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Moslem Sheikhhoshkar, Hind Bril El Haouzi, Alexis Aubry, Farook Hamzeh. An advanced exploration of functionalities as the underlying principles of construction control metrics. *Smart and Sustainable Built Environment*, 2024, 13 (3), pp.644-676. 10.1108/SASBE-12-2023-0379 . hal-04445986

HAL Id: hal-04445986

<https://hal.univ-lorraine.fr/hal-04445986v1>

Submitted on 8 Feb 2024

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An Advanced Exploration of Functionalities as the Underlying Principles of Construction Control Metrics

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Abstract

Purpose

In academics and industry, significant efforts have been made to lead planners and control teams in evaluating project performance and control. In this context, numerous control metrics have been devised and put into practice, often with little emphasis on analyzing their underlying concepts. To cover this gap, this research aims to identify and analyze a holistic list of control metrics and their functionalities in the construction industry.

Design/methodology/approach

A multi-step analytical approach was conducted to achieve the study's objectives. First, a holistic list of control metrics and their functionalities in the construction industry was identified. Second, a quantitative analysis based on Social Network Analysis (SNA) was implemented to discover the most important functionalities.

Findings

The results revealed that the most important control metrics' functionalities could differ depending on the type of metrics (lagging and leading) and levels of control. However, in general, the most significant functionalities include managing project progress and performance, evaluating the lookahead level's performance, measuring the reliability and stability of workflow, measuring the make-ready process, constraint management, and measuring the quality of construction flow.

Originality

This research will assist the project team in getting a comprehensive sensemaking of planning and control systems and their functionalities to plan and control different dynamic aspects of the project.

Keywords: Functionality, Control Metrics, Social Network Analysis (SNA), Project Planning, Lean Construction, Production Control,

1. Introduction

The construction industry is highly complex, involving multiple stakeholders, a multi-organizational and multi-cultural system, and various variables that can significantly impact

project outcomes (Aaltonen and Kujala 2016). Effective planning and control are essential to ensure the project is delivered on time, within budget, and according to the defined objectives. Planning determines the project's objectives and how to accomplish them, while control ensures that the project stays within its scope and achieves its objectives (Hamzeh et al. 2020). To ensure the task remains on schedule and achieves the desired results, developing a set of metrics to monitor and analyze the project's progress, performance, and other vital dynamic aspects is a must.

In this regard, Earned Value Management (EVM) is the commonly employed control system that combines three project management aspects: scope, cost, and time (Hamzeh et al. 2019). Recent studies have indicated that even though EVM has its advantages, it also has several drawbacks including a lack of attention to workflow, an inability to distinguish between critical and non-critical activities, a lack of support for lean construction adoption, inaccurate percentages of work completed and completion prediction, a lack of information about the reliable assignment of work downstream, and increased uncertainty due to detailed planning for long scopes (Cândido et al. 2014; Hamzeh et al. 2019; Hazır 2015; Kim and Ballard 2010; Pérez et al. 2022). To address these issues, a wide variety of control metrics associated with several planning and scheduling methods have been developed and implemented over the past decades.

Most of the developed metrics are embedded within the Last Planner System (LPS), which is a production planning and control system based on lean principles designed to decrease variation and increase planning reliability (Hamzeh et al. 2020). In this method, control metrics focus on assessing completed activities, identifying and analyzing reasons for non-completion (RNCs), eliminating those reasons, planning reliability, constraint removal, resource workload and capacity, construction flow and more (Ballard and Tommelein 2021; Sacks et al. 2017).

In addition, several papers suggested using a dynamic buffer monitoring approach to address and control the complexity of construction projects with high uncertainty degrees (Hu et al. 2016; Zhang et al. 2018). To enhance situational awareness, Lin and Golparvar-Fard (2021) developed new location-driven evaluation metrics to aid forecast and analysis of reliability in lookahead plans and transition task-based processes to location-driven methods. In addition, some academics concentrated on Takt Time Planning and Control (TTP) to manage daily meetings on-site and move control to the location of value generation. To monitor the progress of the work packages, they also established various metrics, such as wagon completion, takt area completion, and time slot completion (Binninger et al. 2017; Keskiniva et al. 2021).

The number of control metrics that facilitate project performance analysis has grown over time. Although various control metrics have increased the scope of options available to the project team for selecting aligned metrics with project objectives, it has also increased the complexity of determining which control metrics are most appropriate. The lack of knowledge and information among project stakeholders on the potential application and effectiveness of project planning and control metrics is cited as another issue (Al Nasser et al. 2016; Sheikhhoshkar et al. 2023). Furthermore, it mindlessly matches appropriate planning skills to various planning activities without understanding the underlying requirements. Another gap that can be mentioned is the lack of knowledge about the functionalities required at the early stages as opposed to the late stages of the project planning process, particularly those needed for planning, control, and both;

functionalities can either be applied proactively (leading) or reactively (lagging); those can be used in the short-term to impact crew production versus long-term ones that influence design decisions, logistics, supply chain management, procurement, subcontractors onboarding time, etc.

To address these concerns and improve the project team's understanding of project planning methods and control metrics, the functionality concept is defined and analyzed. This follows Sheikhhoshkar et al.'s (2023) definition for integrated scheduling methods, aiming to clarify the objectives and concepts underlying project planning methods and control metrics. In this concept, the control metric's functionality is defined as the functions and main targets that can be tracked and controlled by the corresponding metric. To this end, and to better understand the control metrics' functionalities in the construction industry, the objectives of this paper are as follows:

- 1- Extract a holistic list of metrics used to control construction projects
- 2- Identify underlying principles of control metrics as Control Metrics' Functionalities (CMF)
- 3- Analyze the listed functionalities based on their interdependencies and determine the most important functionalities using two perspectives: level of control, type of metrics

The following sections describe the research methodology, analyses and results, validation, research discussions, contributions and future recommendations, and finally, conclusions and limitations.

2. Research Methodology

The authors adopted a multi-step analytical approach to accomplish the aims and objectives of this paper. The methodology process is indicated in Fig. 1. The approach consists of two primary and interconnected processes: data collection and processing, and data analysis. Each is described more deeply in the following subsections.

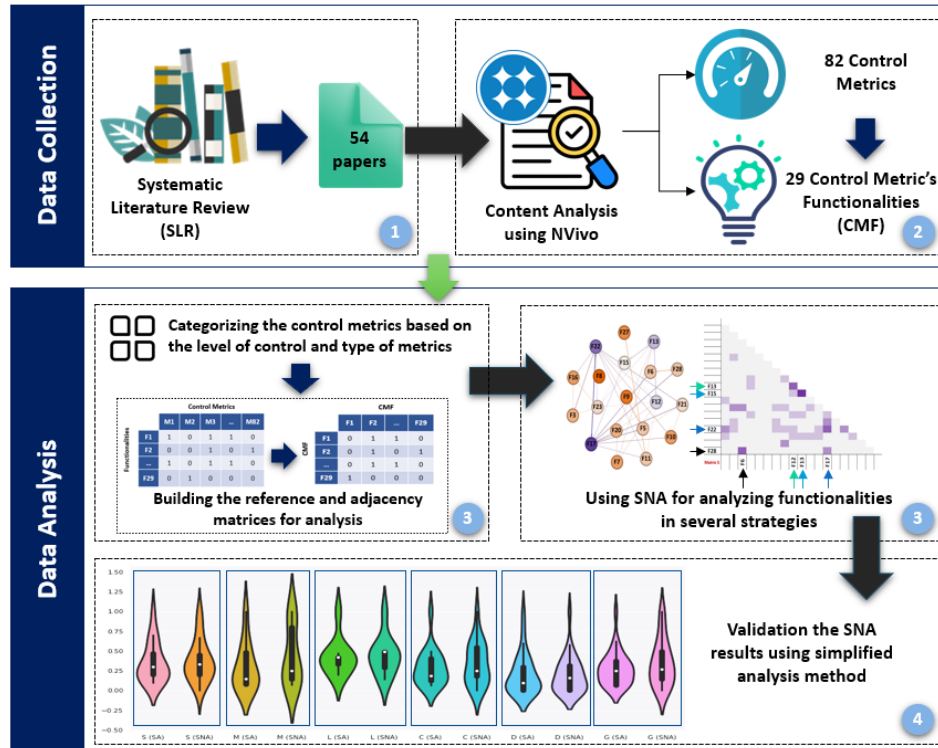


Fig. 1. Overview of the considered research methodology

As seen in Fig. 1, the authors (1) carried out a systematic review and content analysis of the literature on construction site control metrics to gather relevant information, (2) identified the underlying principles of control metrics and defined them as Control Metrics' Functionalities (CMF), (3) applied social network analysis (SNA) to evaluate the significance of each identified functionality and determine the most crucial ones based on their interdependencies in terms of control levels and type of metrics, and (4) validated the SNA results using simplified analysis. The following subsections delve into each component of the research methodology in detail.

2.1. Data Collection

Systematic Literature Review (SLR) and content analysis were employed to acquire the data required for this study. A detailed explanation of these procedures is provided below.

2.1.1. Systematic Literature Review (SLR)

A systematic literature review includes three crucial steps that are undertaken in this study: (1) developing the research questions; (2) identifying and evaluating the publications; (3) analyzing, synthesizing, and presenting the review results (Kitchenham 2004).

Stage 1 - Planning the Review

In order to perform the literature review and collect the required data for the goals of this study, the following two initial research questions were formulated.

- RQ1: what are the metrics used to control construction projects?

- RQ2: what are the underlying principles of control metrics?

These two initial research questions will guide the design of the SRL protocols for stage 2.

Stage 2 - Conducting the Review

Two key bibliographic databases, Scopus and Web of Science (WOS), were employed to perform an exhaustive search in the "Title, Abstract, Keywords". The search query was created by decomposing RQ1 and RQ2 and combining the pertinent terms and synonyms regarding project control metrics using Boolean operators "AND" and "OR", as shown in Table 1. No restrictions were placed on the data collection timeframe, and all records available up to February 2023 were considered. Moreover, several inclusion and exclusion criteria (Table 2) were utilized to ensure the selected articles were relevant to the research questions.

