Sharma, A. and Trivedi, J. (2021). "Application of Information Theory in Last Planner® System for Work Plan Reliability." *Proc. 29th Annual Conference of the International Group for Lean Construction (IGLC29),* Alarcon, L.F. and González, V.A. (eds.), Lima, Peru, pp. 727–736, doi.org/10.24928/2021/0147, online at iglc.net.

APPLICATION OF INFORMATION THEORY IN LAST PLANNER® SYSTEM FOR WORK PLAN RELIABILITY

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ABSTRACT

Last planner system® (LPS) is an effective tool for continuous monitoring and improvement of the planning. One of the main parts of LPS is the constraint removal discussion. Identifying and removing the constraints before the execution can influence the reliability of the plan and can ultimately improve the project performance. Previous research works have indicated the use of Information theory to quantify the effect of constraint removal discussion on the performance of the weekly work plan while using Percentage Plan Complete (PPC) as an indicator of work plan reliability and considering a limited range of constraints categories. Earlier studies have proved that Task Anticipated (TA) and Task Made Ready (TMR) are better indicators of the project duration than PCC. In this paper, the researchers have used information theory to assess the effect of the constraint removal discussion on PPC, TA, and TMR of the construction projects while considering a wider range of constraints. The results signified that the important constraint categories vary for improving PPC and improving TA & TMR. Identifying and discussing the main constraint categories could improve the work plan reliability indicators up to 18%. The framework can be used repeatedly and the results can contribute in improving the effectiveness of weekly meetings in the future.

KEYWORDS

Last planner® system, constraint analysis, make-ready planning, work plan reliability, information theory.

INTRODUCTION

The last planner system was designed by Glenn Ballard and Gregory Howell using the action research approach in the early 1990s'. Construction professionals have been using it widely in the architecture, engineering, and construction (AEC) industry for over two decades. Unlike the critical path method (CPM) the LPS uses pull driven scheduling approach to improve the planning reliability (Dave, Hämäläinen, & Koskela 2015). One of the main features of LPS is the constraint removal discussion. Research works have proved that identifying and removing the constraints prior to the execution can influence the reliability of the look-ahead plan and ultimately improve the project performance (Hamzeh et al. 2015).

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Lindhard and Wandahl (2012) specified nine types of constraints – Design availability, Material availability, Worker availability, Equipment availability, Space availability, Completion of predecessor activities, External conditions (weather related), Safe working conditions, and Unknown working conditions. It is a difficult task for a planner to identify the constraints and discuss them properly with various project stakeholders; in the weekly meeting within a limited time. Thus prioritizing the constraints before the weekly meetings can result in improved workflow reliability. Javanmardi et al. (2020) used information theory to quantify the effect of weekly meetings on just the PPC of the project using a limited number of constraints. The Information theory is a mathematical representation of the transmission and processing of information through communication (Shannon 1948). The research work of Hamzeh et al. (2015) has proved task anticipated (TA) and task made ready (TMR) to be more accurate representative of the project duration than PPC.

The goals of this research were - (1) To quantify the effect of weekly constraint removal discussions on the quality of the work plans, (2) To identify the important constraint categories for improvement of the work plan reliability indicators (PPC, TA and, TMR) using the Information theory, (3) To assess the discrepancy in the important constraint categories for different work plan reliability indicators. The researchers used information theory to quantify the collected data from three sites for five weeks.

LITERATURE REVIEW

Jang and Kim (2008) identified that workflow reliability is highly correlated with the performance of the look-ahead process by using a statistical analysis method. Their research identified a positive correlation between the performance of the look-ahead process and the PPC while using PCR (Percentage Constraint Removal) to assess the performance of the look-ahead planning process. Liu et al. (2011) proved that by implementing LPS, the workflow reliability can be increased which will eventually lead to a significant increase in labour productivity. Another research verified that workflow reliability and schedule performance are significantly correlated while using a quantitative analysis approach by performing two case studies. The paper verified that an increase in PPC suggests an improvement in workflow reliability. (Olano, Alarcón, and Rázuri 2009).

