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# Requirements in performance measurement systems of construction projects from the lean production perspective

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**Abstract** Performance measurement (PM) generates useful data for process control, facilitates communication between different sectors, and helps to align efforts on the most important aspects of the business. Thus, PM plays a key role in the management of projects and organizations. PM is also important in the implementation of lean production principles and methods, such as reducing the share of nonvalue-adding activities, increasing process transparency, building continuous improvement into the process, and benchmarking. Moreover, the adoption of the lean production philosophy requires changes in PM. Despite its importance, limited studies have been conducted on the use of PM systems for assessing the impact of lean production programs in construction projects. In addition, studies on how lean companies (or projects) use performance measurement and to what extent the indicators adopted reflect the result of actions that have been undertaken are limited. This study proposes a set of requirements in PM systems of construction projects from the perspective of lean production and a taxonomy of performance metrics for lean production systems. Five empirical studies have been carried out on construction companies from South America involved in the implementation of lean production systems. The scope of this investigation is limited to the construction projects as production systems rather than PM at the level of construction organizations.

**Keywords** performance measurement, lean construction, production management, continuous improvement, metrics

## 1 Introduction

Performance measurement (PM) has attracted considerable attention from researchers since the 1990s in the fields of operations (Neely et al., 1997) and construction management. Different types of contributions regarding the construction industry can be found in the literature, such as conceptual approaches (Kagioglou et al., 2001), criteria for assessing PM systems (Costa and Formoso, 2004), implementation models (Love and Holt, 2000), comparisons between metrics adopted by different companies (Costa et al., 2006), and PM in specific sectors or processes (Robinson et al., 2005). Moreover, several initiatives promoted by industrial organizations have proposed key performance indicators or benchmarking clubs for construction organizations (Costa et al., 2006).

The design of a PM system involves more than the selection and definition of appropriate measures for assessing the efficiency or effectiveness of processes and organizations (Costa and Formoso, 2004). This type of system should contain the following key elements: (i) procedures for collecting and processing data, (ii) timetables and protocols for the distribution of performance information to users within and outside the organization, (iii) a learning approach in which actions for improving performance are defined, and (iv) a review process with the aim of regularly updating the PM system (Neely et al., 1997).

PM systems play a key role in business management because they provide the necessary information for process control, enable the establishment of challenging and feasible goals, and facilitate communication between different managerial levels (Hall et al., 1991). Moreover, such systems help to align the efforts and resources on the important aspects of the business (Lantelme and Formoso, 2000) and produce data that can be used as a reference for process improvement (Pavlov and Bourne, 2011).

Despite their importance, many problems involving PM

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in construction projects have been pointed out in the literature. For example, (i) several companies use traditional lagging indicators, focused on results, which are ineffective in supporting timely decisions (Sarhan and Fox, 2013); (ii) some PM systems contain too many measures, most of them concerned with supporting rather than critical processes (Costa and Formoso, 2004); (iii) the implementation of PM systems is often limited to the selection of isolated measures (Beatham et al., 2004); and (iv) PM systems are ineffectively integrated with continuous improvement initiatives (Kennerley and Neely, 2003).

PM is also important in the implementation of innovations in managerial systems. The introduction of the lean production philosophy in the construction industry demands this type of innovation, as it was originally developed in the automobile industry and later adapted to other sectors, such as aerospace, consumer products, metal processing, and healthcare (Koskela, 1992; Womack and Jones, 2003). Thus, the implementation of some lean production principles, such as reducing the share of nonvalue-adding activities (waste), increasing process transparency, building continuous improvement into the process, and benchmarking, requires changes in PM (Koskela, 2000). Moreover, studies on how companies involved in such programs use PM and to what extent the indicators adopted reflect the result of actions that have been undertaken are limited (Bellisario and Pavlov, 2018).

Despite the growing interest from the construction industry in the adoption of the lean production philosophy, research on PM for lean production systems in this sector is scarce. Several companies involved in the implementation of lean concepts and principles in production management use only metrics related to the Last Planner System apart from the traditional cost and time deviation indicators (Formoso and Moura, 2009; España et al., 2012; Sacks et al., 2017). Sarhan and Fox (2013) pointed out that the improper use of PM systems is a critical factor for failure in lean implementation programs in construction. Therefore, there are opportunities for improving PM in construction companies that have adopted the lean production philosophy, especially in the use of some leading indicators related to certain core principles, such as pull production, work-in-progress (WIP), and continuous flow. By contrast, PM cannot be considered an end in itself; it must be regarded as a support activity because it does not add value to the product (Koskela, 1992). Thus, it is only worth using performance metrics if they are used to drive improvement (Hopkins, 2009). Moreover, there is a risk of spending too much effort on the application of performance metrics, rather than considering them as countermeasures (Spear and Bowen, 1999).

This study proposes a set of requirements for devising PM systems in construction companies from the perspective of lean production. Given that it is necessary to extend the scope of PM, this study devises a taxonomy of performance metrics for lean production systems in

construction. This investigation is based on empirical studies carried out on five companies from South America, which have been involved in the implementation of lean production systems. The scope of this investigation is limited to the production stage of construction projects rather than PM at the level of construction organizations.

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## 2 Criticism of traditional PM systems

Traditional PM systems have been criticized in the literature on performance measurement in general. (i) Centrally driven financial accounting-based systems are excessively emphasized (Waggoner et al., 1999; Kaplan and Norton, 1992). (ii) The majority of metrics are reactive and focused on past results (Neely, 1999). (iii) Too many measures are used due to the lack of prioritization of critical processes (Sánchez and Pérez, 2004). (iv) The increasing importance of indirect costs is not considered enough (Kennerley and Neely, 2003; Bhasin, 2008). Finally, (v) the strategic aspects of PM are often overlooked (Kagioglou et al., 2001; Bellisario and Pavlov, 2018).