Table 1. Combined search terms, *created by authors*

Search engines	Search query
Web of Science & Scopus	("Last planner system metrics" OR " Project performance " OR " project control metrics " OR "Buffer control" OR "Takt control" OR "Earned value " OR "schedule control" OR "EVM" OR "earned schedule") AND ("Project Planning" OR "Project Scheduling" OR "Project Control" OR "Construction Planning" OR "Construction Scheduling" OR "Production Control")

Table 2. Inclusion and exclusion criteria for the paper’s screening, *created by authors*

Inclusion criteria	Exclusion criteria
Peer-reviewed journal articles, conference papers, and book chapters from prominent scientific construction and manufacturing journals and conferences.	Not peer-reviewed; master and PhD dissertations, technical reports.
English language resources.	Research in languages other than English.
Publications relevant to the two research questions.	Unrelated papers to the two research questions.
Studies that examined at least one construction site control metric.	Studies that discussed the project control domain without taking into account control metrics
Applicable to the construction industry.	Not applicable to the construction industry.

The screening phase was conducted by the first author and evaluated and approved by the other authors of the article. Also, backward and forward citation searches were used to cover all relevant articles.

Stage 3 - Presenting the Review Results

The review process results are indicated in Fig. 2. The initial attempt to collect data yielded 943 articles. This first collection of papers was screened and reviewed using a multi-step procedure that involves applying filtering functions in Scopus and WOS, such as document type, subject area, and source title, removing duplicates, assessing titles and abstracts for relevance, and applying inclusion and exclusion criteria. These steps reduced the number of papers to 47, and

after applying backward and forward citation searching to them, seven further related articles were discovered, bringing the total number of articles for content analysis to 54.

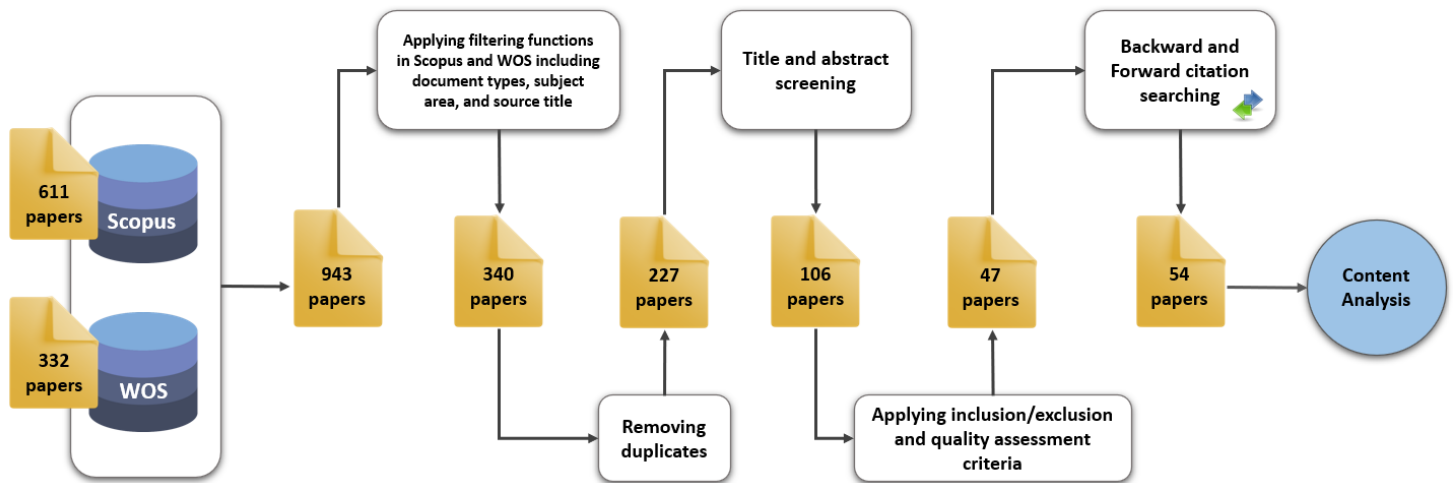


Fig. 2. Adopted review process

2.1.2. Content Analysis

To collect the required data for achieving the goals and objectives of this research, full-text content analysis was applied to the 54 finalized articles after the review procedure. To do so, NVivo 12 was utilized as the platform for the thematic analysis of the collected papers' content since thematic data analysis is a widely used methodology in qualitative research (Hajirasouli et al. 2022). The collected data for this research were first coded using four codes: 1) respective scheduling methods, 2) control metrics definitions and objectives, 3) level of control (short-term, mid-term, long-term and multi-level) and 4) type of control metrics (lagging and leading). After coding the retrieved papers, 82 control metrics related to seven scheduling methods were extracted. Next, by studying the definition and goals of control metrics, 113 control metrics' objectives were retrieved as their functionalities. Duplicate functionalities were removed, and functionalities with similar concepts, such as measuring the budgetary conformance of actual cost and measuring the cost performance, were reviewed and merged by the authors, bringing the overall number of control metrics' functionalities for further analysis to 29. The methodology for conducting an in-depth analysis of the control metrics' functionalities is presented in the following subsections.

2.2. Data Analysis

Following content analysis, SNA was applied to quantitatively analyze extracted control metrics' functionalities from different perspectives. The details of the analysis approach are presented as follows.

2.2.1. Classifying the Control Metrics and Developing Reference Matrices

The first step of quantitative studies with social network analysis is to prepare a reference matrix. To do this, after retrieving the control metrics and their functionalities from the literature, the

authors categorized the control metrics to analyze their functionalities from different aspects according to the following perspectives:

Perspective 1: Level of Control

In this perspective, the control metrics were classified based on their level of control: short-term, mid-term, long-term and multi-level. Multi-level refers to metrics that can control multiple levels of the schedule. For instance, the Commitment Level (CL) metric is considered a multi-level control metric since it controls and aligns long-term and short-term plans (Hamzeh et al. 2019).

Perspective 2: Type of Metrics

This perspective categorized metrics based on their type, lagging and leading. Lagging measures assess past performance, while leading ones predict future performance. Table 3 depicts the classification of control metrics, the number of metrics in each class and the related matrix for further analysis.

Table 3. Classification perspectives of control metrics, *created by authors*

Class	Perspective	Perspectives Details	Related Matrix	No. Metrics
1	Level of Control	Short-term	S	29
1	Level of Control	Mid-term	M	18
1	Level of Control	Long-term	L	4
1	Level of Control	Multi-level: short-term & long-term, short-term & mid-term, long-term & mid-term, long-term & mid-term & short-term	C	31
2	Metrics Type	Lagging	G	57
2	Metrics Type	Leading	D	25

After grouping the control metrics for studying the identified functionalities, six reference matrices were generated based on the provided classes in Table 3. The identified functionalities are represented as rows, and the control metrics as columns in a reference matrix. If functionality reflects a control metric, the cell for it would have a value of 1; if it does not, it would have a value of 0. In Fig. 3, a reference matrix is illustrated as an example. In this example, F_i is an identified functionality, and M_j refers to a control metric. As shown in Fig. 3, the functionality F_i is associated with the control metrics M_j and M_j . Consequently, a value of one is entered in the respective cells, while cells below the other control metrics receive a value of zero. Leveraging the created reference matrices and utilizing the SNA approach, the authors conducted a quantitative analysis and subsequently validated their results via a simplified analysis. Further details are provided in the following subsections.

		Control Metrics (CM)			
		CM	M_j	M_{j+1}	...
Functionalities	F				
	F_i	1	0	0	1
	F_{i+1}	1	1	0	0
	...	0	0	1	0
	F_l	0	1	0	1

Fig. 3. An example of a reference matrix

2.2.2. Applying Social Network Analysis

2.2.2.1. Developing the Social Network

The weighted adjacency matrices must be developed after constructing the reference matrices for implementing the SNA by studying control metrics and their functionalities. The weighted adjacency matrix represents a network in which (1) the matrix rows and columns represent n nodes illustrating the control metrics' functionalities and (2) the matrix values a_{ij} represent a set of edge weights that indicate the edge strength or connection between each pair of nodes or functionalities.

Using Eq. (1), the weighted adjacency matrix is computed by multiplying the reference matrix by its transpose and then replacing zeros for its diagonal values.

$$A_{f \times f} = \begin{cases} R_{f \times m} \times R_{f \times m}^T & \text{for } i \neq j \\ 0 & \text{for } i = j \end{cases} \quad (1)$$

where $A_{f \times f}$ = weighted adjacency matrix; $R_{f \times m}$ = reference matrix; $R_{f \times m}^T$ = transpose of the reference matrix; f = number of identified functionalities (i.e., 29); and m = number of control metrics (i.e., 19 in matrix M).

To efficiently evaluate the network and quantify the significance of the discovered functionalities, the authors adopted Degree of Centrality (DC), which quantifies the number of times each functionality occurred with other functionalities in the same control metric. The DC for each functionality of control metrics F_i is calculated by summing the values of the i th row of the weighted adjacency matrix, illustrated by Eq. (2).

$$DC_i = \sum_{j=1}^n a_{ij} \quad (2)$$

where DC_i = degree centrality of functionality i ; and a_{ij} = value of i th row and j th column of the weighted adjacency matrix. As the number of links and functionalities of the networks in this study are different, a normalized scale, ranging from 0 to 1, of the DC values is calculated to make

it easier to compare the functionalities. As illustrated in Eq. (3), normalized DC is determined by dividing the DC of each functionality by the maximum DC value in the associated network.

$$\overline{DC}_i = \frac{DC_i}{\max\{DC_m\}} \quad (3)$$

To apply the SNA in this study, all reference matrices \mathbf{S} , \mathbf{M} , \mathbf{L} , \mathbf{C} , \mathbf{D} , and \mathbf{G} , were converted into weighted adjacency matrices using the above procedure.

2.2.2.2. Simplified Analysis

Several studies considered the simplified analysis for validating SNA findings (Assaad and El-Adaway 2020; Elsayegh and El-adaway 2021; Sheikhhoshkar et al. 2023). The same manner was used to verify the SNA outcomes in this research. In this method, a score is determined for each functionality by summing all related cells in the row using Eq. (4). For instance, a score of 16 for functionality $F5$ using reference matrix \mathbf{G} indicates that this functionality is regarded in 16 of the lagging control metrics.

$$S_i = \sum_{j=1}^n r_{ij} \quad (4)$$

where S_i = normalized simplified score of functionalities i ; and r_{ij} = value of i th row and j th column of the reference matrix. Following the normalization reason and process for DCs, the normalized score for the simplified analysis approach is calculated via Eq. (5).

$$\overline{S}_i = \frac{S_i}{\max\{S_m\}} \quad (5)$$

The simplified analysis approach was also applied to verify the SNA findings on all reference matrices.

3. Results and Analysis

This section provides and discusses the research findings from data collection to analysis.