Hamzeh et al. (2019) discovered that projects tend to run behind the scheduled milestones due to poor performance in (1) making tasks ready and removing constraints, (2) committing to critical tasks, and (3) matching load to capacity. A latest research proposed a few new matrices and revealed a mismatch problem between load and capacity resulting in wasted resources due to poor allocation strategies in weekly work plan that negatively impacted project performance. Another research showed (Hamzeh et al. 2019). Shehab et al. (2020) have developed a simulation model to modify planned production rates and to generate a more realistic production rate named Improved Production Rate (IPR). The proposed model proved to be useful as a basis for a decision support system for planners to evaluate the reliability of their planned production rates.

Javanmardi et al. (2020) identified the lack of research to quantify constraint removal discussions and how they affect the work plan reliability. They used information theory to identify the information gain and its transmission efficiency to identify its effect on the work plan reliability. The research used *only PPC as the indicator of work plan reliability* while using a *limited set of constraints*. Recently identified more accurate indicators of work plan performance - TA and TMR were not considered (Hamzeh et al. 2015).

METHODOLOGY

The research included six phases in twelve steps (refer Figure-1). In the first two phases extensive study was performed on LPS related works, which lead to defining the topic, identification of research gaps and determining the objective and scope of work. Third phase was to find case study sites. In fourth phase the data collection was done in two steps - (1) the frequency of constraint removal discussions during the weekly meetings were recorded, and (2) various work plans were collected to compute the values of work plan reliability indicators. In the fifth phase the data analysis was performed in two steps - (1) the performance indicators were divided into two groups using the k-means clustering algorithm, and (2) constraint removal entropy, performance indicator's entropy, mutual information between constraint removal and indicator, and information gain from constraint removal discussions were calculated. In the final phase the researchers identified the important constraint categories and their impact on various work plan reliability indicators was calculated for each site.