Many criticisms of traditional PM systems also come from the literature on lean production. (i) Several metrics adopted in PM systems, such as cost deviation, time deviation, and utilization rates, are strongly related to the mass production paradigm (Maskell, 1991; Koskela and Howell, 2002). (ii) Some metrics are concerned with very specific tasks (typically value-adding work) and often lead to local optimization (Koskela, 1992). (iii) Learning and collaboration are not considered enough (Neely, 1999; Bourne et al., 2000). Finally, (iv) minimal attention is given to factors that have become critical in global competition, such as flexibility, service, and innovation (Womack and Jones, 2003).

Regarding lean production implementation programs, traditional PM systems may discourage managers to go on, as there might be a reduction in productivity (Karlsson and Åhlström, 1996) or a short-term decrease in financial performance (Bellisario and Pavlov, 2018) at the beginning. Therefore, increased emphasis on other types of metrics, such as leading, proactive, or intermediate indicators, is necessary to evaluate the impact of managerial changes in the early stages of implementation (Karlsson and Åhlström, 1996). In this context, operation-based measures and controls are more effective in supporting lean implementation efforts than financial accounting-based metrics (Bellisario and Pavlov, 2018).

Regarding the construction industry, the implementation of lean production creates additional demands in PM systems in relation to what has been suggested in the literature for project management, as shown in Table 1.

The following innovative PM practices have been introduced by some lean production methods that have been successfully implemented in the construction industry:

**Table 1** Role of PM systems

Traditional construction project management	Lean construction project management
① In process control, performance is measured at the output (or input), and deviations to standards must be detected for correcting processes (Koskela and Howell, 2002). This assumption encourages the minimization of variance rather than continuous improvement (Bourne et al., 2000).	① A PM system should provide not only the necessary data for process control but also information that can be used as a reference for process improvement and learning (Pavlov and Bourne, 2011). This premise indicates that the root causes of deviations must be identified to ensure that problems can be eliminated (Koskela and Howell, 2002).
② Performance measures can be used to align efforts and resources to the most important aspects (or strategic objectives) of the business (Lantelme and Formoso, 2000).	② Apart from strategic goals, measures should also focus on lean goals, such as elimination of waste, reduction of variability, and improvement of value generation (Koskela, 1992).
③ PM systems must be used to disseminate challenging and feasible goals in the company (Hall et al., 1991).	③ In addition to the dissemination of goals, PM should point out shortcomings, which can be regarded as sources of creative tensions for continuous improvement (Spear and Bowen, 1999).
④ Effective information flows must be used to provide communication between different managerial levels and departments (Hall et al., 1991).	④ Apart from being disseminated through information flows, performance measures should be made available in information fields (i.e., sets of visual devices), in which invisible process attributes are made visible to several people (Koskela, 1992).

(i) The Last Planner System of Production Control (Ballard and Howell, 1998) is a widely disseminated planning and control model that has two key metrics: The percentage of plans completed (PPC) and the number of made-ready tasks. Both are measures of planning reliability that create opportunities for learning by monitoring the causes of planning failures.

(ii) Location-based Planning (Seppänen et al., 2010) is a planning tool strongly rooted in metrics related to WIP control, batch size, and continuous and uninterrupted flow.

(iii) Prototyping (Fazinga et al., 2016) and first-run studies (Howell and Ballard, 1997) are methods that provide opportunities for learning, often based on measurements. Different types of improvements, such as elimination of nonvalue-added activities, the definition of standard operations, and quality improvement, can be achieved.

(iv) Andon (Tezel et al., 2010) represents a decentralized mechanism for identifying problems and solving them rapidly for control. This tool also generates metrics for process reliability and encourages learning.

(v) A3 Report (Shook, 2008) is a visual device that communicates the result of an improvement initiative, which usually involves metrics for result assessment.

### 3 Requirements in PM systems for lean construction projects

Several requirements in PM systems for lean construction projects have been proposed in the literature. However, given that such requirements have been individually investigated in separate studies, these were grouped in categories as follows.

**(i) Performance metrics must have a direct alignment with high goals.** Performance metrics must be aligned with the company's high goals for two reasons. First, it is

necessary to assess whether strategic goals are being achieved, based on actions being taken (Bhasin, 2008). Secondly, strategies need to be translated into operational measures, which point out goals that are important to the company. In the case of the implementation of lean production programs, high goals may be related either to the company's corporate strategy or lean goals, such as elimination of waste and generation of value from the perspective of the final customer (Koskela, 2000). Bhasin (2008) pointed out the importance of communicating metrics that disseminate the important goals of the company as a mechanism to obtain the commitment from different sectors of the company.

**(ii) PM systems must combine leading and lagging indicators.** Lagging indicators are used to assess the final results, whereas leading indicators enable decisions to be made on future activities on the basis of the outcome of ongoing processes (Beatham et al., 2004). Moreover, leading indicators provide evidence in understanding how a particular result is achieved (Costa et al., 2006; Kagioglou et al., 2001). By contrast, lagging indicators, such as some financial measures, are important for measuring the impact of improvement initiatives and external reporting, but not as guidance to daily actions (Manoochehri, 1999). In the case of lean production programs, leading indicators are important for assessing the implementation of core principles, such as monitoring continuous improvement and keeping variance under control.