3.1. Data Collection Efforts

The performed systematic review efforts by the authors included 54 research papers to meet the requirements of this study, illustrated in Table 4. The distribution of the published articles across three decades indicates that most publications were conducted after 2013. The complexity of construction projects and the availability of data collection and analysis methods and technologies have led to a dramatic increase in the focus on this field of study over the last decade.

Table 4. Final papers for the content analysis, *created by authors*

Time scope	Full-text analyzed papers	No. of papers
1994-2003	Ballard and Howell (1998), Chitla and Abdelhamid (2003)	2
2004-2013	Mitropoulos (2005), Kenley and Seppänen (2006), Jang and Kim (2007), Jung and Kang (2007), González et al. (2008), Plaza (2008), Kim and Ballard (2010), Hamzeh and Aridi (2013)	8
2014-2023	Wang et al. (2014), Colin et al. (2015), Colin and Vanhoucke (2015), Hamzeh et al. (2015), Hamzeh et al. (2015), Hazır (2015), Kim (2015), Roofigari-Esfahan et al. (2015), Emdanat and Azambuja (2016), Hamzeh et al. (2016), Hu et al. (2016), Kim et al. (2016), Rouhana and Hamzeh (2016), Binninger et al. (2017), El Samad et al. (2017), Hamledari et al. (2017), Lin and Golparvar-Fard (2017), Martens and Vanhoucke (2017), Rizk et al. (2017), Sacks et al. (2017), Hammad et al. (2018), Nguyen and Waikar (2018), Orgut et al. (2018), Zhang et al. (2018), Ballesteros-Pérez et al. (2019), Hamzeh et al. (2019), Hamzeh et al. (2019), Chen et al. (2020), Hamzeh et al. (2020), Hamzeh et al. (2020), Haugen et al. (2020), Lagos et al. (2020), Demachkieh and Abdul-Malak (2021), Keskiniva et al. (2021), Lagos and Alarcón (2021), Lin and Golparvar-Fard (2021), Abusalem (2022), Aramali et al. (2022), Ezzeddine et al. (2022), Mayo-Alvarez et al. (2022), Pérez et al. (2022), Shehab et al. (2022), Shehab et al. (2022), Hansen et al. (2023)	44

By studying the papers in Table 4, the authors identified 82 control metrics and their definitions in the construction sector, as detailed in Appendix A. To assess these control metrics from various perspectives, Table A1 in the Appendix furnishes supplementary details for each metric, encompassing considerations such as the level of control and the type of metric. Moreover, as described in the content analysis section, authors found 29 control metrics' functionalities based on 54 finalized articles and 82 control metrics mentioned above, illustrated in Table 5.

Table 5. Control metrics' functionalities, created by authors

ID	Control metrics' functionalities
F1	Achieve an integrated cost/schedule progress monitoring and control
F2	Manage constraints removal
F3	Maintain continuity of trade work
F4	Control of uncertainty
F5	Control project progress and performance
F6	Manage corrective actions
F7	Evaluate the performance of the lookahead level
F8	Forecast project duration
F9	Control the cost of the project in progress
F10	Identify highly sensitive activities
F11	Measure labor productivity
F12	Measure labor resource reliability
F13	Measure the efficiency of resource allocation
F14	Measure long-term and short-term plans alignment
F15	Measure the quality of capacity planning
F16	Measure the quality of the construction flow
F17	Measure reliability and effectiveness of weekly work plan and lookahead plan
F18	Measure the achievability of a target project duration
F19	Measure the make-ready process
F20	Measure the percentage of differentiate tasks in the WWP
F21	Measure the quality of the commitments
F22	Measure the reliability and stability of the workflow

F23	Maintain production rate stability
F24	Provide managerial information
F25	Quantify the reliability of starting or finishing the task on time
F26	Identify root causes for deviations.
F27	Relate workflow reliability to productivity
F28	Improve continuous learning
F29	Align the work plan assignment with the lookahead

To analyze the control metrics' functionalities from several aspects, the authors created six reference matrices and networks based on the classification perspectives described in the research methodology section, Table 3. The classification of each control metric, along with the corresponding matrix within perspectives 1 and 2, is exhaustively delineated and presented in Table A2 in the Appendix.

3.2. Investigating the Scheduling Methods Associated with Control Metrics

There is a tight relationship between scheduling methods and control metrics. Planning and scheduling methods are utilized to plan and manage a construction project, while control metrics are used to assess and monitor progress against the planned schedule (Hamzeh et al. 2012). In order to evaluate the planning and scheduling methods associated with control metrics, Fig. 4 depicts the distribution of control metrics across the seven scheduling methods. As seen, although the Critical Path Method (CPM) is the most common and traditional method of planning and scheduling in construction projects, most control metrics (55%) are related to the Last Planner System (LPS). Since the monitoring and control of the project require data from the construction site, it makes sense that the LPS, with its frequent huddle meetings and more emphasis on the short-term and weekly plan, provides the most appropriate data for project control from various aspects. This fact can be a reason for more attention being paid to control metrics in this method compared to other methods. Furthermore, several studies have emphasized increasing the efficiency of LPS using Location-Based Management System (LBMS) and Takt Time Planning (TTP) techniques (Ballard and Tommelein 2021; Nutt III et al. 2020; Seppänen et al. 2010). However, the analysis of control metrics related to scheduling methods in Fig. 4 indicates little focus on control metrics of LBMS and TTP methods, with 10% and 6%, respectively. This highlights the need for more research and focus on developing control metrics for these methods. Lin and Golparvar-Fard (2021)'s study can be cited as one of the limited studies on the metrics related to these techniques. They proposed location-related metrics such as the Location Risk Index (LRI) to measure workflow stability based on activities' completion risk and readiness per work location. Moreover, it should be noted that due to prevalent contractual constraints that often hinder the widespread adoption of the Last Planner System (LPS) in construction projects, integrating control metrics associated with both the Critical Path Method (CPM) and LPS becomes imperative for a practical and comprehensive approach to effectively address delay concerns in construction projects.

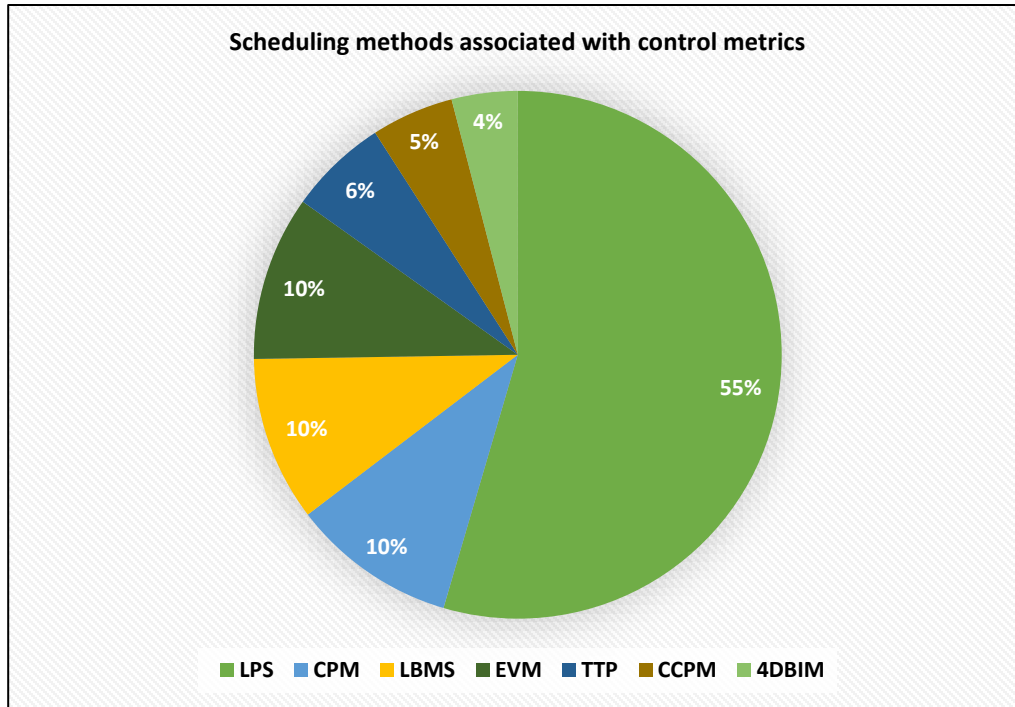


Fig. 4. Scheduling methods associated with control metrics

3.3. Quantitative Analysis of the Control Metrics' Functionalities

In this section, the authors implemented SNA as a quantitative technique to the reference matrices and verified the SNA findings using the simplified analysis outlined in the research methodology.

3.3.1. Social Network Analysis

The weighted adjacency matrices were developed based on the established reference matrices to calculate the DCs of the identified functionalities and visualize the networks using the Gephi software package. The networks of each perspective are presented and analyzed as follows.

Analyzing the Networks of Perspective 1

In this study, four networks, *S*, *M*, *L*, and *C*, represent different levels of control perspectives. Node color indicates functionality strength, with darker purple denoting higher values than orange. Edge thickness signifies interconnectivity between functionalities, with a thick purple line indicating strong co-occurrence. Moreover, a color-coded matrix complements this analysis, visually representing co-occurrence patterns between functionalities.

In Fig. 5 (a), network *S*, focusing on short-term control metrics' functionalities, 18 out of 29 functionalities are supported. Notable functionalities include F17 (measure reliability and effectiveness of weekly planning), F22 (measure the reliability and stability of workflow), F13 (measure the efficiency of resource allocation), and F12 (measure labor resource reliability), while F9 (control the cost of the project in progress), F27 (relate workflow reliability to productivity), F28 (improve continuous learning), and F16 (measure the quality of construction

flow) receive less attention. The color-coded matrix reveals specific pairs with high co-occurrence in short-term control metrics' functionalities. The co-occurrence of F15 (measure the quality of capacity planning) and F13 (measure the efficiency of resource allocation), F13 (measure the efficiency of resource allocation) and F12 (measure labor resource reliability), F28 (improve continuous learning) and F6 (manage corrective actions), and F22 (measure the reliability and stability of workflow) and F17 (measure reliability and effectiveness of weekly planning) have been employed the most in the short-term control metrics.

Fig. 5 (b) explores mid-term control metrics, indicating that 10 out of 29 functionalities are addressed. Prominent functionalities include F7 (evaluate the performance of the lookahead level), F2 (manage constraints removal), and F19 (measure the make-ready process), with less attention given to F9 (control the cost of the project in progress), F25 (quantify the reliability of starting or finishing the task on time), and F4 (control of uncertainty). Regarding the co-occurrence analysis of the functionalities at the mid-term level of control, the combination of F7 (evaluate the performance of the lookahead level) and F2 (manage constraints removal), F19 (measure the make-ready process) and F2 (manage constraints removal), and F19 (measure the make-ready process) and F7 (evaluate the performance of the lookahead level) have been considered the most in the mid-term control metrics.

