

- Liberada con Atraso (LATR): cuando una restricción

ha sido liberada después de haberse cumplido el plazo
máximo de liberación comprometido.

De este modo, cuando se instancia una restricción, dado un
responsable, en el contexto de la primera semana, son creadas
en el estado inicial Pendiente en Plazo (PP). Después de esto,
cuando avanzamos a la semana siguiente, las restricciones
pueden tomar el valor de liberada a tiempo (LAT), liberada
con atraso (LATR) o atrasada (ATR), según el hito temporal
de entrega comprometido. En este trabajo, el estado de las
restricciones es importante para entender las reglas con que
definimos la relevancia de éstas.

B2. Importancia de las Restricciones: Las restricciones
que conforman un caso poseen distintos niveles de importancia
(ALTA, MEDIO, BAJO). Dicho nivel, junto con el estado de las
restricciones, condiciona la forma como se categorizan las
actividades (GREEN, YELLOW, RED).

En nuestro modelo nos hemos enfocado en aquellas res-
tricciones que aún no han sido liberadas; pendiente en plazo
(PP) y atrasadas (ATR), y para ellas definimos los siguientes
criterios ilustrados en las Tablas I y II.

La lectura de las Tablas I y II es la siguiente: para el caso
de porcentaje de restricciones en ALTA, entre 20 % y 50 %,
y si el complemento distribuye en «a lo menos» un 80 % de
MEDIAS y un 20 % de BAJAS, entonces el estado es RED.
En otras combinaciones de restricciones MEDIAS y BAJAS, el
estado será YELLOW.

C. Orden de actividades

Cada una de las actividades del proceso representa una
de las semanas dentro del lookahead. Consecuentemente,
se utiliza el orden entre las semanas como el orden entre
actividades. Formalmente, definimos una instancia del proceso
σ como la secuencia ordenada:

\[ \sigma = (a_1, a_2, \ldots, a_n) \] donde \( a_i \in A \)
donde \( n \) es el número de semanas del lookahead (e.g., 4 o 5),
y \( a_i \) representa la actividad de la semana \( i \) dentro del universo
A de actividades definidas (i.e., GREEN, YELLOW, RED).

D. Atributos de Caso y Actividad

Tanto las actividades como los casos se encuentran enrique-
cidos en su caracterización mediante atributos adicionales que
representan características más específicas del negocio.

D1. Caso: incluye atributos como id de caso, id de
responsable y su nombre correspondiente.

D2. Actividades: se agregan a los atributos adicionales el
id de la semana dentro del lookahead, fecha de inicio y
término del mismo, caracterización de las restricciones según
importancia (ALTA, MEDIA, BAJA) y según el tipo (Diseño,
Condiciones Previa, Mano de Obra, Materiales, Otros).

IV. EL CASO IMPERA

La presente sección muestra el despliegue del modelo
CBPM aplicando la metodología LPS, con datos obtenidos
a partir de un software de gestión y planificación llamado
IMPERA. A partir de su aplicación, se realiza un experimento
y se analizan diferentes tipos de preguntas a responder usando
el modelo propuesto.

A. Contexto

IMPERA es un software desarrollado para la implementa-

ción de LPS creado en 2002 por el Centro de Excelencia en
Gestión de Producción de la Pontificia Universidad Católica de
Chile (GEPSUC). La herramienta ha sido utilizada en diversos
países de Latinoamérica [17], creando más de 80 indicadores.
que apoyan a la toma de decisiones del proyecto. En el presente informe, para el modelo de CBPM, se utilizan diversos proyectos correctamente documentados en la plataforma de IMPERA.

B. Datos

En el contexto del experimento a realizar, se consideró la generación de datos correspondientes a 200 casos para diez responsables en 20 lookahead. En este caso, la duración de cada lookahead se ha fijado en 4 semanas. Se generaron los comportamientos de las variables consideradas teniendo especial cuidado en que su comportamiento sea representativo a los datos de IMPERA.

C. Método

Posterior a la obtención de los datos para este experimento, se utiliza el algoritmo de descubrimiento (conocido como process graph) de la suite Celonis Process Mining. Este es un algoritmo de la familia Heuristic Miner que permite obtener resultados claros y entendibles del flujo del proceso para mejorar la toma de decisiones. Además, permite la configuración de distintos dashboards personalizables para analizar más a fondo los datos dependiendo de las necesidades del usuario.