**(iii) Meaningful and timely feedback must be provided to users.** PM systems must provide fast, relevant, and reliable information to support decision-making (Neely et al., 1997). There is a growing potential for using information technology to automate data collection and processing (e.g., the use of mobile computing) to ensure that timely information is provided (Bhasin, 2008). Moreover, stakeholders should understand

the meaning and importance of the information provided (Maskell, 1991). Therefore, the choice of metrics and how these are displayed depend on the specific needs of each user (e.g., managers, workers, and subcontractors). This type of feedback allows for the early detection of deviations to ensure that decision-making and corrective actions can be undertaken rapidly (Fullerton and Wempe, 2009). In lean production programs, this requirement is strongly related to two core principles, “reduction of batch size” and “reduction of cycle time”, which enable early process feedback (Koskela, 2000). “Increase process transparency” is another principle strongly related to the effectiveness of feedback: Visual devices should be designed for specific users and placed closed to the users so that the necessary information is available at the point of use (Valente et al., 2017).

**(iv) PM systems must promote improvement and learning.** As shown in Table 1, PM systems must provide information that encourages improvement and learning rather than being used only for monitoring. Metrics must indicate areas with opportunities for improvement and also what is being performed well (Maskell, 1991). The combination of quantitative and qualitative information is generally necessary to ensure that the root causes of problems are appropriately understood. Regarding learning, moments of reflection must be made available for evaluating results and proposing improvements. For instance, formal meetings could be held at specific work times in which the participation of the stakeholders should be encouraged (Lantelme and Formoso, 2000). In this context, process transparency can be used to facilitate collaboration among team members (Ewenstein and Whyte, 2007), to mitigate problems related to the management of complexity (Viana, 2015), and to increase the motivation of the workforce (Galsworth, 1997).

**(v) PM systems must create local control systems.** The idea of local control systems is based on the assumption that providing a certain degree of freedom for managers or teams to adopt indicators that meet their specific needs is beneficial to the company. In this type of control, metrics should consider actions at the operational level and provide a reliable assessment of the existing reality for people involved in improvement initiatives (Bellisario and Pavlov, 2018). These systems generally adopt constructs for defining controls, i.e., local concepts relevant to a specific context. Therefore, some of these metrics might be difficult to use for comparisons without understanding the context behind them. For instance, the number of Kaizen initiatives is a metric adopted by some companies although there is no widely accepted definition of a Kaizen initiative (Maskell, 1991). This type of metric may differ from one production system (or project) to another. These indicators aim to stimulate the involvement of operational teams in continuous improvement initiatives, which is an important element of lean production systems.

**(vi) PM systems must be flexible and updated from**

**time to time.** “Flexibility is the ability to respond effectively to changing circumstances” (Gerwin, 2005). A PM system must be flexible and adaptable to keep pace with changes in the production system (Maskell, 1991), while satisfying the requirements of each situation, in the case of flexible production systems (Koskela, 1992). Changes in the external business environment may also require the updating of PM systems (Kennerley and Neely, 2003). In lean production programs, organizations must continuously adapt their performance measurement systems to suit the given context and consequently stimulate debate and create opportunities for learning (Bellisario and Pavlov, 2018).

**(vii) The scope of PM systems must be extended.** The metrics adopted in PM systems must be directly related to the implementation of some lean production concepts and principles. Koskela (1992) makes some recommendations for the development of PM systems to support the application of lean production concepts: (i) investigating the causes of the problems; (ii) measuring waste through the assessment of the share of nonvalue-added activities; (iii) monitoring of variability, cycle time, and defects; and (iv) promoting continuous improvement (or learning). Karlsson and Åhlström (1996) proposed a set of categories for the measurable attributes of lean production systems in manufacturing. Those categories are strongly based on the conceptualization proposed by Womack et al. (1990). Sánchez and Pérez (2004) put forward a similar framework of indicators for companies involved in the implementation of lean production in services. Table 2 lists the taxonomies and examples of metrics proposed by Karlsson and Åhlström (1996) and Sánchez and Pérez (2004), in which waste elimination and continuous improvement are clearly emphasized. Moreover, both studies proposed several metrics related to organizational issues (e.g., multifunctionality, decentralized responsibility, integrated functions, and information systems). Such metrics emphasize the need to consider human factors in the implementation of the lean production philosophy. However, these two taxonomies ignore the importance of monitoring variability and measuring value generation, as suggested by Koskela (2000).

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## 4 Research method

Design science research is the methodological approach adopted in this investigation. This approach has a prescriptive character, and consists of devising solution concepts called artifacts to solve classes of problems (van Aken, 2004; Holmström et al., 2009). In this study, the proposed artifact is a set of requirements that can be used for assessing or devising PM systems for construction projects in companies involved in the implementation of lean production programs. Such requirements have been established through the analysis of the PM systems of five

**Table 2** Categories and examples of performance metrics proposed for lean production systems

Karlsson and Åhlström (1996)		Sánchez and Pérez (2004)	
Category	Example of metric	Category	Example of metric
Elimination of waste	Value of rework in relation to sales	Elimination of waste	Inventory rotation
Continuous improvement	Number of suggestions per employee and year	Continuous improvement	Percentage of employees' suggestions implemented by the company
Zero defects	Workers take out and adjust defective parts	–	–
Just-in-time	Production run time between setups	Just-in-time delivery	Percentage of items delivered just-in-time by suppliers
-Pull instead of push	Number of process stages that are pulled in relation to the total number of stages	–	–
Multifunctional teams	Percentage of employees working in teams	Multifunctional teams	Percentage of employees working in teams
-Decentralized responsibility	Number of functional areas under the responsibility of teams	–	–
-Integrated functions	Number of different indirect tasks performed by teams	–	–
-Vertical information systems	Number of areas contained in the information given to employees	-Flexible information systems	Number of monthly meetings involving top managers and employees
–	–	Supply chain integration	Average length contract with key suppliers

different construction companies from Latin America.

Table 3 shows a brief description of each company. These companies were selected for the following reasons: They (i) had well-structured PM systems, (ii) successfully implemented a number of lean production practices, and (iii) were willing to provide access to information.