Fig. 5 (c) delves into long-term control metrics, covering nine functionalities out of 29. It should be noted that in this research, the long-term level refers to the master and phase planning of the last planner system. F5 (control project progress and performance) is identified as the most crucial functionality, while F4 (control of uncertainty) and F10 (identify highly sensitive activities) receive minimal attention. Moreover, the color-coded matrix displays co-occurrence patterns, with, F5 (control project progress and performance) and F24 (provide managerial information) standing out.

As 38% of the control metrics have the potential to apply and monitor more than one level of the schedule, including short-term & long-term, short-term & mid-term, long-term & mid-term, and long-term & mid-term & short-term, a class called multi-level of control was considered for analyzing their functionalities.

Fig. 5 (d) illustrates a multi-level control class (**C**) with 18 functionalities. F5 (control project progress and performance), F28 (improve continuous learning), F26 (identify root causes for deviations), and F16 (measure the quality of construction flow) are frequently used, while F25 (quantify the reliability of starting or finishing the task on time), F14 (measure long-term and short-term plans alignment), and F1 (achieve an integrated cost/schedule progress monitoring and control) receive less attention. In addition, co-occurrence analysis in the color-coded matrix highlights that the combination of F4 (control of uncertainty) and F5 (control project progress and performance), F24 (provide managerial information) and F5 (control project progress and performance), and F26 (identify root causes for deviations) and F28 (improve continuous learning) have been utilized the most often in multi-level control metrics.

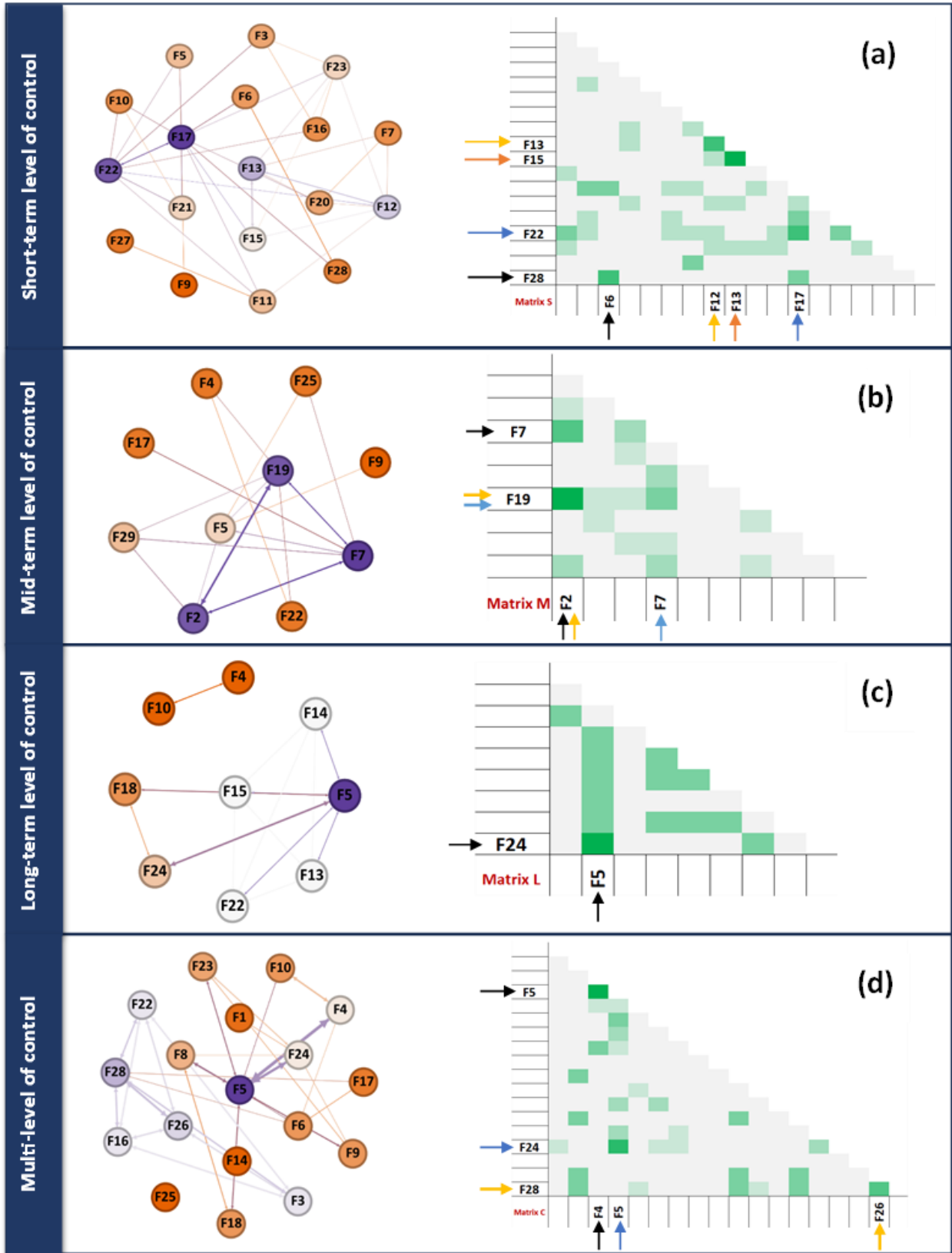


Fig. 5. Networks and color-coded matrices of metrics' functionalities for different levels of control

To summarize the analysis related to the control metrics' functionalities at different schedule levels, word clouds of top-ranked functionalities at each control level were created. Identifying the occurrence of words in each word cloud can facilitate grasping the main underlying control concepts for each scheduling level provided by its corresponding control metrics. As shown in Fig. 6, the main control concepts at the long-term level of control are project cost/time progress monitoring and project performance monitoring. At the mid-term level, constraint management, make-ready process control, and lookahead performance monitoring are the most critical concepts of control. Also, resource allocation, commitment management, and workflow management are the highlighted concepts of control at the short-term level of control.

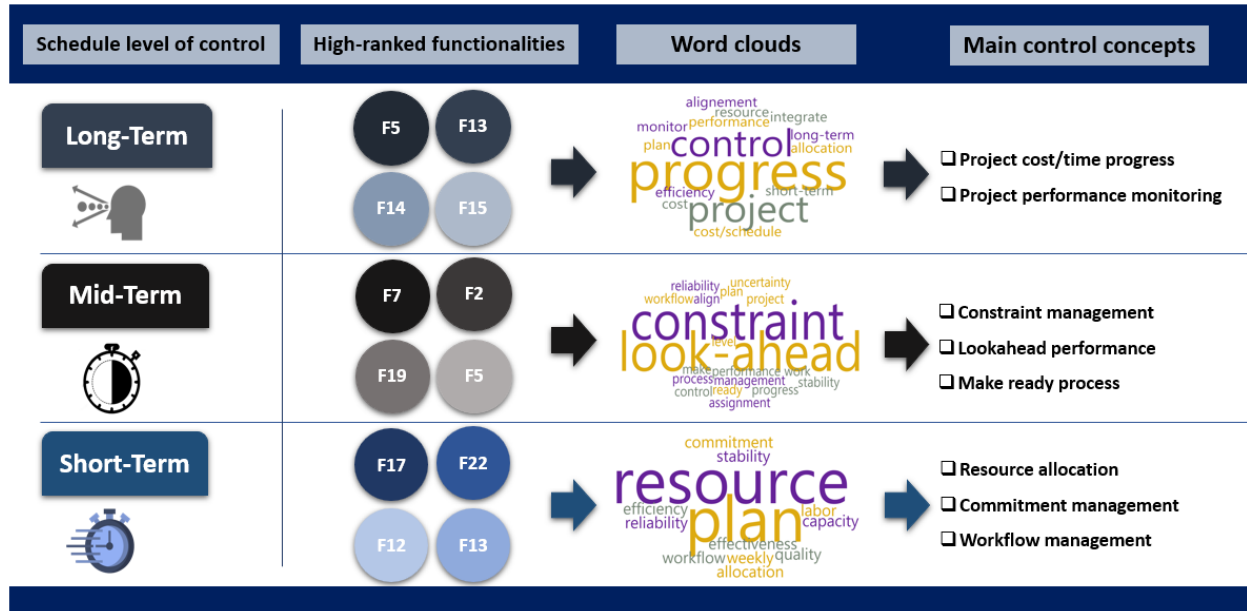


Fig. 6. Underlying concepts of control at each schedule level

Analyzing the Networks of Perspective 2

This perspective was designed to evaluate control metrics and their functionalities based on the type of metrics, lagging and leading. The collected data about completed tasks, including actual progress, consumed resources, delays, risks, labour availability, and root causes of deviations from the construction site, can be converted into useful information in the form of control metrics for analyzing what occurred on the site and deciding on future corrective actions. These metrics, known as lagging, depending on the project's past performance.

On the other hand, through predictive analytics, project teams are able to estimate and highlight future schedule delays and other issues before they occur on the construction site by evaluating production data. This enables them to resolve issues proactively before they occur. Therefore, it is imperative that actionable information be shared in a proactive manner regarding probable delays and other concerns on construction sites to enhance schedule reliability (Lin and Golparvar-Fard 2021). This is accomplished using a second set of control metrics, leading metrics, to predict future performance. Most of these leading metrics are based on lean principles and support regular monitoring of planning reliability during the project execution phase (Hamzeh et

al. 2020). So, adequate understanding and awareness of both types of metrics and their functionalities are crucial for the project's control. This section's analyses will considerably assist the project manager in understanding and evaluating various metrics and their functionalities to decide on the most appropriate metrics.

There are two networks in this perspective: networks **D** and **G**. Fig. 7 (a) shows the network and color-coded matrix of leading metrics' functionalities. Network **D** addresses 18 out of 29 functionalities, emphasizing its capability to handle the majority. Notably, F5 (control project progress and performance) and F7 (evaluate the performance of the lookahead level) receive the most attention, while F29 (align the work plan assignment with the lookahead), F25 (quantify the reliability of starting or finishing the task on time), F20 (measure the percentage of differentiate tasks in the Weekly Work Plan (WWP)), and F21 (measure the quality of the commitments) are given the least focus. Also, the co-occurrence of F7 (evaluate the performance of the lookahead level) and F2 (manage constraints removal), F19 (measure the make-ready process) and F2 (manage constraint removal), F8 (forecast project duration) and F5 (control project progress and performance), F18 (measure the achievability of a target project duration) and F5 (control project progress and performance), and F10 (identify highly sensitive activities) and F4 (control of uncertainty) have been employed as the most often combinations of functionalities in the leading control metrics.