D. Resultados y Discusión

El algoritmo de descubrimiento de procesos de Celonis permitió obtener un modelo CBPM (cf. Figura 2), representación de los diversos patrones de comportamiento con que se relacionan las actividades definidas y las transiciones entre actividades.

A partir de este modelo, se pueden definir preguntas desde la perspectiva de procesos con interés para los responsables del proyecto. En concreto, se pueden definir preguntas sobre los casos y sus características con 1) presencia de alguna actividad, 2) presencia de una transición concreta entre actividades, y 3) presencia de patrones de transición más complejos.

En concreto, analizando el contexto de proyectos de construcción, se proponen las siguientes preguntas a modo ilustrativo:

- ¿Cómo se comportan las trazas (lookahead) que pasan por una Actividad RED?
- ¿Cómo se comportan los casos en que hay un cambio de GREEN a RED? ¿Logran recuperarse?
- ¿Cómo se comportan los casos en que hay loops entre estados? ¿Cuáles se “recuperan”? ¿Cuáles empeoran?

Nótese que, dada las limitaciones del papel, el análisis de los resultados que se puede hacer sobre él se hace de manera estática, listando las variantes y mostrando los resultados filtrados. Sin embargo, el análisis propuesto en el modelo CBPM se realizaría de una forma interactiva, estableciendo filtros en tiempo real (on-the-fly) sobre actividades o transiciones, o bien, filtros utilizando criterios más complejos (e.g., actividades con patrones como eventually follow).

Para los casos que terminan en RED, las restricciones del tipo MATERIALES y M.O son dominantes. Estas restricciones poseen importancia ALTA como se puede apreciar en la Tablas III, IV y la Figura 4.

D1. ¿Cómo se comportan las trazas (lookahead) que pasan por una Actividad RED?: Como se puede ver en la Figura 3, todos los casos que pasan por la Actividad RED. Dentro de estos casos, se pueden identificar 3 grupos: Casos que terminan en YELLOW; Casos que terminan en RED; y Casos que terminan en GREEN. Nos centraremos en los casos que terminan en RED y en YELLOW.

Figura 2. Proceso descubierto para todas las variantes.

Figura 3. Proceso descubierto para la pregunta 1

Para los casos que terminan en YELLOW, las restricciones del tipo Condiciones previas son dominantes. Estas restricciones poseen importancia ALTA como se puede apreciar en la Tablas III, IV y la Figura 4.
Tabla III
CASOS POR TIPO DE RESTRICCIONES QUE FLUYEN A TRAVÉS DE RED Y TERMINAN EN YELLOW

<table>
<thead>
<tr>
<th>Variante</th>
<th>%C.Previas</th>
<th>%M.O.</th>
<th>%Materiales</th>
<th>%Diseño</th>
<th>%Otros</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-R-Y-Y</td>
<td>50 %</td>
<td>50 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>G-R-R-Y</td>
<td>57 %</td>
<td>43 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Y-R-Y-Y</td>
<td>67 %</td>
<td>33 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>G-Y-R-Y</td>
<td>71 %</td>
<td>29 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Y-R-R-Y</td>
<td>83 %</td>
<td>0 %</td>
<td>17 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>

Tabla IV
CASOS POR IMPORTANCIA DE RESTRICCIONES QUE FLUYEN A TRAVÉS DE RED Y TERMINAN EN YELLOW

<table>
<thead>
<tr>
<th>Variante</th>
<th>%ALTA</th>
<th>%MEDIAS</th>
<th>%BAJAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-Y-R-Y</td>
<td>43 %</td>
<td>0 %</td>
<td>57 %</td>
</tr>
<tr>
<td>Y-R-Y-Y</td>
<td>75 %</td>
<td>0 %</td>
<td>25 %</td>
</tr>
<tr>
<td>G-R-Y-Y</td>
<td>75 %</td>
<td>0 %</td>
<td>25 %</td>
</tr>
<tr>
<td>Y-R-R-Y</td>
<td>83 %</td>
<td>0 %</td>
<td>17 %</td>
</tr>
<tr>
<td>G-R-R-Y</td>
<td>86 %</td>
<td>0 %</td>
<td>14 %</td>
</tr>
</tbody>
</table>