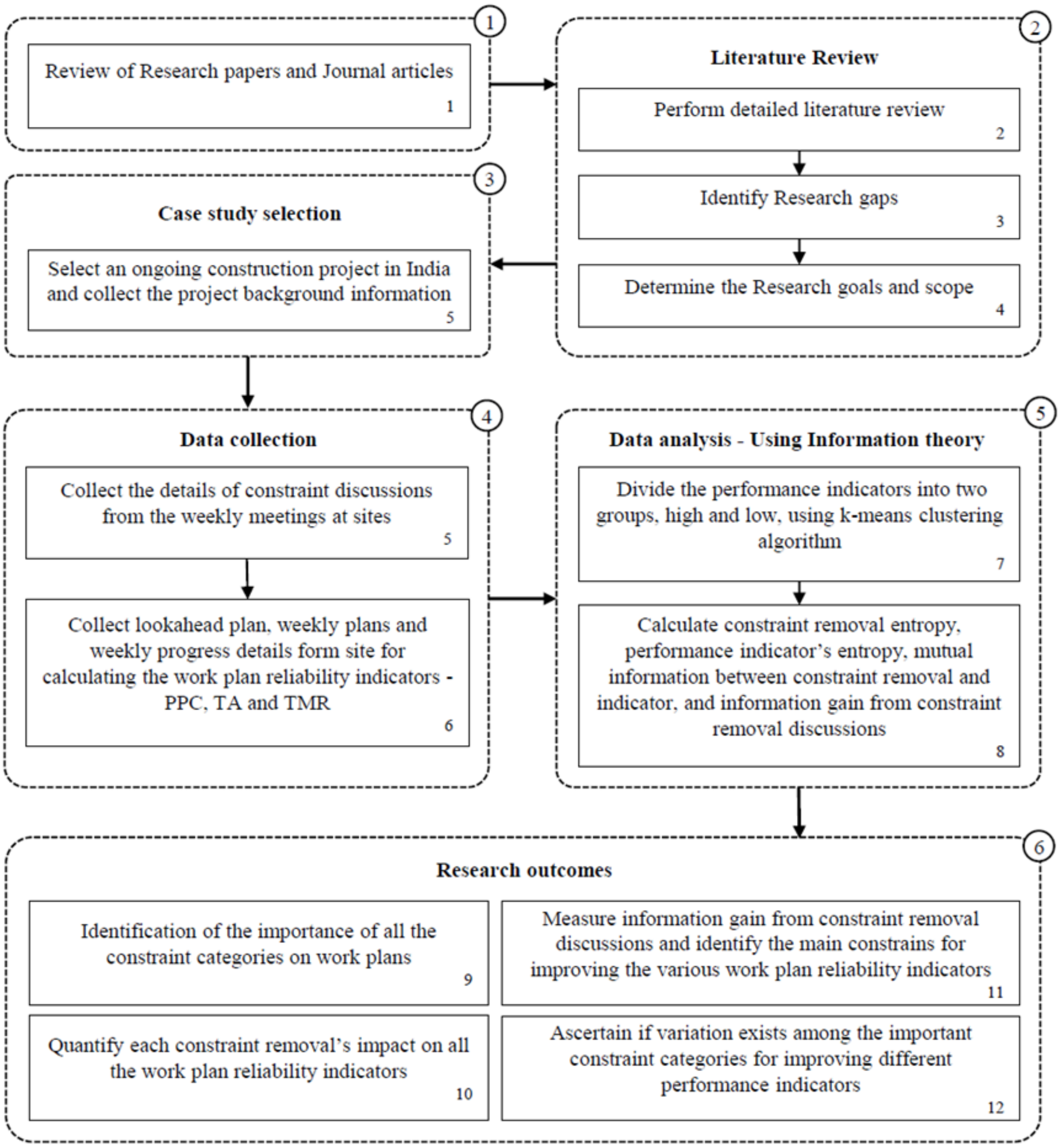

Figure 1: Flowchart of research methodology

CASE STUDIES

Various construction organizations across the nation were approached with an aim of exploring their live construction projects as case studies. The organizations which responded positively were selected as case studies. Two case studies were of a national level contracting firm, while the other case study was of a local city contractor. The details of these sites and their weekly meetings are given in the table below:

Table 1: Details of case studies

	Case study 1	Case study 2	Case study 3
Type	Residential	Industrial	Residential
Built-up area	23,000 sqm	3,10,000 sqm	17,000 sqm
Status of work during data collection	Finishing	Finishing	RCC, Finishing
Contractor	C1	C1	C2
Avg. Duration of weekly meetings	54 minutes	65 minutes	38 minutes
Avg. nos. of participants	18	22	8

All the case study sites were using LPS upto different extent. The level of implementation was as shown in Table 2.

Table 2: Level of implementation of LPS

LPS Component	Case Study - 1	Case Study -2	Case Study - 3
Phase Scheduling	Not Implemented	Not Implemented	Not Implemented
Look-ahead Planning	Partial Implementation	Partial Implementation	Not Implemented
Weekly Planning	Implemented	Implemented	Implemented
Analysis and Continuous Improvement	Implemented	Implemented	Partial Implementation

The phase scheduling was not implemented in any of the projects. Contractor 1 (C1) had implemented the look-ahead planning by involving the last planners and identifying constraints at an early stage. Whereas on the site of case study-3 the look-ahead planning stage of LPS was not implemented. The last planners were not involved and constraints were not identified at look ahead stage. The look-ahead plan was prepared by extracting the master schedule. The weekly planning was done at every site. At sites of case study-1 & 2 analysis and continuous improvement was fully implemented. The site personnel used to identify the reason of delays and for future improvement a plan was made on monthly basis. On the site of case study-3 only the reasons of delay were identified, which showed partial implantation of the last component of LPS.