Table 3 in the methodology section indicates that 70% of control metrics are linked to lagging metrics, suggesting their broader support functionalities. This is visually depicted in Fig. 7 (b), where the network and matrix **G** associated with lagging metrics appear denser than those for leading metrics. Notably, Network **G**'s 25 nodes predominantly address key functionalities, with F5 (control project progress and performance), F22 (measure the reliability and stability of workflow), F28 (improve continuous learning), and F16 (measure the quality of construction flow) being crucial for lagging control metrics. Conversely, F1 (achieve an integrated cost/schedule progress monitoring and control), F10 (identify highly sensitive activities), F27 (relate workflow reliability to productivity), and F21 (measure the quality of the commitments) have the least focus in this context. Furthermore, co-occurrence analysis in the color-coded matrix of Network **G** reveals frequent combinations, such as F5 (control project progress and performance) and F4(control of uncertainty), F3 (maintain continuity of trade work) and F22 (measure the reliability and stability of workflow), and F24 (provide managerial information) and F5 (control project progress and performance) emphasizing their importance in lagging control metrics.

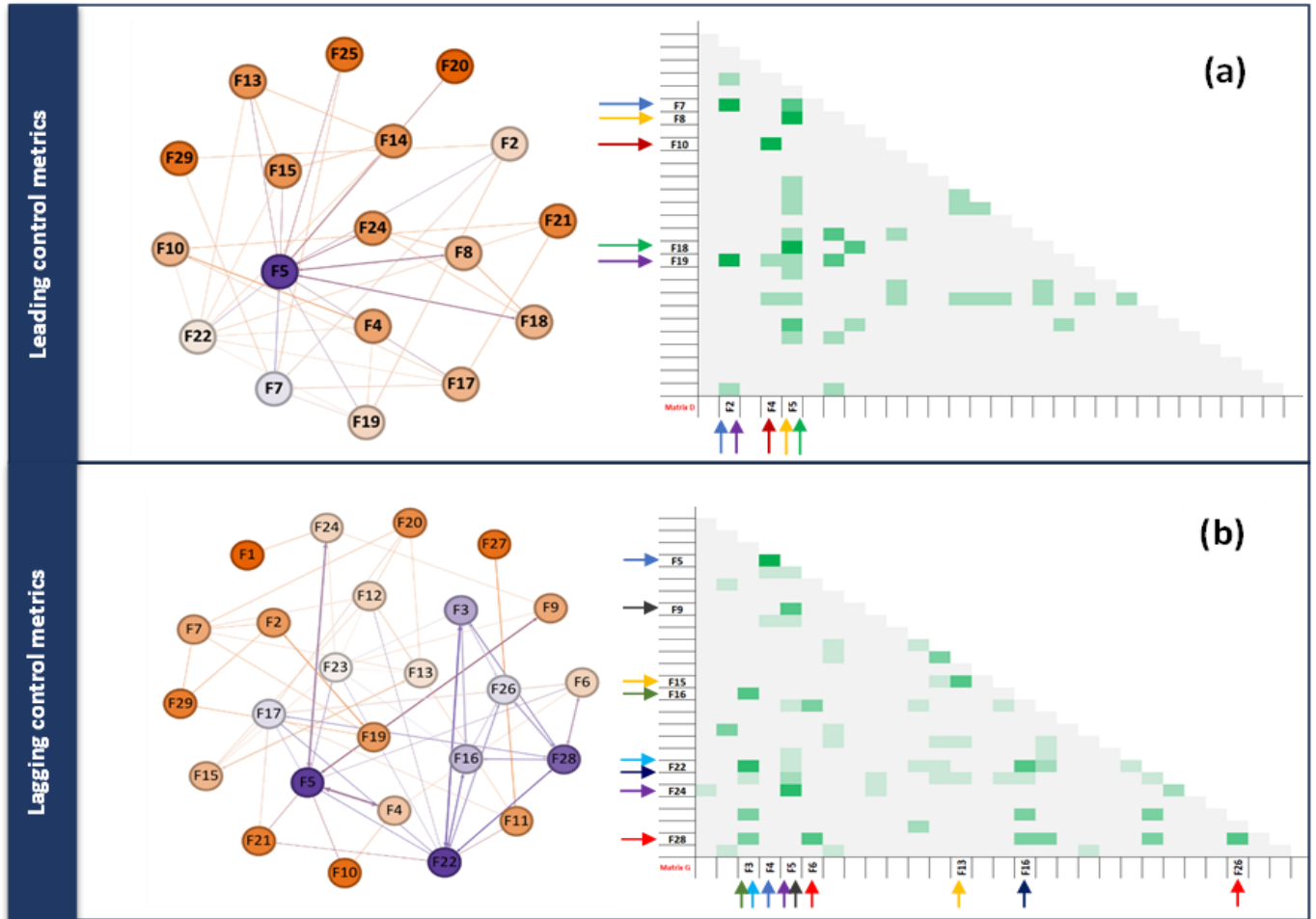


Fig. 7. Networks and color-coded matrices of the leading and lagging control metrics' functionalities

To clearly illustrate and understand the differences between the most significant functionalities in leading and lagging control metrics presented above, the authors developed Fig. 8, which represents the difference in normalized DCs of the D and G (D-G) networks. The positive values imply that the leading control metrics have emphasized the corresponding functionalities more. On the other hand, the negative values indicate that the related functionalities have been supported more by the lagging control metrics. Fig. 8 also clearly shows that lagging metrics have significantly supported most control metrics' functionalities (negative values). Although leading metrics, as previously mentioned, are crucial for project management and control, insufficient attention has been paid to them and their functionalities in research and industry. This issue can direct future studies on these types of metrics.

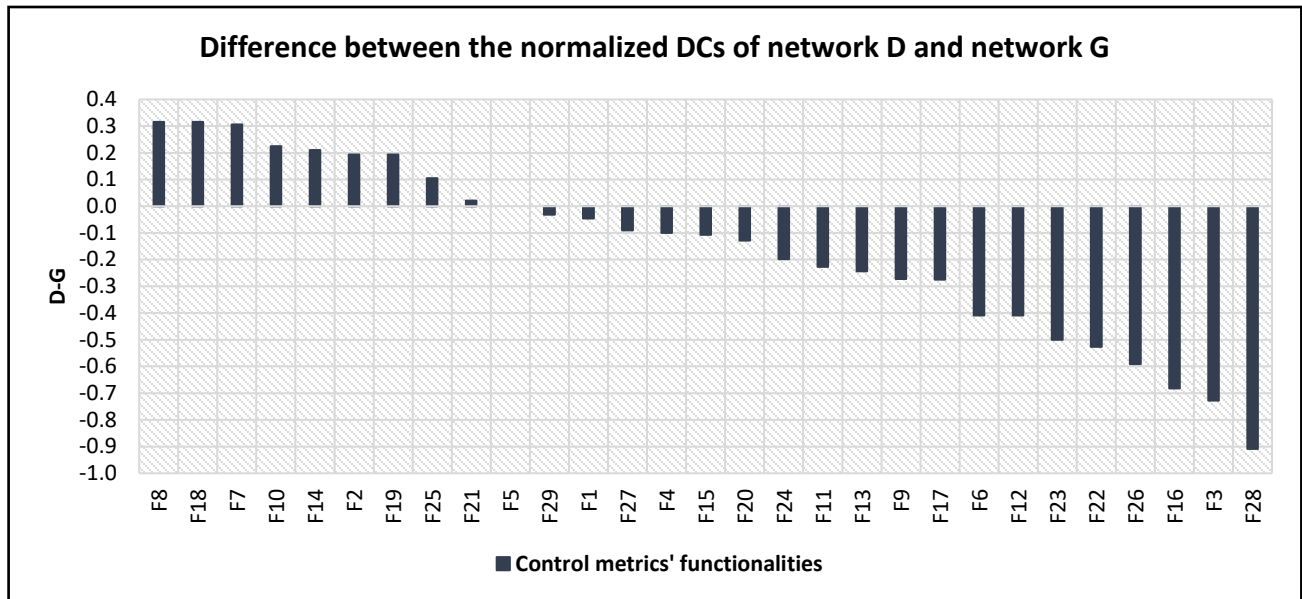


Fig. 8. Calculated differences between the DCs of the D and G networks

3.4. Validation

In this study, the authors validate Social Network Analysis (SNA) results through a simplified analysis, comparing normalized scores with Degree Centrality (DC) values. Statistical metrics like Spearman and Pearson correlation, variance, and standard deviation are employed to scientifically assess the correlation between SNA and simplified analysis (Sheikhhoshkar et al. 2023). Pearson correlation is a statistical metric that evaluates linear associations between variables. It utilizes a scale ranging from -1 to +1 to determine the strength and direction of their relationship. A value of -1 signifies a perfect negative correlation, +1 indicates a perfect positive correlation, and 0 denotes no correlation.

Additionally, variance and standard deviation serve as measures to gauge the extent of deviation of data points from the mean, allowing them to quantify the degree of variability or dispersion within the dataset. The results of the mentioned statistics tests are presented in Table 6. Furthermore, to demonstrate the differences in normalized scores between the SNA and the simplified analysis, Fig. 9 depicts violin plots for the findings of two techniques for all matrices. A violin plot combines a box plot and a kernel density plot. In addition to summary statistics, it can also display the probability density of the data. As seen in Table 6, Pearson correlation results above 0.85 indicate a high linear relationship between the results of these two methods presented in this study. Moreover, in the case of violin plots for each matrix, both violin plots, representing simplified analysis and SNA, reveal identical distribution shapes with smooth and symmetric kernel density curves. This similarity indicates that data points are concentrated around similar values, leading to comparable distribution patterns. Moreover, the box plots of both violin plots exhibit striking similarities, suggesting that the data sets share comparable measures of central tendency, spread, and overall distribution. Consequently, it can be reasonably concluded that the two compared methods possess similar characteristics and statistical properties. As a result, the presented statistics in Fig. 9 and Table 6 reveal that the SNA is performing as expected.