Tabla V
CASOS POR TIPO DE RESTRICCIONES QUE FLUYEN A TRAVÉS DE RED Y TERMINAN EN RED

<table>
<thead>
<tr>
<th>Variante</th>
<th>%C.Previas</th>
<th>%M.O.</th>
<th>%Materiales</th>
<th>%Diseño</th>
<th>%Otros</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-R-R-R</td>
<td>0 %</td>
<td>43 %</td>
<td>43 %</td>
<td>0 %</td>
<td>14 %</td>
</tr>
<tr>
<td>Y-Y-R-R</td>
<td>0 %</td>
<td>0 %</td>
<td>100 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>

Tabla VI
CASOS POR IMPORTANCIA DE RESTRICCIONES QUE FLUYEN A TRAVÉS DE RED Y TERMINAN EN RED

<table>
<thead>
<tr>
<th>Variante</th>
<th>%ALTA</th>
<th>%MEDIAS</th>
<th>%BAJAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-Y-R-R</td>
<td>100 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>Y-R-R-R</td>
<td>100 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>

**Figura 4.** Proceso descubierto para los casos que fluyen por RED y terminan en YELLOW.

**Figura 5.** Proceso descubierto para los casos que fluyen por RED y terminan en RED.

**D2.** ¿Cómo se comportan los casos en que hay un cambio de GREEN a RED? ¿Logran recuperarse?: Estos casos son representados en las Tablas VII, VIII y en la Figura 6. Como se puede apreciar, la tendencia es que las restricciones del tipo COND.PREVIAS sea dominante, junto con las restricciones de importancia ALTA.

**D3.** ¿Cómo se comportan los casos en que hay loops entre estados? ¿Cuáles se “recuperan”? ¿Cuáles empeoran?: Se pueden descubrir los siguientes Loops en la figura 2: GREEN- YELLOW, YELLOW-GREEN; GREEN- RED, RED-GREEN; GREEN- GREEN; YELLOW- YELLOW; RED-RED. Centraremos nuestro análisis en los loops GREEN- RED, RED-GREEN y RED- RED.

Respecto de los loops GREEN- RED, RED-GREEN, son casos que terminan en GREEN, poseen un 80% de Condiciones Previas. Un 60% de ellas tienen importancia ALTA.
Tabla VII
CASOS POR TIPO DE RESTRICCIONES QUE TIENEN SECUENCIA GREEN-RED

<table>
<thead>
<tr>
<th>Variante</th>
<th>%C.Previas</th>
<th>%M.O.</th>
<th>%Materiales</th>
<th>%Diseño</th>
<th>%Otros</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-R-Y-Y</td>
<td>57 %</td>
<td>43 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>G-R-G-G</td>
<td>80 %</td>
<td>0 %</td>
<td>20 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
<tr>
<td>G-R-Y-Y</td>
<td>50 %</td>
<td>50 %</td>
<td>0 %</td>
<td>0 %</td>
<td>0 %</td>
</tr>
</tbody>
</table>

Tabla VIII
CASOS POR IMPORTANCIA DE RESTRICCIONES QUE TIENEN SECUENCIA GREEN-RED

<table>
<thead>
<tr>
<th>Variante</th>
<th>%ALTA</th>
<th>%MEDIAS</th>
<th>%BAJAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-R-G-G</td>
<td>60 %</td>
<td>0 %</td>
<td>40 %</td>
</tr>
<tr>
<td>G-R-Y-Y</td>
<td>75 %</td>
<td>0 %</td>
<td>25 %</td>
</tr>
<tr>
<td>G-R-R-Y</td>
<td>86 %</td>
<td>0 %</td>
<td>14 %</td>
</tr>
</tbody>
</table>

Figura 6. Proceso descubierto para los casos con cambio GREEN a RED.

Como este caso corresponde a una sola variante (G-R-G-R), su tendencia se puede apreciar en la Figura 7.