Multiple sources of evidence were used in each empirical study:

(i) Analysis of the historical database of performance metrics adopted during the implementation of the lean program in each company;

(ii) Analysis of documents, such as production plans,

control charts, quality control procedures, safety management instructions, managerial reports, and presentation slides;

(iii) Participant observations in look-ahead and short-term production planning and control meetings;

(iv) Direct observation of construction sites, including visual devices, pathways, inventory areas, and logistics operations; and

(v) Secondary sources of data, including papers and research reports (Barth and Formoso, 2008; Saurin et al., 2008; 2015; Costa and Formoso, 2011; Fireman et al., 2013; Formoso et al., 2017; Valente et al., 2017; de Vargas

**Table 3** Description of the five companies

	Company A	Company B	Company C	Company D	Company E
Company size	Large	Large	Small	Large	Medium
Main activities	Construction and real estate development for middle- and upper middle-class residential markets	Services and integrated solutions in the construction of industrial buildings and offshore platforms	Construction and real estate development for middle- and upper middle-class residential markets	Construction and real estate development for lower-, middle-, and upper middle-class residential markets	Development and construction buildings for private clients (mostly industrial and healthcare projects)
Main characteristics	Considered as a benchmark in lean construction, started lean implementation in the 1990s	Multinational company, started lean implementation in complex projects (e.g., offshore) 7 years ago	Family-owned company, started lean implementation less than 4 years ago	Started lean implementation less than 3 years ago	Worked mostly as a contractor in a wide range of projects, started lean implementation 15 years ago
Main lean practices adopted	Last Planner Kanban 5S Prototyping Visual management Standardized work	Last Planner Kanban Multifunctional teams Visual management Standardized work Value stream mapping	Last Planner Visual management Task completion control Takt-time planning	Last Planner Visual management 5S Task completion control Takt-time planning	Last Planner Production system design Visual management Takt-time planning Prototyping

et al., 2018), were used in Companies A, C, and E.

After processing and analyzing qualitative data, an overall description of the PM system was produced for each company, including the following information: The main information flows, detailed descriptions of metrics related to the lean implementation program, meetings in which those metrics were analyzed and discussed, personnel involved in data processing and analysis, and visual devices used for disseminating information.

## 5 Results

### 5.1 Overview of PM systems developed by the companies

This section describes some features of the PM systems devised by the five companies in the implementation of the lean production philosophy. Therefore, the practices related to lean production are emphasized. All companies used other metrics, which are not reported in this paper, related to the traditional way of measuring performance, such as cost deviation, project delays, and project progress.

Company A is a large firm that develops and builds mostly for middle- and upper middle-class residential projects. This company is considered a leading company in the implementation of lean production in Brazil. It has a production planning and control systems strongly based on the Last Planner System and a well-structured quality control system for production processes. This company has also implemented some lean practices that are considered advanced in the construction industry, such as visual management, Kanban for site logistics, performance dashboards, and standardized work. The offices in all their construction sites have a control panel displaying all the production management metrics. Some metrics are systematically discussed in monthly meetings which involve representatives of all construction sites.

Company B is an international firm that provides services and integrated solutions in construction, insulation, and interior finishing for industrial building and offshore platforms. Its lean production program is strongly based on waste reduction and workforce development. The existing PM system is a combination of leading and lagging indicators. This company has successfully implemented several lean practices in an offshore platform

project, including the Last Planner System, standardized work, multifunctional teams, and visual management.

Company C is a small-sized family-owned company that delivers residential building projects in the south of Brazil. This company started to develop a planning and control system that combines elements of the Last Planner System and Location-based Planning 4 years ago.

Company D is a large firm that develops and builds residential building projects in Chile. This company started the implementation of lean production practices less than 3 years ago. This implementation started with the development of a planning and control system strongly based on the Last Planner System. The offices in all construction sites also have a control panel displaying several metrics and plans, including a location-based plan. Monthly workshops are held to present the results and lessons learned from the implementation process, involving project managers and representatives of all construction sites involved in the implementation.

Company E is a medium-sized contractor that delivers complex projects, such as hospitals and industrial buildings, for highly demanding clients. The majority of their projects consist of refurbishment or extension of existing facilities in a short duration. This company devised a very comprehensive lean production management system, which consisted of several elements, including the Last Planner System, Location-based Planning, production system design, performance dashboards, and integrated safety and production control (for some construction sites).

Table 4 shows the assessment of the degree of adoption of six requirements in the PM systems of the five companies. The requirement related to the scope of PM systems is discussed in the following section. Three different grades based on the perception of the research team, namely, totally (T), partially (P), and not adopted (N), have been used in this assessment. Companies A and B can be considered the most advanced in terms of PM. Moreover, most companies were effective in terms of implementing rapid feedback to users and process transparency. The least considered requirement was the “creation of local control systems”. In Companies D and E, the PM systems had not been systematically updated because lean construction was in the early stages of implementation. Some measures for local control (e.g., Last Planner System metrics, number of improvements,

**Table 4** Adoption of requirements in the design of PM systems

Requirements	Company A	Company B	Company C	Company D	Company E
Direct alignment with high goals	P	T	P	P	P
Combine leading and lagging indicators	T	T	P	T	P
Provide meaningful and timely feedback to users	T	T	T	T	T
Promote improvement and learning	T	T	P	T	P
Create local control systems	P	P	N	N	P
Be flexible and updated from time to time	T	P	P	N	N

measurement of WIP) were identified in the companies studied, being used to support local improvements by operational teams. Nevertheless, those measures were not strongly aligned with strategical goals, remaining as something to be better explored in those companies.

## 5.2 Performance metrics adopted by the companies

Table 5 shows an overview of the metrics adopted by the companies in the implementation of lean production programs. These metrics were grouped into categories as follows.