DATA COLLECTION

The researcher collected discussion data by attending the weekly meetings for five weeks. For the purpose of these research it had been considered that all the decisions affecting the performance of the work plan are discussed only in the weekly meetings.

The other part of data collection consisted of collecting the lookahead plan, weekly plan and the actual weekly progress from site in order to calculate the performance indicators – PPC, TA and TMR. The formula used for the performance indicator calculation are:

$$Percentage\ Plan\ Complete = \frac{Number\ of\ tasks\ executed\ in\ a\ week}{Total\ number\ of\ tasks\ planned\ for\ a\ week} \times 100\%$$

$$Task\ Anticipated = \frac{Number\ of\ anticipated\ tasks\ from\ look\ ahead\ plan}{Total\ number\ of\ tasks\ on\ weekly\ work\ plan} \times 100\%$$

$$Task\ Made\ Ready = \frac{Number\ of\ completed\ tasks\ out\ of\ anticipated\ tasks}{Total\ number\ of\ tasks\ on\ weekly\ work\ plan} \times 100\%$$

In the data collection the constraint categories has been classified into nine types - X1 to X9. The undiscussed constraint category for each site has been not taken into consideration. The crosstab between the week and the constraints category represents the number of times a certain category of constrain was discussed for the activities in the next weekly plan. The value of the performance indicators for the next week is presented.

Table 3: Constraint Removal Discussion & work plan reliability indicators for case study 1

Week	X_1	X_2	X_3	X_4	X_5	X_6	X_8	PPC	TA	TMR
1	3	4	5	2	3	5	3	72%	82%	62%
2	0	1	3	0	3	3	2	67%	75%	46%
3	1	3	2	0	0	4	2	85%	75%	48%
4	1	1	2	0	1	4	3	72%	82%	66%
5	0	3	2	0	4	2	2	68%	72%	46%

Table 4: Constraint Removal Discussion & work plan reliability indicators for case study 2

Week	X_1	X_2	X_3	X_4	X_5	X_6	X_8	PPC	TA	TMR
1	1	3	5	1	0	1	1	79%	83%	52%
2	1	1	3	0	1	0	0	77%	80%	48%
3	0	4	5	1	1	3	0	85%	70%	38%
4	2	2	4	1	0	2	0	70%	86%	39%
5	0	2	3	1	0	2	0	74%	65%	26%

Table 5: Constraint Removal Discussion & work plan reliability indicators for case study 3

Week	X_1	X_2	X_3	X_4	X_5	X_6	X_8	PPC	TA	TMR
1	0	0	2	0	2	1	0	89%	86%	76%
2	0	1	2	1	4	2	0	68%	87%	52%
3	0	2	3	1	3	0	0	74%	74%	50%
4	1	1	2	0	3	0	0	78%	69%	52%
5	2	0	4	0	4	0	2	56%	72%	33%

Here; X_1 - Design availability, X_2 - Material availability, X_3 - Worker availability, X_4 - Equipment availability, X_5 - Space availability, X_6 - Completion of predecessor activities, X_7 - External Conditions (weather related), X_8 - Safe working conditions, X_9 - Unknown working conditions

DATA ANALYSIS

The collected data was processed using Information theory, for which the following steps were followed (Shannon 1948):

1. As discussed in the data collection chapter, a cross-tab is generated between every *X* (i.e. X_1, X_2, ..., X_9) and *Y (performance indicators - PPC, TA & TMR)*. Each cross-tab display the distribution of *X* tab against *Y* tab.
2. The performance indicators are classified in two distinct non-overlapping categories using the k- means clustering algorithm *(by NCSS 2020 software)*.
3. Add rows and columns at the end and take the sum of all rows and columns of the cross-tabs generated in the previous step.
4. Calculate Joint and Marginal probabilities by dividing every cell of cross-tabs in step (ii) by the total sum.
5. Calculate joint and marginal entropies using the following equation:

$$H(X,Y) = \sum_{i=1}^{m_x}\sum_{j=1}^{m_y} p(x_i, y_j)\log_2 \frac{1}{p(x_i, y_j)} \ bits$$