Respecto de los loops RED-RED (ver Figura 8), se puede apreciar que las restricciones de importancia ALTA son las predominantes.

Figura 7. Proceso descubierto para los casos con loops GREEN-RED, RED-GREEN.

V. TRABAJO RELACIONADO

La capacidad de procesar grandes volúmenes de información ha impulsado a diversas industrias a obtener nueva información valiosa respecto a los procesos involucrados. Este fenómeno, llamado Big Data, ha aparecido en diversas áreas siendo la construcción una de ellas. En la actualidad, se han desarrollado técnicas de Data Mining para aprender de proyectos pasados [18], hasta implementación de técnicas de Machine Learning y modelos de regresión para predecir tiempos de ciclo en actividades de construcción [19]. Sin embargo, una mirada desde la vista de Process Mining no ha sido estudiada [5]. Process Mining resulta ser la conexión directa entre Data Science (ej.: Big Data) y Process Science. Esta disciplina combina herramientas de las tecnologías de la información y de gestión con el fin de mejorar distintos procesos operacionales [6]. Su aplicación ha sido exitosa en diversas áreas, tales como procesos de negocios, salud [20], y asignación de recursos humanos [21]; áreas donde también se ha aplicado de forma exitosa la filosofía Lean [22]. Más detalles acerca de la relación entre los conceptos de Process Science y Data Science pueden ser encontrados en [9].

VI. CONCLUSIONES Y TRABAJO FUTURO

Este trabajo ilustra el potencial de utilizar Process Mining en un contexto de la industria de la construcción, permitiendo concluir que es posible generar valor para este contexto, siempre y cuando, durante el proceso de Process Mining
se genere un diseño orientado a éste, que incluya todos los atributos necesarios para una sólida definición de casos y actividades. Es por este que este artículo propone el Constraint Bag Process Model (CBPM), como una herramienta útil para tal análisis. El modelo generado, resulta ser una herramienta efectiva en la representación de casos particulares y generales desde una perspectiva de procesos, identificando cambios en el cumplimiento de restricciones semana a semana. La definición de actividades incluida en CBPM abre la posibilidad de ir descubriendo nuevos atributos relacionados en concordancia con lo buscado según el negocio y/o usuario; es decir, el modelo propuesto es altamente expansible y permite añadir diferentes atributos que permitan contestar diferentes preguntas. Queda como trabajo futuro, considerar nuevas perspectivas de análisis; por ejemplo, enriqueciendo la paleta de atributos descriptores propios del negocio y otros atributos calculados para estos propósitos. Además, es importante indicar que se puede hacer un estudio considerando los recursos (personas) así como su especialidad para analizar la incidencia de éstos en el comportamiento específico de las variantes detectadas.

**AGRADECIMIENTOS**

Los autores quieren agradecer a Celonis Academic por permitirnos utilizar la herramienta y al Centro de Excelencia de Gestión de Producción (GEPRO) por facilitarnos los datos disponibles en su software IMPERA. Este trabajo ha sido parcialmente financiado por el Departamento de Ciencias de la Computación UC / Fond-DCC-2017-0001.

**REFERENCIAS**


---

**Tabla IX**

<table>
<thead>
<tr>
<th>Variante</th>
<th>%C. Previsas</th>
<th>%M. O.</th>
<th>%Materiales</th>
<th>%Diseño</th>
<th>%Otros</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-R-R-Y</td>
<td>83%</td>
<td>0%</td>
<td>17%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Y-R-R-R</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>G-R-R-Y</td>
<td>57%</td>
<td>43%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Y-R-R-G</td>
<td>43%</td>
<td>57%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

**Tabla X**

<table>
<thead>
<tr>
<th>Variante</th>
<th>%ALTA</th>
<th>%MEDIAS</th>
<th>%BAJAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-R-R-Y</td>
<td>83%</td>
<td>17%</td>
<td>0%</td>
</tr>
<tr>
<td>G-R-R-Y</td>
<td>86%</td>
<td>0%</td>
<td>14%</td>
</tr>
<tr>
<td>Y-R-R-R</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Y-R-R-G</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>G-R-R-Y</td>
<td>86%</td>
<td>0%</td>
<td>14%</td>
</tr>
</tbody>
</table>