(i) Last Planner metrics: All the companies implemented the Last Planner System and adopted metrics often used at the look-ahead and weekly planning level, including: Overall PPC, PPC for different crews or subcontractors, causes for the noncompletion of work packages, overall number of constraints identified, percentage of constraints removed, and number of constraints for each category.

(ii) Effectiveness of Last Planner implementation: Three out of five companies also used a metric that assesses the degree of implementation of planning and control practices. Such a metric is based on a checklist composed of 15 practices that were originally proposed by Bernardes and Formoso (2002). This checklist covers three planning levels and allows the evaluation of the degree of maturity of planning systems. The companies did not use maturity models in conducting a broad assessment of lean implementation beyond Last Planner.

(iii) Daily OTP (on-time performance): One company used another production control tool called daily OTP, which monitors the percentage of daily tasks completed in relation to the number of tasks planned through cards in a tool called the planning and performance management (PPM) board<sup>1)</sup>. This metric is similar to the PPC indicator but it is displayed daily in a visual panel concerned with a work zone or the project as a whole. The weekly OTP

indicator is an overview of the performance over a 4-week period and provides some details of the current week (e.g., the progress of work by the team, supervisor, and area). This indicator can also be used for monitoring deviations in relation to the takt time on a daily basis, process efficiency, and capacity utilization, especially in bottleneck resources. Correction and prevention actions are proposed in response to the deviations pointed out by this indicator. These actions may be defined and documented in A3 Reports.

(iv) Task diminishment and WIP control: This concept was proposed by Patton (2013), which consists of tasks executed in a nonconforming way but are difficult to detect in control inspections and will likely lead to rework or value loss. This problem is strongly related to two categories of waste often found in construction sites, namely making-do (Koskela, 2004) and unfinished work (Fireman et al., 2013). Making-do is a reduction in performance when a task is started or continued although a complete set of necessary inputs is unavailable (Koskela, 2004). By contrast, unfinished work refers to the situation in which some small finishing tasks are left behind when the crew leaves the workplace (Fireman et al., 2013). Both categories can contribute to the increase of WIP, cycle time and the share of nonvalue-adding activities. Although making-do is difficult to measure (Formoso et al., 2017), two companies adopted some metrics for monitoring WIP and uncompleted batches. These are, respectively, the percentage of hastened tasks, which is the ratio between the number of tasks that started before the schedule and the total number of tasks, and the percentage of interrupted batches (de Vargas and Formoso, 2020). These indicators are generated from a matrix, shown in Fig. 1, which allows the completion of activities (columns) in different production units (rows) to be monitored. Each cell presents information on the task status (whether the task is in progress, stopped, or not released (not started)). In the case

**Table 5** Indicators used by the five companies to support the implementation of lean practices

Indicators	Company A	Company B	Company C	Company D	Company E
Last Planner metrics	×	×	×	×	×
Effectiveness of Last Planner implementation	×		×	×	
Daily OTP (on-time performance)		×			
Task diminishment and WIP control			×	×	
Number of Kaizen ideas		×			
Gemba walk wastes		×	×		
Control of batch completion rhythm	×		×	×	×
Batch adherence control				×	×
Cycle time				×	×
Integrated safety and production control	×				×

1) Daily visual planning panel, similar to a Heijunka Box, which contains a daily schedule, being often used for on-site prefabrication. This panel should be based on a takt time on a daily basis and be connected to short-term plan.

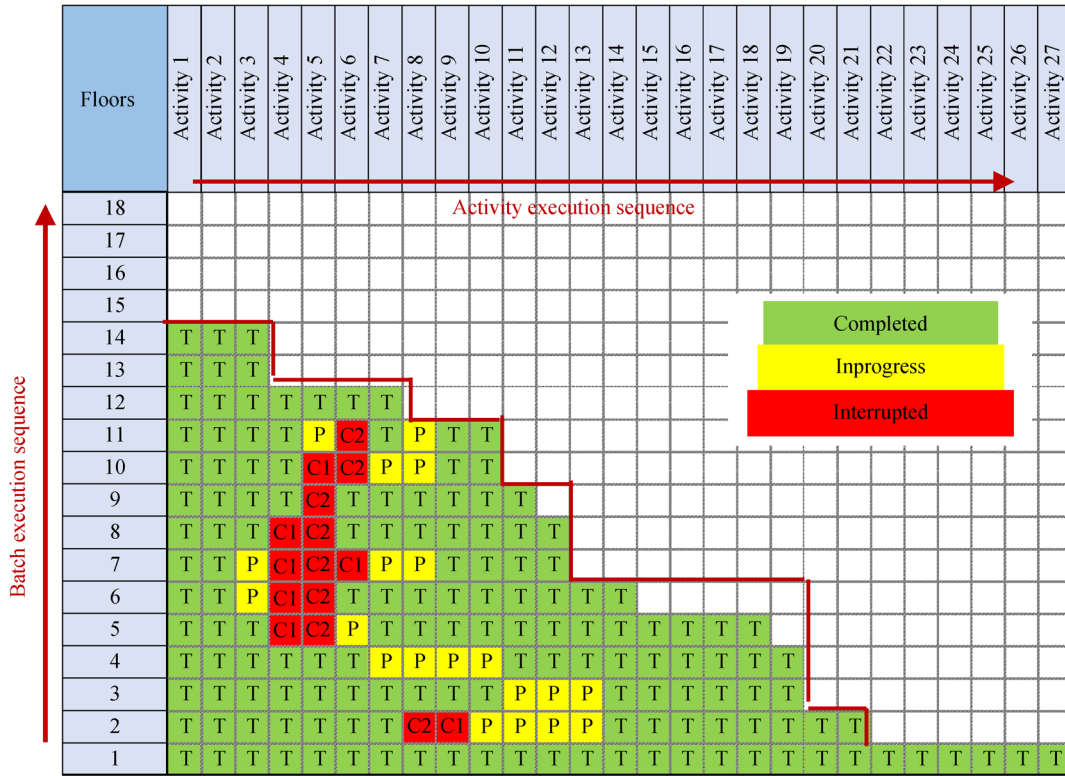


Fig. 1 Example of a tool used for controlling unfinished work and WIP.