Table 6. Statistical test results on the simplified analysis and SNA for all matrices of this study, *created by authors*

Statistics tests	Matrix <i>S</i>		Matrix <i>M</i>		Matrix <i>L</i>		Matrix <i>C</i>		Matrix <i>D</i>		Matrix <i>G</i>	
	<i>S</i> (SA)	<i>S</i> (SNA)	<i>M</i> (SA)	<i>M</i> (SNA)	<i>L</i> (SA)	<i>L</i> (SNA)	<i>C</i> (SA)	<i>C</i> (SNA)	<i>D</i> (SA)	<i>D</i> (SNA)	<i>G</i> (SA)	<i>G</i> (SNA)
Mean	0.300	0.333	0.154	0.250	0.350	0.490	0.188	0.250	0.100	0.158	0.250	0.273
Variance	0.061	0.066	0.085	0.129	0.048	0.056	0.049	0.070	0.064	0.052	0.044	0.085
Standard Deviation	0.248	0.257	0.291	0.359	0.218	0.237	0.222	0.265	0.253	0.227	0.209	0.292
Pearson Correlation	0.862		0.891		0.890		0.905		0.934		0.839	

*SA: Simplified Analysis, SNA: Social Network Analysis

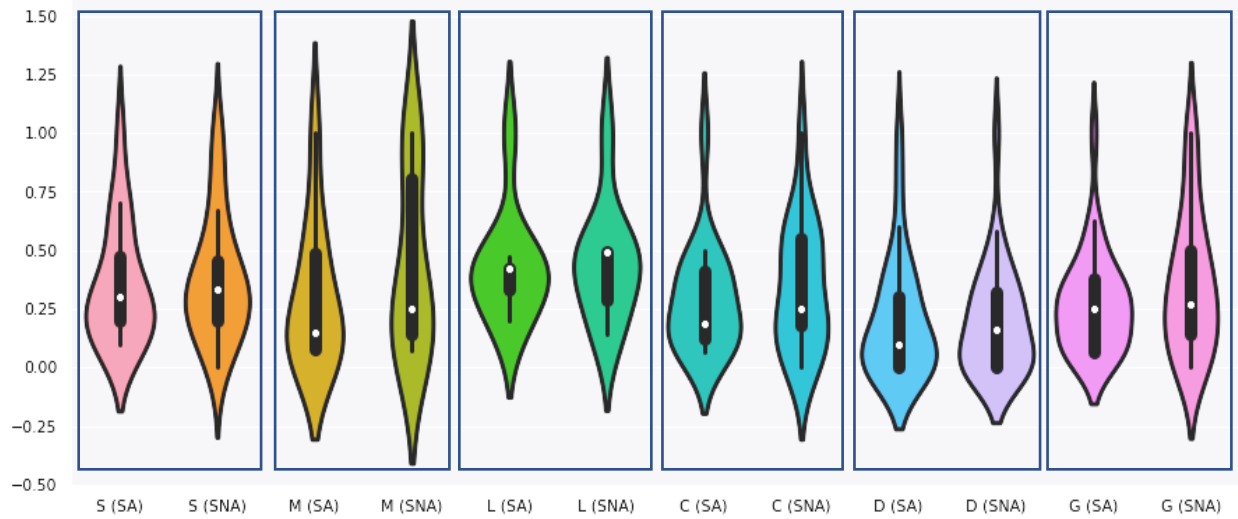


Fig. 9. Violin plots for the findings of Simplified Analysis (SA) and SNA for all matrices

4. Research Discussions, Contributions, and Future Recommendations

This study contributes to the body of project planning and control knowledge through combines the findings from previous efforts and employs them to build a foundation for further studies. In this regard, the procedures of this study have identified domains with excess focus and have highlighted areas that have received the least attention where further studies are needed. Therefore, using intuitions derived from the meta-analysis performed on the data extracted from the literature, this section discusses the key findings of this article in light of the identified control metrics and their functionalities.

Many control metrics and inadequate comprehension and awareness of project planning and control theories and methods among project stakeholders (Al Nasser et al. 2016) led to the definition of the functionality concept. This research found and analyzed control metrics' functionalities to enhance the sensemaking of control metrics. The findings can assist project teams in choosing the most appropriate metrics for keeping track of their projects, attentively matching the right planning skills to various planning activities, and promoting the knowledge and understanding of the functionalities required at the early stages and late stages of the project planning process, particularly those needed for planning, control, and both;

functionalities can either be applied proactively (leading) or reactively (lagging); those can be used in the short-term, mid-term, and long-term.

The evaluation of 82 extracted control metrics revealed they were related to seven scheduling methods. Despite the fact that the Critical Path Method (CPM) is the most legally utilized planning and scheduling method in the standard form of contracts in construction projects, the majority of control metrics (55%) are related to the Last Planner System (LPS). The large number of control metrics associated with LPS emphasizes that, unlike traditional methods such as CPM, in lean-based production planning and control, attention has been paid to the control of various dynamic aspects of the project, including resources, constraints, flow of work, uncertainty, process, human workload, delays, and so on. This analysis also revealed that, despite the definition of several effective metrics to control various aspects of the project, EVM-based metrics or metrics which monitor only the project's time and cost were still utilized in BIM-based integrated scheduling methods, particularly 4D BIM. Future research may need to adopt lean-based metrics into BIM-based scheduling methods to address this gap. Additionally, several studies have integrated LPS and EVM with successful outcomes to control more sides of the project (Kim and Ballard 2010; Novinsky et al. 2018). Based on this, the authors propose integrating the scheduling methods and their associated control metrics to improve planning reliability and enable the control of more dynamic project aspects.

The network analysis findings in perspective 1 of this study demonstrated that the control metrics' functionalities network and color-coded matrix were denser in the short-term than at the mid-and long-term levels. This implies that the control metrics and their functionalities are more focused on monitoring the short-term level to manage the uncertainties ahead, flows in the construction site, etc. Future studies should be given more significant consideration to the mid-term and long-term levels, as well as the alignment of the three control levels of the schedule.

Analyzing the short-term level control metrics' functionalities network indicated that measuring the reliability and effectiveness of weekly planning, the reliability and stability of workflow, the efficiency of resource allocation, and labor resource reliability are the most often used functionalities in this level of control. The word cloud of these top-ranked functionalities showed that the main control concepts at the short-term level are flow management, resource allocation and management, and commitment management. In addition, although improving continuous learning and measuring the quality of construction flow are essential functionalities of the short-term level of the schedule (Hamzeh et al. 2019; Hamzeh et al. 2020), the control metrics of this level provide limited support for these functionalities. This issue can be considered more in future studies.

Findings of the mid-term level control metrics' functionalities network illustrated that evaluating the performance of the lookahead level), managing constraints removal, and measuring the make-ready process are the most often utilized functionalities at the mid-term level of control. The word cloud of high-ranked functionalities at this level of control indicated that constraint management, make-ready process control, and lookahead performance monitoring are the main control concepts at the mid-term schedule level. The low rank for F4 (control of uncertainty) at the mid-term level reflects the limited coverage for this functionality in the available control

metrics at this level of the schedule. To handle the monitoring and management of process uncertainties at this level, the authors propose adopting buffer control metrics in combination with advanced lean-based control metrics.

A look at the results of long-term functionalities network analysis clarifies that the F5 (control project progress and performance) is the most crucial functionality at this level of control. Moreover, the word cloud analysis of high-ranked functionalities illustrated that project cost/time progress monitoring and project performance monitoring are the primary control concepts at the long-term level. Furthermore, like mid-term control metrics, at the long-term level, the control metrics paid little attention to the risk and uncertainty-based functionalities that are F4 (control of uncertainty) and F10 (identify highly sensitive activities). Future studies may benefit from integrating robustness and resilience measures with current control metrics to address this issue.

As the last discussion of the results of perspective 1, evaluating the multi-level control metrics' functionalities network revealed that measuring the project progress and performance, improving continuous learning, identifying root causes for deviations, and measuring the quality of construction flow are the most highlighted functionalities at the multi-level of control. Although control metrics with the capability to monitor multi-levels of the schedule cover a more comprehensive range of functionalities, they are insufficient for supporting some crucial functionalities, such as F14 (measure long-term and short-term plans alignment) and F1 (achieve integrated cost/schedule progress monitoring and control). It can also be concluded that while multi-level metrics are intended to create integration between the control of all three schedule levels, short-term, mid-term, and long-term, the integration between the short-term and mid-term levels is prioritized. Considering the significant proportion of the control metric associated with Lean-based production planning and control techniques (LPS, LBMS, and TTP with 71%), it can be stated that these methods are still deficient in terms of synchronizing the project's short- and mid-term level with its long-term level from the project control perspective.

Networks analysis results for perspective 2 highlighted that lagging control metrics had a denser functionalities network and color-coded matrix than leading control metrics. This outcome indicates that the control metrics and their functionalities are more focused on evaluating past performance and everything that occurred in the project before the computation of the metrics, as opposed to the proactive forecast and analysis of the future. Research by Lin and Golparvar-Fard (2021) also highlighted the same concern. Even though lean-based metrics have been developed to provide more proactive performance measures, these metrics are currently limited due to the lack of actual high-frequency data from the construction site (Lin and Golparvar-Fard 2021). However, the emerging construction 4.0 technologies, such as reality capture, laser scanning, Unmanned Aerial Vehicles (UAVs), artificial intelligence, the Internet of Things (IoT), Radio-Frequency Identification (RFID), and wearable sensors enable the collection and analysis of reliable as-built data from the construction site (Dawood et al. 2022; González et al. 2022; Ibrahim et al. 2022; Sawhney et al. 2020). So, employing more leading control metrics to monitor different aspects of the project is feasible and essential. As a result, future research should focus more on these types of control metrics and their functionalities to enhance project performance through proactive decision-making.

Regarding the practical aspects, this study not only supports the project team and stakeholders in getting an improved grasp of control metrics and their functionalities, but the paper's analysis may also serve as a foundation for developing effective project control dashboards. In this respect, although studies such as Shehab et al. (2022) and Hamzeh et al. (2019) presented frameworks and dashboard developments for visualizing project control metrics, they did not take into account the type of metrics, levels of control and key concepts of control at each level of schedule. This study can be applied in practice to develop dashboards with the flexibility to monitor and evaluate both lagging and leading metrics. In addition, employing the main control concepts and their functionalities, as provided in this study, at each level of the schedule will be of invaluable assistance in designing multi-level control dashboards for more effective project management and control.

5. The Implications of the Findings:

This part provides an in-depth discussion of the findings' implications about the identified control metrics and their functionalities from theoretical and practical perspectives.