6. Calculate every X and Y entropies using the following equation and summing marginal entropies calculated in step (v).

$$H(X) = \sum_{i=1}^{m} p(x_i)\log_2 \frac{1}{p(x_i)} bits$$

7. Calculate the mutual information using the following equation based on the results of steps (v) and (vi).

$$I(X,Y) = H(X) + H(Y) - H(X,Y) \ bits$$

The data analysis was done for all three case study for each of the performance indicators (PPA, TA, and TMR). Here an example of detailed analysis for the TA of Case study 1 has been presented.

The following table shows the clustering results achieved by k-means analysis using the NCSS 2020 software. The results of TA values were classified into two categories A and B. Group A has TA of 82%. Category B has an average TA of 74% with values ranging from 72% to 75%.

Table 6: Constraint removal discussion and TA categorization for case study-1

Week	X_1	X_2	X_3	X_4	X_5	X_6	X_8	TA	Category
1	3	4	5	2	3	5	3	82%	A
2	0	1	3	0	3	3	2	75%	B
3	1	3	2	0	0	4	2	75%	B
4	1	1	2	0	1	4	3	82%	A
5	0	3	2	0	4	2	2	72%	B

Here; X_1 - Design availability, X_2 - Material availability, X_3 - Worker availability, X_4 - Equipment availability, X_5 - Space availability, X_6 - Completion of predecessor activities, X_7 - External Conditions (weather related), X_8 - Safe working conditions, X_9 - Unknown working conditions

By following the calculation steps enlisted in this chapter the *H(X)*, *H(Y)*, *H(X,Y)* and *I(X,Y)* were calculated. The results can be seen in the following table:

Table 7: Entropy and mutual information for TA for case study-1

Constraint	H(X)	H(X) Rank	H(Y)	H(X,Y)	I(X,Y)	I(X,Y) Rank
X_1	1.52	3	0.97	1.92	0.57	2
X_2	1.52	3	0.97	1.92	0.57	2
X_3	1.37	5	0.97	1.92	0.42	6
X_4	0.72	7	0.97	1.37	0.32	7
X_5	1.92	1	0.97	2.32	0.57	2
X_6	1.92	1	0.97	2.32	0.57	2
X_8	0.97	6	0.97	0.97	0.97	1

Here Entropy of constraint discussions *H(X)* represents the information gained by observing the frequency of constraint discussions. Entropy of performance indicators *H(Y)* signifies the information gained by observing the value of performance indicator. The Joint Entropy *H(X,Y)* quantifies the information gained by observing both - the frequency of discussion of a particular constraint and the performance indicator. Mutual Information *I(X,Y)* signifies the quantify the information gained about a performance indicator by observing the frequency of discussion of a particular constraint category.

For identification of the main constraint categories affecting the work plan reliability a graph of Mutual information *I(X,Y)* vs. the Entropy *H(X)* was plotted as shown in Figure 2. The dotted lines shows the average values of entropy and mutual information.