of stoppage, a cause must be reported. An additional indicator can be used to point out the causes of interrupted batches. Moreover, the matrix itself provides a visual map of the project status and information that can be used to monitor cycle time. Another tool used for WIP control is called “heatmaps”, which are visual representations of where the workers are located in the production units, as shown in Fig. 2. WIP control can be used to monitor the number of people working on each floor, apartment, or batch. When this tool is combined with an indicator of interrupted batches, it provides an overview of the project progress to ensure that problems related to the excessive amount of WIP or unfinished work can be detected. If workers are scattered in the construction site, then the control effort to keep track of task execution tends to increase.

(v) Number of Kaizen ideas: This indicator is based on improvement initiatives that are usually conducted by teams in a collaborative way at a very operational level. Each idea is devised and tested by a team, and a recommendation may be given on whether or not it should be implemented in other projects. This metric is often calculated on a monthly basis (e.g., number of Kaizens applied per month). This indicator can be used for giving awards to individual employees or teams whose ideas result in the best improvement (e.g., reduction in the number of man hours or elimination of nonvalue-adding time). Sometimes the proportion of top-down and bottom-

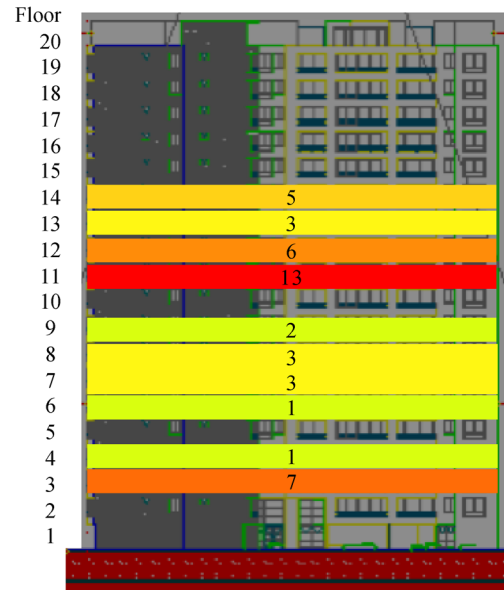


Fig. 2 Example of a heatmap for controlling WIP.

up Kaizen ideas is also produced, such as the ratio between the number of Kaizen ideas originated at the shop floor and the number of Kaizens ideas coming from top managers, senior managers, and directors.

(vi) Gemba walk waste: Gemba walk aims to identify waste (nonvalue-adding activities) in the processes being

executed in the construction site. This tool is used regularly by top and site managers to promote the identification and removal of waste in learning cycles (e.g., every 2 weeks). Observing how the process is carried out in the work area and speaking with workers performing the job are essential during a Gemba walk to ensure that the process is fully understood. During a Gemba walk, one should identify the different types of waste at distinct workstations, follow the material and information flows, and look out for possible causes. This indicator monitors the frequency of events related to each type of waste identified on Gemba walks and possibly the rate of success to eliminate them. Some waste categories can be the focus of this improvement initiative, such as the seven wastes identified by Ohno (1988), such as transportation, waiting, and overproduction, or other categories that are specific to the construction industry, such as making-do (Formoso et al., 2017) or unfinished work (Fireman et al., 2013).

(vii) Control of batch completion rhythm: This metric is used to compare the actual rhythm of a critical process to the planned rhythm or takt time (Frandsen et al., 2015), if available. It is calculated by the ratio between the number of batches (or substages) completed and the number of batches (substages) planned for a specific period. This metric is based on the rate of completion of batches, whereas traditional metrics of project progress may consider incomplete tasks. This indicator encourages the entire team, including subcontractors, to focus their work on completing each batch before starting the next one. Figure 3 shows how this tool can be used to assess the impact of the pace of a critical process on other processes: Changes in one line (or completion rate) need to be monitored to assess whether the plans for other processes need to be changed.

(viii) Batch adherence control: As a result of the implementation of “reduce cycle time” and “reduce WIP” principles, the traditional project progress charts

become insufficient for controlling the project pace and duration. Moreover, the control of batch adherence is also limited because the starting date of each batch is unclear. Two companies adopted the batch adherence indicator, which monitors whether or not the batches are being executed in the sequence and pace according to plan, with consideration for the location-based system adopted, that is, the division of the project in small batches. This control is usually performed at the look-ahead planning level. Viana (2015) pointed out that monitoring batch adherence can contribute to the reduction of WIP. Figure 4 shows an example of this type of control, wherein the trend of starting new work packages (new batches) without the completion of the previous ones increases the amount of WIP.

(ix) Cycle time: According to Rother and Shook (1999), cycle time refers to how often a part of or a product is completed, including processing time, storage, inspection, and rework. If there is repetition of similar production batches, it is important to monitoring both the duration and the variance of cycle time. This action generates alerts for the planning process, specifically when the pull production principle is adopted. Maintaining a short cycle time indicates that WIP is not increasing, resulting in short cycles of deviation detection and correction (Koskela, 1992) and fast delivery to the customer (Ballard, 2001).