5.1. Theoretical Implications

The theoretical implications of this study are rooted in the functionality concept, which emerges from the insufficient comprehension of project planning and control theories among project stakeholders. By identifying and analyzing control metrics' functionalities, this research enhances the understanding of these metrics and provides a framework for project teams to choose metrics judiciously based on their project's requirements. Furthermore, the study suggests the integration of lean-based metrics into Building Information Modeling (BIM)-based scheduling methods, particularly addressing gaps in metrics used in 4D BIM. The proposed integration of scheduling methods and associated control metrics aims to improve planning reliability and effectively control dynamic project aspects. Additionally, the study highlights the importance of aligning control metrics across short-, mid-, and long-term levels of the schedule, emphasizing the need for future research to explore methodologies that achieve better synchronization. Identifying gaps in control metrics related to uncertainty at the mid-term level leads to a theoretical proposition – adopting buffer control metrics in combination with advanced lean-based control metrics to enhance the monitoring and management of process uncertainties during the mid-term phase of a project. Lastly, the study encourages future research to integrate robustness and resilience measures with existing control metrics at the long-term level to provide a more comprehensive approach to project control.

5.2. Practical Implications

On the practical side, this study has significant implications for developing project control dashboards. By considering the type of metrics, control levels, and key concepts identified in this research, practitioners can design flexible dashboards capable of monitoring both lagging and leading metrics. This approach aligns with the proposed functionalities and ensures effective project management and control. Additionally, the study emphasizes the importance of leading control metrics for proactive decision-making. With emerging Construction 4.0 technologies providing reliable high-frequency data, future research should focus on developing and

implementing more leading control metrics to enhance project performance through proactive analysis. Furthermore, the practical applications extend to developing frameworks and dashboards for visualizing project control metrics. While previous studies presented frameworks and dashboard developments, they often overlooked the type of metrics, control levels, and key concepts of control at each schedule level. This study provides a foundation for developing dashboards considering these critical factors, offering invaluable assistance in designing multi-level control dashboards for more effective project management and control. By integrating the main control concepts and functionalities identified in this research at each level of the schedule, practitioners can create comprehensive tools that cater to the diverse needs of project teams and stakeholders.

In essence, this study bridges the gap between theoretical insights and practical applications, providing a holistic approach that can significantly advance the field of project planning and control.

6. Conclusion and Limitations

In conclusion, this study delves into the intricate landscape of construction project control metrics, revealing their diverse nature and the challenges they address. Seven distinct planning and control approaches were identified through a rigorous evaluation of 82 metrics and 29 functionalities using SNA. The research emphasizes the importance of understanding metric objectives and functionalities, empowering project teams to make informed decisions. Lean-based methods, particularly LPS, LBMS, and TTP, were closely associated with most metrics.

The analysis showcased a spectrum of functionalities across short-term, mid-term, and long-term control levels. Short-term metrics, crucial for immediate project management, focused on weekly planning reliability, workflow stability, resource allocation efficiency, and labor reliability. Mid-term metrics played a pivotal role in maintaining project momentum and strategic planning, emphasizing lookahead level performance and constraint removal. Long-term metrics concentrated on overarching project progress and performance.

Examining metrics through a leading and lagging lens underscored the forward-looking nature of leading metrics. While lagging metrics are pivotal in facilitating various functionalities, leading metrics and their associated functionalities have not received as much attention in current practices. This nuanced analysis highlights the evolving landscape of project control metrics, offering a comprehensive understanding and indicating potential areas for future research and practice development.

This study makes a substantial contribution to the realm of project planning and control knowledge by thoroughly exploring construction project control metrics. It enriches understanding and provides project teams with enhanced project management awareness by meticulously defining and analyzing the functionalities of control metrics. Acknowledging limitations in data derivation, future research should incorporate expert viewpoints for a more practical analysis. The dominance of CPM and its related control metrics in practice over lean-based planning and control methods prompts a crucial question for future investigation, particularly concerning delay analysis concerns when employing LPS and its control metrics. In

sum, the research contributions outlined in this study advance both theoretical understanding and practical applications in project planning and control, paving the way for continued innovation and improvement in the field.

7. Acknowledgements

This study was conducted at the Nancy Automation Research Center (CRAN) laboratory through the National Research Agency of France (ANR-20-CE10-0011) financial support for the ISoBIM project.

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8. Appendices

Table A1. Identified control metrics, *created by authors*

Control Metrics	Definition	Level of Control	Type of metrics
Activity Productivity Indexes (API)	Measures the ratio of the average labor productivity to the maximum labor productivity	Short-term	Lagging
Actual to Planned Labor Ratio (APLR)	Measures actual expended labor to planned labor per activity	Short-term	Lagging
Buffer monitoring parameter (H _i)	Represents the excessive consumption of project buffer.	Short-term & Mid-term	Lagging
Buffer Performance Index (BPI)	Measures the expected remaining buffer	Short-term & Mid-term	Lagging
Buffer Variance (BV)	Calculates the amount of remaining buffer at the end of each reporting period	Short-term & Mid-term	Lagging
Capacity Planning Quality (CPQ)	Measures the quality of capacity planning	Short-term	Lagging
Capacity to Load Ratio (CLR)	Measures the tasks completed based on the capacity available to the chosen load	Short-term	Lagging
Commitment Level (CL)	Measures the percentage of the committed required activities (critical activities) to the total required activities in a given work plan cycle	Short-term & Long-term	Leading
Completed Uncommitted (CU)	Measures the number of activities completed but were not committed to on the WWP out of the total completed work (the Backlog and New tasks are included)	Short-term	Lagging
Constraint Removal Efficiency Ratio (CRE)	CPT over CRT; values closer to or greater than one indicate removal time less than planned; lower values indicate removal times greater than planned	Mid-term	Lagging
Constraint Identification Time (CIT)	Measures the difference (days) between the constraint's required removal date and its registration date	Mid-term	Leading
Constraint Planning Efficiency Ratio (CPE)	CPT over CIT; values closer to 1 indicate most look-ahead planning scope used to manage constraints	Mid-term	Leading
Constraint Planning Time (CPT)	Measures the difference (days) between the constraint's planned removal date and its registration date	Mid-term	Leading
Constraint Removal Time (CRT)	Measures the difference (days) between the constraint's actual removal date and its registration date	Mid-term	Lagging
Constraints Per Week (CWP)	Measures the ratio of the average constraints registered across the entire execution scope to the total project weeks	Mid-term	Leading
Construction Flow Index (CFI)	Measures the quality of construction flow in repetitive construction projects	Short-term	Lagging
Corrective Actions Per Week (APW)	Indicates the average number of corrective actions registered per week	Short-term	Lagging
Cost overrun ratio(R ^c)	Measures the ratio of the total actual cost to the total committed cost for included quantities	Long-term & Mid-term & Short-term	Lagging
Cost performance index (CPI)	Measures the cost efficiency of budgeted resources expressed as a ratio of earned value to actual cost.	Long-term & Mid-term & Short-term	Lagging
Cost Variance (CV)	Indicates the difference between the actual cost and the budgeted cost	Long-term & Mid-term & Short-term	Lagging
Cost-Schedule Index (CSI)	Measures the project's overall efficiency and indicates how likely a project that's deviating from baselines is to recover	Long-term & Mid-term & Short-term	Lagging
Critical Path Length Index (CPLI)	Measures the relative efficiency required to complete a milestone on-time	Long-term	Leading
Criticality Index (CI)	Measures the probability that the activity is on the critical path of the network	Mid-term & Short-term	Leading
Customer Earned Value (CEV)	Measures the budgeted amount of work completed and used by the successors on a network	Long-term & Mid-term	Lagging
Delta 1	Measures the constraints that are expected to be removed from the total constraints identified	Mid-term	Leading
Delta 2	Measures the actual removed constraints	Mid-term	Lagging
Delta 3	Measures new identified constraints.	Mid-term	Lagging

Table A1. (continued)

Control Metrics	Definition	Level of Control	Type of metrics
Earn Schedule max (ES _{max})	Measures the project progress of its most advanced path	Long-term & Mid-term & Short-term	Leading
Earn Schedule min (ES _{min})	Measures the project progress of its most delayed path	Long-term & Mid-term & Short-term	Leading
Estimate-at-Completion (EAC)	Indicated current expectation of total cost at the end of a project	Long-term & Mid-term & Short-term	Leading
Expected Progress	Measures the percentage of the work expected to be completed by the inspection date.	Long-term & Mid-term & Short-term	Leading
Feeding buffer burn rate (FBBR)	Measures the total feeding buffer consumed	Short-term & Mid-term	Lagging
Glut	Measures the number of non-critical activities completed and consequently taking available resources from critical tasks	Short-term	Lagging
Labor Hours Reliability Index (LHRI)	Compares the percent of work completed in terms of labor hours with respect to the total amount of expected labor hours.	Short-term	Lagging
Labor Utilization Factor (LUF)	Measures the effective and non-effective utilization of labors	Short-term	Lagging
Lean Workflow Index (LWI)	Uses multiple location-based scheduling parameters to describe the workflow	Short-term	Lagging
Location Risk Index (LRI)	Measures the stability of workflow based on tasks—completion risk and tasks' readiness, per work location	Mid-term	Leading
Milestone Variance (MV)	Measures the difference in days between the forecasted date to complete all remaining activities and the required date of the milestone	Long-term	Leading
Misallocation Factor (MF)	Reflects the overall waste in capacity planning	Short-term	Lagging
New duration	takes into consideration both the as-designed duration and the performance index	Short-term & Long-term	Lagging
Number of Backlog Activities (NBA)	Measures the activities that are ready for execution but are Not Critical/ Not Required	Mid-term	Leading
Number of Corrective Actions (N° CA)	Measures the total number of CAs registered by the project	Long-term & Mid-term & Short-term	Lagging
Number of corrective actions per RNC (APR)	Total number of corrective actions over the total number of RNC	Short-term	Lagging
Percent Activities Started on Time (PAST)	Measures the activities that started on time	Short-term & Mid-term	Lagging
Percent Complete New (PCN)	Measures the number of New tasks completed out of the total number of New tasks committed	Short-term	Lagging
Percent Improvement Complete (PIC)	Quantifies the team's reliability in completing the tasks that needed improvement during the week	Short-term	Leading
Percent milestones achieved (PMA)	Measures the percentage of milestones that are finished	Long-term	Lagging
Percent of Constraint Removal (PCR)	Measures the number of ready tasks when scheduling the WWP (Ready) to the total number of planned tasks found in the look-ahead plan	Mid-term	Leading
Percent of short-term periods with corrective actions (STP w/CA)	Measures the percent of weeks in which at least one corrective action was registered	Short-term	Lagging
Percent Planned Complete (PPC)	Measures the number of completed tasks from the total tasks expected to be finished during the planning window.	Short-term	Lagging
Percent Required Completed or Ongoing (PRCO)	Measures the percentage of required/critical activities that are completed or expected to be completed (ongoing) on or before their promised completion dates concerning the total required activities committed to on the work plan	Short-term & Long-term	Lagging
Percent work packages on budget (PWPB)	Measures the percentage of work packages that are on budget	Mid-term	Lagging
Performance Factor (PF)	Measures the actual labor hours to earned productivity	Short-term	Lagging
Phase network complexity (Ci)	Measures the number of critical activities in phase	Long-term	Leading