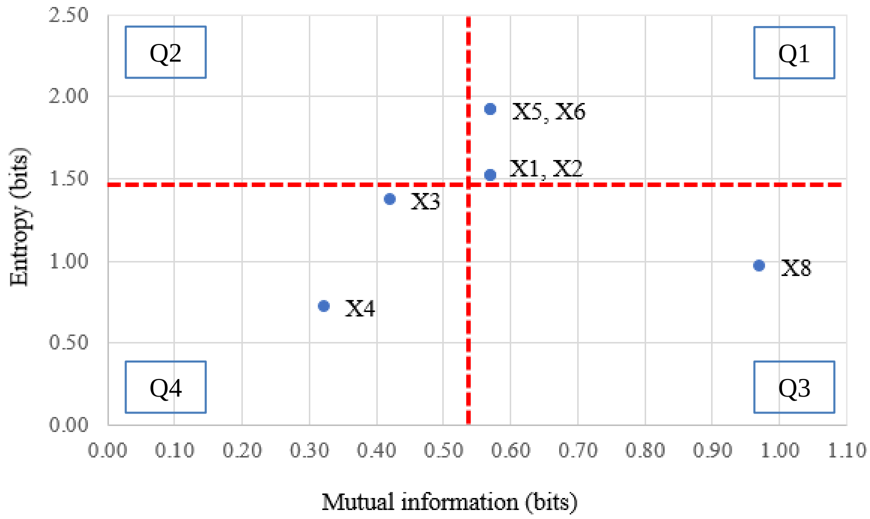

Figure 2: Mutual information vs. Entropy for constraints for case study-1 (TA) (Based on the theory adapted from Javanmardi et al. (2018); Javanmardi et al. (2020))

The constraint categories in the 1st quadrant are both important for TA improvement and discussed effectively. Thus the site team should continue discussing them in the same manner. In this project, discussion of Design availability, Worker availability, Completion of predecessor activity, and Safe working conditions are in this category.

In the 2nd quadrant, the constraint categories were less important for TA improvement but discussed effectively. Such constraint categories shall be addressed by the participants briefly with less effort in the future. No such constraint categories are present here.

The constraint categories in the 3rd quadrant are important for TA improvement but were not discussed effectively by the participants. Unsafe working conditions fall in this quadrant. For instance, the scaffolding work for painting work of ceiling was not meeting the safety standard. Due to which the performance indicator value suffered. Despite its massive effect on the work plan reliability, the constraint was not discussed enough.

In the 4th quadrant, the constraint categories were less important for TA improvement and were discussed briefly. Equipment availability and worker availability were discussed briefly and they didn't have a significant impact on the TA. Prioritizing the constraint discussion in this way will assure that sufficient information for TA improvement is gained during the meetings.

To quantify the effect of constraint removal on Improvement of work plan reliability the relative importance of each constraint category was calculated using the following formula:

$$\text{Relative importance of a constraint category} = \frac{\mathrm{I}(\mathrm{x}_1, \mathrm{y})}{\Sigma_{\mathrm{i}} \mathrm{I}(\mathrm{x}_{\mathrm{i}}, \mathrm{y})}$$

The relative importance is then multiplied by the overall Performance Indicator improvement, which is the difference between the average performance indicators of Groups made by k-means analysis. For instance, Relative importance of $X_8 \times$ Performance indicator (TA) improvement is equal to $0.24 \times 8\% \simeq 1.9\%$.