(x) Safety: Two companies used metrics that resulted from the integration of safety management and the Last Planner System, as suggested in Saurin et al. (2008). Company A included the metric “percentage of safety work packages concluded” in its short-term planning to monitor the effectiveness of the execution of work packages related to safety-related tasks (e.g., installation of collective protective equipment). Company E adopted in some construction sites a metric called the percentage of safe work packages, wherein work packages without safety problems (i.e., nonconformances, accidents, and near

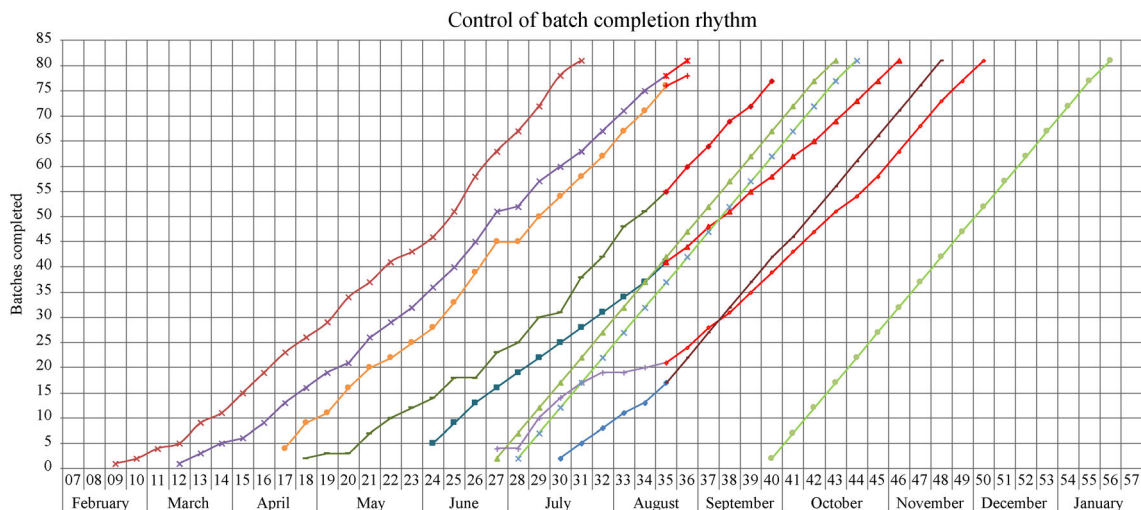


Fig. 3 Example of a chart monitoring the rhythm of different processes.

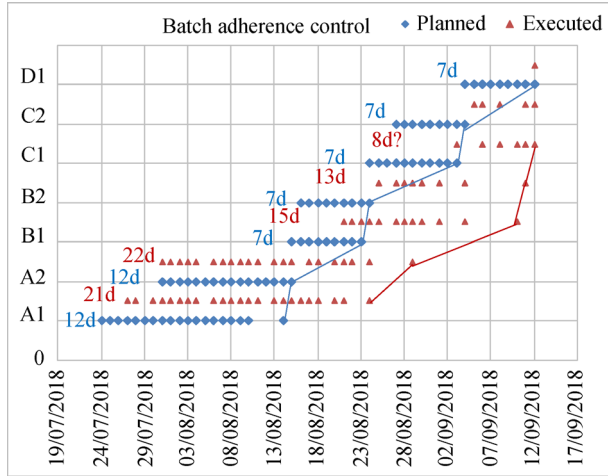


Fig. 4 Example of a chart monitoring batch adherence.

misses) were detected. In both cases, the causes of the lack of safety could be systematically identified. Both companies also used a metric for monitoring near misses (Saurin et al., 2015). These three metrics can be directly related to the concept of resilience, as they were designed to cope with uncertainty and help anticipate the risks due to their proactive character. Resilience is “the ability of a system to adjust its functioning prior to, during, or following events (changes, disturbances, and opportunities), and thereby sustain required operations under both expected and unexpected conditions” (Hollnagel et al., 2006). This concept has been effectively adopted in the safety management of highly complex systems, such as aviation and healthcare, and can also be potentially applied in construction.

## 6 Discussion

On the basis of the requirements proposed in this investigation, the assessment of the PM systems of the five companies has pointed out some improvement opportunities, such as aligning metrics with high goals and the development of local control systems.

Although the companies have successfully provided meaningful and timely feedback to users in planning and control meetings and promoted improvement and learning, the scope of existing PM systems is relatively limited. Table 6 shows the classification of performance metrics adopted by the firms according to the core principles or concepts involved. The majority of metrics are focused on process reliability. The majority of metrics are directly related to the implementation of the Last Planner System, and similar to those observed in construction companies of previous studies (España et al., 2012; Sacks et al., 2017). However, certain companies have recently started to use metrics related to Location-based Planning, which can be used for controlling takt time, WIP, and cycle time.

Table 6 Classification of indicators according to lean principles or concepts

Core principle or concept	Performance measures
Continuous improvement and collaboration	Number of Kaizen ideas Gemba walk wastes
Waste elimination	Task diminishment and WIP control Gemba walk wastes
Process reliability (production planning and control)	Last Planner metrics Daily OTP Task diminishment and WIP control Rhythm deviation Batch completion rhythm Batch adherence control Cycle time
Safety (resilience)	Percentage of safe work packages Percentage of safety work packages completed Number of near misses

Despite the collaborative character of the Last Planner System, three of the companies have no measures related to “continuous improvement and learning” and “collaboration and empowerment”, which are two important elements of the lean production philosophy. Only two metrics associated with these elements (number of Kaizen ideas and Gemba walk wastes) were used by Companies C and D.

Finally, none of the companies adopted metrics related to value generation, zero defects, just-in-time, and supply chain integration, as suggested in the literature (Karlsson and Åhlström, 1996; Koskela, 2000; Sánchez and Pérez, 2004). Notably, all the companies had metrics related to quality control strongly based on the detection of nonconformances. However, such metrics had a secondary role in production management due to its poor integration to planning and control, and were not used to support zero-defect programs.