Table A1. (continued)

Control Metrics	Definition	Level of Control	Type of metrics
Planned Work Ready (PWR)	Measures the percentage of work expected to be ready as planned in the look-ahead horizon	Mid-term	Leading
Process Reliability index (PRI)	Measures the actual to planned weekly progress of a certain activity	Short-term	Lagging
Progress Accuracy Index (PAI)	Measures the accuracy of progress information by using standardized and automated systems	Long-term & Mid-term & Short-term	Lagging
Progress Priority (PP)	Measures the amount of work done and the amount of work opened by the completed activities for downstream tasks compared to the amount expected to be opened.	Short-term	Lagging
Project Productivity Index (PPI)	Measures the real productivity	Short-term	Lagging
Quantity Overrun Ratio (R ^Q)	Measures the ratio of the total actual quantity to the total planned quantity for each location	Short-term	Lagging
Readiness Index (RI)	Measures reliability of the look-ahead plan	Mid-term	Leading
Readiness Reliability Index (RRI)	Measures reliability of the look-ahead plan	Mid-term	Leading
Reason for Non-Compliance (RNC)	Measures the total reasons for noncompliance registered by the project across the entire execution scope	Long-term & Mid-term & Short-term	Lagging
Reasons for Variance (RV)	Measures the reliability of the near-term plans	Short-term	Lagging
Relative Buffer Consumption Index (RBCI)	Indicates the overall project schedule performance by calculating the current project buffer consumption rate concerning the progress in finishing the critical chain.	Short-term & Mid-term	Lagging
Required Capacity Ratio (RCR)	It gives the planners an indication of how many tasks were critical out of all those executed that week	Short-term	Lagging
Required Level (RL)	Measures the number of Required activities to the total number of activities committed to on the WWP	Short-term	Leading
Required Percent Complete (RPC)	Measures the percentage of critical tasks completed on a specific week	Short-term	Lagging
Schedule Performance Index (SPI)	Measures the conformance of actual progress (earned value) to the planned progress	Long-term & Mid-term & Short-term	Lagging
Schedule Sensitivity Index (SSI)	Measures the relative importance of activity, taking the criticality index into account	Mid-term & Short-term	Leading
Schedule variance (SV)	Indicates how much a project is ahead or behind schedule	Long-term & Mid-term & Short-term	Lagging
Starvation	Measures the critical activities that are starving for resources	Short-term	Lagging
Takt Area Completion (TAC)	Examines the realization of the takt schedule by construction zone	Short-term & Mid-term	Lagging
Takt Time Slot Completion (TTSC)	Examines the realization of the takt schedule by work packages	Short-term & Mid-term	Lagging
Takt Wagon Completion (TWC)	Examines the realization of the takt schedule by wagons	Short-term & Mid-term	Lagging
Task Readiness (TR)	Measures the readiness for executing the upcoming task <i>i</i> by quantifying the status of all task predecessors and their task constraints <i>j</i> —procurement and logistical—based on their past productivity profiles	Mid-term	Leading
Tasks Anticipated (TA)	Measures total anticipated tasks out of the total tasks found on the Weekly Work Plan (WWP)	Mid-term	Leading
Tasks Made Ready (TMR)	Measures executed tasks that were made ready by removing all their constraints and that continued from the look-ahead week	Mid-term	Lagging
To-Complete Schedule Compression Ratio (TCSCR)	Establishes dynamic control thresholds for schedule performance evaluation and risk tracking.	Long-term & Mid-term & Short-term	Lagging
To-Complete Schedule Performance (TCSPI)	Measures the achievability of a target project duration.	Long-term & Mid-term & Short-term	Lagging
Value-in-Process (VIP)	Represents the difference between the EV and CEV which indicates the level of WIP between two activities	Long-term & Mid-term	Lagging
Weekly Deviation (WD)	Measures the extent of deviation from the WWP	Short-term	Lagging

Table A2. Classes of control metrics and associated reference matrices, *created by authors*

Code	Control Metrics	Related Matrix						Code	Control Metrics	Related Matrix					
		S	M	L	C	G	D			S	M	L	C	G	D
M1	Activity Productivity Indexes (API)	X	-	-	-	X	-	M42	Number of Corrective Actions (N° CA)	-	-	-	X	X	-
M2	Actual to Planned Labor Ratio (APLR)	X	-	-	-	X	-	M43	Number of corrective actions per RNC (APR)	X	-	-	-	X	-
M3	Buffer monitoring parameter (Hi)	-	-	-	X	X	-	M44	Percent Activities Started on Time (PAST)	-	-	-	X	X	-
M4	Buffer Performance Index (BPI)	-	-	-	X	X	-	M45	Percent Complete New (PCN)	X	-	-	-	X	-
M5	Buffer Variance (BV)	-	-	-	X	X	-	M46	Percent Improvement Complete (PIC)	X	-	-	-	-	X
M6	Capacity Planning Quality (CPQ)	X	-	-	-	X	-	M47	Percent milestones achieved (PMA)	-	-	X	-	X	-
M7	Capacity to Load Ratio (CLR)	X	-	-	-	X	-	M48	Percent of Constraint Removal (PCR)	-	X	-	-	-	X
M8	Commitment Level (CL)	-	-	-	X	-	X	M49	Percent of short-term periods with corrective actions (STP w/CA)	X	-	-	-	X	-
M9	Completed Uncommitted (CU)	X	-	-	-	X	-	M50	Percent Planned Complete (PPC)	X	-	-	-	X	-
M10	Constraint Removal Efficiency Ratio (CRE)	-	X	-	-	X	-	M51	Percent Required Completed or Ongoing (PRCO)	-	-	-	X	X	-
M11	Constraint Identification Time (CIT)	-	X	-	-	-	X	M52	Percent work packages on budget (PWPB)	-	X	-	-	X	-
M12	Constraint Planning Efficiency Ratio (CPE)	-	X	-	-	-	X	M53	Performance Factor (PF)	X	-	-	-	X	-
M13	Constraint Planning Time (CPT)	-	X	-	-	-	X	M54	Phase network complexity (Ci)	-	-	X	-	-	X
M14	Constraint Removal Time (CRT)	-	X	-	-	X	-	M55	Planned Work Ready (PWR)	-	X	-	-	-	X
M15	Constraints Per Week (CWP)	-	X	-	-	-	X	M56	Process Reliability index (PRI)	X	-	-	-	X	-
M16	Construction Flow Index (CFI)	X	-	-	-	X	-	M57	Progress Accuracy Index (PAI)	-	-	-	X	X	-
M17	Corrective Actions Per Week (APW)	X	-	-	-	X	-	M58	Progress Priority (PP)	X	-	-	-	X	-
M18	Cost overrun ratio (R ^c)	-	-	-	X	X	-	M59	Project Productivity Index (PPI)	X	-	-	-	X	-
M19	Cost performance index (CPI)	-	-	-	X	X	-	M60	Quantity Overrun Ratio (R ^Q)	X	-	-	-	X	-
M20	Cost Variance (CV)	-	-	-	X	X	-	M61	Readiness Index (RI)	-	X	-	-	-	X
M21	Cost-Schedule Index (CSI)	-	-	-	X	X	-	M62	Readiness Reliability Index (RRI)	-	X	-	-	-	X
M22	Critical Path Length Index (CPLI)	-	-	X	-	-	X	M63	Reason for Non-Compliance (RNC)	-	-	-	-	X	-
M23	Criticality Index (CI)	-	-	-	X	-	X	M64	Reasons for Variance (RV)	X	-	-	-	X	-
M24	Customer Earned Value (CEV)	-	-	-	X	X	-	M65	Relative Buffer Consumption Index (RBCI)	-	-	-	X	X	-
M25	Delta 1	-	X	-	-	-	X	M66	Required Capacity Ratio (RCR)	X	-	-	-	X	-
M26	Delta 2	-	X	-	-	X	-	M67	Required Level (RL)	X	-	-	-	-	X
M27	Delta 3	-	X	-	-	X	-	M68	Required Percent Complete (RPC)	X	-	-	-	X	-
M28	Earn Schedule max (ES _{max})	-	-	-	X	-	X	M69	Schedule Performance Index (SPI)	-	-	-	X	X	-
M29	Earn Schedule min (ES _{min})	-	-	-	X	-	X	M70	Schedule Sensitivity Index (SSI)	-	-	-	X	-	X
M30	Estimate-at-Completion (EAC)	-	-	-	X	-	X	M71	Schedule variance (SV)	-	-	-	X	X	-

M31	Expected Progress	-	-	-	X	-	X	M72	Starvation	X	-	-	X	-
M32	Feeding buffer burn rate (FBBR)	-	-	-	X	X	-	M73	Takt Area Completion (TAC)	-	-	-	X	X
M33	Glut	X	-	-	-	X	-	M74	Takt Time Slot Completion (TTSC)	-	-	-	X	X
M34	Labor Hours Reliability Index (LHRI)	X	-	-	-	X	-	M75	Takt Wagon Completion (TWC)	-	-	-	X	X
M35	Labor Utilization Factor (LUF)	X	-	-	-	X	-	M76	Task Readiness (TR)	-	X	-	-	-
M36	Lean Workflow Index (LWI)	X	-	-	-	X	-	M77	Tasks Anticipated (TA)	-	X	-	-	-
M37	Location Risk Index (LRI)	-	X	-	-	-	X	M78	Tasks Made Ready (TMR)	-	X	-	-	X
M38	Milestone Variance (MV)	-	-	X	-	-	X	M79	To-Complete Schedule Compression Ratio (TCSCR)	-	-	-	X	X
M39	Misallocation Factor (MF)	X	-	-	-	X	-	M80	To-Complete Schedule Performance (TCSPI)	-	-	-	X	X
M40	New duration	X	-	-	-	X	-	M81	Value-in-Process (VIP)	-	-	-	X	X
M41	Number of Backlog Activities (NBA)	-	X	-	-	-	X	M82	Weekly Deviation (WD)	X	-	-	-	X