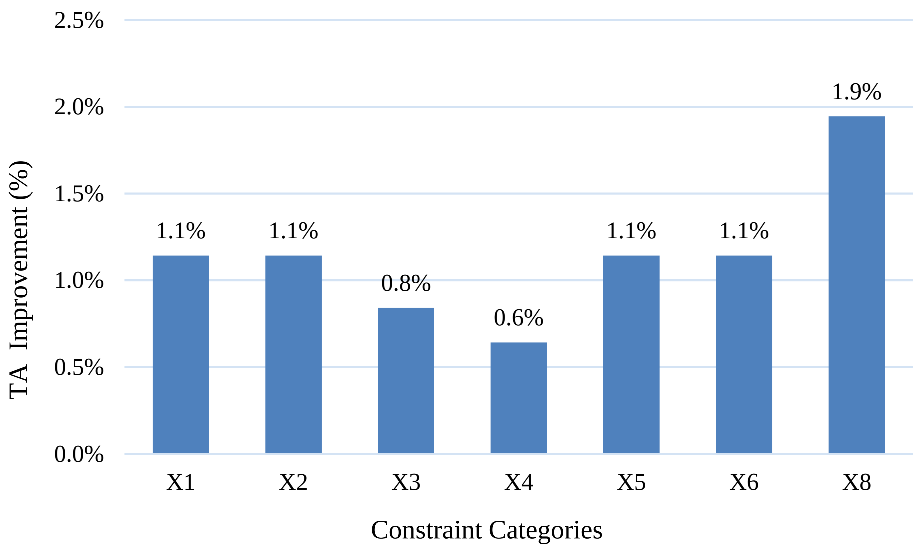

Figure 3: Expected TA improvement by various constraint categories for case study-1 (Based on the theory adapted from Javanmardi et al. (2020))

To quantify the effect of constraint removal on the improvement of work plan reliability the relative importance of each constraint category was calculated. The barchart shows that discussions on Safe working conditions (X_8) had the highest (1.9%) contribution to the TA improvement, followed by a 1.1% improvement from Design availability (X_1), Material availability (X_2), Space availability (X_5), Completion of predecessor activities (X_6). This indicates that removing constraints related to safe working conditions will have the highest positive impact on the TA.

The data analysis was performed in the same manner for all the performance indicators of each case study.

CONCLUSION

The data analysis performed using the Information theory identified the most and least important constraint categories affecting the work plan reliability. It will help the project managers in conducting more effective weekly meetings with defined agenda. The quantified values of the expected improvement in performance indicators (PPC, TA, and TMR) helped in understanding the importance of efficient constraint removal discussions. The study can be applied to any construction project using LPS anywhere in the world.

The results of case study-1 indicated that design availability, material availability, space availability, and completion of predecessor activities were the four most important constraint categories for improving work plan reliability. The analysis signified that the removal of these four constraints could improve PPC by 11%. For TA and TMR the important constraints for increasing the work plan reliability were safe working conditions and design availability. These two categories can improve the TA and TMR by 3% and 6%, respectively. The important categories for PPC and TA-TMR were different.

The results of case study-2 showed that material availability, worker availability, and completion of predecessor activities were the three most important constraint categories for improving work plan reliability. The analysis revealed that the removal of these three constraints could improve PPC by almost 6%. For TA and TMR the important categories were design availability, material availability, and completion of predecessor activities. These three categories can improve the TA and TMR by 13% and 12%, respectively. Again the important categories for PPC and TA-TMR were found to be different.

The results of case study-3 indicated that completion of predecessor activities and material availability were two main important constraint categories for improving the work plan reliability. The analysis signified that the removal of these two constraints could improve PPC by almost 9%. For TA and TMR the important constraints for increasing the work plan reliability were safe working conditions and completion of predecessor activities. These two categories can improve the TA and TMR by 8% and 18%, respectively. Again the important categories for PPC and TA-TMR were different. A direct effect of the project parameters (area, duration of a meeting, etc.) and the LPS implementation level on the results have not been discovered in any of the case studies.

The results proved that the important constraint categories for improvement of TA and TMR varies from the important constraint categories for PPC improvement. This research is applicable to any construction project applying the LPS anywhere in the world. The result of the analysis only indicates the important constraint categories at a particular stage of the project. That means the main constraint categories can vary for various stages of execution. The important constraint categories while working on the basement level will be different from the important constraint categories in the finishing stage of the project. Thus the analysis has to be repeated as the project progresses from one stage to another. The organizations may apply this analysis to their projects at every stage and the results can be used to create a database of important constraint categories at various stages of the project.

It was observed that few of the constraints were interrelated. For example, due to absence of the labours the plumbing work could not be finished, which shows material related constraints. Fixing of pipes was a predecessor activity for other finishing activities and due to fewer labours the plumbing work could not be finished. As a result, the successor activities couldn't get complete. These inter-relations can be studied to enhance the outcomes of the research.

In this research, the constraint removal discussion were counted based on frequency regardless of the duration of discussion. Future research work can look into finding a way to incorporate the time aspect in the data analysis.

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