Regarding supply chain management, although some of the companies had partnering relationships with key suppliers, no metrics were used for assessing the degree of supply chain integration. In fact, the lean implementation programs were mostly limited to the construction companies and had not been extended to their supply chains, such as in the implementation of just-in-time delivery. This feature is another improvement opportunity, specifically in large housebuilding companies, which tend to maintain the same suppliers across several projects.

Based on the literature review and on the lessons learned from the five empirical studies, a taxonomy for performance metrics related to the implementation of lean production in production management is proposed (Table 7). This taxonomy of metrics distinguishes between metrics related to the goals of lean production (waste elimination and value generation) and those concerned with the means to reach their goals.

Companies involved in lean production implementation must have a set of metrics for assessing the achievement of lean production goals. Regarding waste elimination, the most relevant types of waste, such as delays, defects, rework, waiting time, and accidents, must be identified in the specific context of each company. For value generation, metrics related to the degree of satisfaction with products and services provided by the company must be used on the basis of a deep understanding of what is valued for different customer profiles.

Regarding the means, the following six metric categories are proposed:

(i) **Process reliability:** This category includes all metrics related to production planning and control, such as those related to the Last Planner System and Location-based Planning, and also those produced by quality control. It is necessary to monitor not only the deviations (e.g., PPC, delays, and defects) but also their causes, as both types of information are useful to encourage learning.

(ii) **Slack control:** Slack is a mechanism for reducing interdependencies and minimizing the possibility of one process affecting another (Safayeni and Purdy, 1991). Slack can be regarded as a cushion of current or potential resources that enable an organization to adapt to the internal or external pressures successfully (Bourgeois III, 1981). The most common types of slack are inventories of materials. However, other types of cushions, such as time or capacity buffers and multifunctional teams, can be used.

This metric category replaces the use of metrics for simply monitoring the degree of just-in-time implementation, which is limited to material buffers.

(iii) **Supply chain integration:** The implementation of lean production depends strongly on the integration of the construction company with its suppliers. Several measures can be used to assess the level of integration, such as the number of suppliers involved in partnerships, degree of participation of suppliers in the early project stages, and integration of suppliers in the internal managerial processes.

(iv) **Safety from a resilience engineering perspective:** This category must include proactive metrics for safety management considering emergent risks, which are difficult to predict due to the complexity of the production system. Accordingly, metrics should support not only process monitoring and controlling but also risk anticipation and learning from both accidents and normal work, as suggested by Hollnagel (2017).

(v) **Continuous improvement and learning:** This metric category was proposed by Karlsson and Åhlström (1996) and Sánchez and Pérez (2004). This type of monitoring can be achieved by creating specific measures, such as the number of Kaizen projects, or by exploring existing metrics belonging to other categories. For instance, Last Planner metrics can provide evidence that continuous improvement occurs in production planning, such as the elimination of problems and growing PPC.

**Table 7** Taxonomy of performance metrics in lean production systems

	Categories of metrics	Examples of metrics
Categories related to lean production goals	Waste elimination	Cost of rework in relation to sales Number of wastes identified in Gemba walks
	Value generation	Degree of customer satisfaction Number of customer complaints
Categories related to lean production means (principles)	Process reliability	
	-Time reliability	Last Planner metrics Batch completion rhythm Batch adherence control Task diminishment
	-Quality reliability	Number of batches without defects Percentage of defective products
	Slack control	Inventory rotation Amount of WIP Number of items delivered just-in-time
	Supply chain integration	Degree of participation of suppliers in early project stages Integration of suppliers in internal managerial processes
	Resilience (safety)	Percentage of safe work packages Number of near misses
	Continuous improvement and learning	Number of Kaizen ideas Cost reduction resulting from Kaizen initiatives
Collaboration and empowerment	Number of suggestions per employee Number of decentralized control tools (e.g., Kanban)	

(vi) Collaboration and empowerment: This type of metric is necessary because lean production implementation often leads to decentralized responsibilities, reduction in the number of hierarchical levels, and involvement of workers in continuous improvement initiatives (Koskela, 1992; Karlsson and Åhlström, 1996). Several metrics, such as degree of responsibility given to employees, degree of participation of employees in collaborative processes, and implementation of decentralized planning and control tools (e.g., Kanban and Andon), can be used.

## 7 Conclusions

The main contribution of this study is a set of requirements for devising PM systems in companies involved in the implementation of the lean production philosophy. Such requirements are meant to encourage companies to focus on the improvement of PM systems as a whole rather than only considering the definition of isolated metrics. In the development of the requirements, tension exists between the improvement of PM systems and limiting the effort involved in data collection and processing. Therefore, given that PM is a nonvalue-adding activity, this investigation has considered the need to increase the effectiveness of PM systems rather than simply increasing the number of metrics and consequently the workload of employees.

The second contribution of this study is the taxonomy of metrics for the implementation of lean production in construction. Previous studies have proposed taxonomies for lean production systems but not in the construction industry.

The PM systems of five South American companies were assessed, considering the requirements and taxonomies that have been proposed in the literature. Some improvement opportunities, such as the need to align indicators with high goals, develop local control systems, and keep the PM system updated, were identified in the companies involved in this study. The five empirical studies confirmed that there is a strong emphasis on process reliability in PM systems adopted by construction companies. Some important gaps regarding PM, such as value generation, quality, slack, and supply chain integration, were identified in these companies.

An important limitation of this study is that the proposed set of requirements for PM systems have not had their utility assessed. Therefore, further work is necessary to evaluate and refine these requirements by using them in the lean implementation programs carried out by construction companies. There are also opportunities for future studies on the use of the proposed taxonomy to identify gaps in PM systems of construction companies and devise new metrics and tools for monitoring the implementation of lean production. Moreover, specific studies on the development of metrics for slack control, supply chain

integration, and collaboration and empowerment are necessary because these key elements in lean implementation programs have not been assessed properly.

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