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Moving toward lean construction through automation of planning and control in last planner system: A systematic literature review

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ABSTRACT

The Last Planner System (LPS) is a production planning and control system based on Lean Construction (LC) principles. Effectively implementing the LPS in the construction industry remains challenging, impeding the realization of LC principles. Automation of planning and control in the LPS has gained attention to address this challenge. However, research exploring the state-of-the-art of such automation and its impacts on realizing LC principles is still lacking. Therefore, this study performed a systematic literature review of 112 relevant studies, identifying 50 functionalities and associated benefits of automation across six LPS stages, with the lookahead planning stage having the maximum functionalities. Analyzing their interactions with LC principles revealed that automated planning and control in the LPS can support achieving ten LC principles. Future research directions are suggested in areas such as constraint management, knowledge reuse, dynamic replanning, and construction workforce training.

1. Introduction

The construction industry is expected to lead the global economic recovery and growth from COVID-19 (*Future of Construction*, 2021). However, it continues to suffer from low productivity growth (*Reinventing Construction: A Route to Higher Productivity*, 2017) and a high project time and cost overrun rate globally (Global Construction Survey 2015: Climbing the curve, 2015). With the rapidly changing characteristics of the construction market, projects are becoming increasingly complex to manage (*The next normal in construction*, 2020). This leads to the ineffectiveness of traditional project management tools, such as the Critical Path Method (CPM), in meeting project requirements (Ballard and Howell, 2003a). To this end, Koskela (2000) advocated for the development of a new production theory in construction, known as 'Lean Construction' (LC). It marked a paradigm shift by considering construction projects as a set of value-adding and non-value-adding activities rather than only value-adding activities considered by traditional project management methods. Several LC principles have been suggested for implementing the new production theory in construction, e.g., decrease of workflow variability, simplification, increase of transparency, and so forth (Koskela, 1992, 2000). Building on the LC principles, the Last Planner System (LPS) for production planning and control in construction was developed. Planning addresses defining how, in what sequence, when, where, by whom, and at what cost the work is done. Control focuses on steering toward the plans, making planned work ready for execution, selecting tasks for daily execution, reliable handover of work between the specialists, and, if needed, identifying alternative ways to accomplish the plans. The LPS is a hierarchical system that focuses on increasing the level of detail of plans as the execution time nears and enhancing the reliability of plans by reducing workflow variability. It considers social aspects crucial in planning and control. To this end, it emphasizes aspects such as involving the field execution team in the planning process, collaboration between various stakeholders, making reliable commitments in public, and keeping the plans in public view (Ballard and Tommelein, 2021).

Despite the proven benefits, such as improving the reliability of planning on construction projects (Fernandez-Solis et al., 2013), the construction industry is lagging in fully reaping the benefits of the LPS

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due to the technical and people-related challenges faced during its implementation. Common challenges in implementing the LPS in construction projects include the need for extra resources in planning, lack of knowledge and training about the LPS, poor constraint analysis, resistance to change, and inadequate information flow between different stakeholders (Dave et al., 2015b; McHugh et al., 2022; Perez and Ghosh, 2018; Porwal et al., 2010).

Recent years have witnessed a growing interest in utilizing automation to address challenges faced in implementing the LPS. In the context of this study, automation refers to the use of tools, technology, and algorithms to automatically perform planning and control tasks with minimal or no human intervention, which are otherwise performed by humans manually (Zhu et al., 2023). Merely using tools and technologies doesn't imply automation; for instance, using Building Information Modelling (BIM) just for visualization purposes during planning is not considered automation. Significant efforts have been made to automate different components of the LPS, for instance, the generation of multiple accurate near-optimal schedules (Dong et al., 2013), automated information flow, and constraint checking in real-time (Soman, 2020). Different tools and technologies have enabled this automation, such as Simulation Modeling (Abdelmegid et al., 2023), BIM (Heigermoser et al., 2019), Linked Data (Soman, 2020), and Artificial Intelligence (AI) (Soman and Molina-Solana, 2022). Efforts toward automation have been found to provide profound benefits to LPS implementation, for instance, the improved accuracy of plans, the possibility of selection from different plan alternatives, reduced time-space conflicts on construction sites, and so forth. As the LPS is a crucial tool of LC (Salem et al., 2006), improvement in the LPS implementation also supports making construction projects leaner.

Despite the technological advancements, much attention has not been given to understanding the state of automation of planning and control in the LPS and its contribution to realizing LC principles through better implementation of the LPS. Existing research in this direction has focused majorly on utilizing the potential of BIM for supporting LPS implementation (Sbiti et al., 2021; Schimanski et al., 2020). However, their findings reveal that BIM provides limited automation capabilities in the LPS. The potential of recent technological advancements, such as AI, optimization, and semantic web, to underpin the LPS implementation through automation and enable the achievement of LC principles on construction projects remains unexplored. As Lean Construction moves towards the new paradigm of Lean Construction 4.0 (González et al., 2022), which focuses on integrating the People, Process, and Technology aspects of Lean Construction with Industry 4.0-driven smart and digital technologies, automation is expected to play a significant role in this transformation (González et al., 2022; McHugh et al., 2022). As the LPS is one of the most frequently used LC methodologies (Larsson and Ratnayake, 2021; AlSehaimi et al., 2014), evaluating the state of automation in the LPS and its benefits in achieving LC principles is essential. Developing such understanding can motivate the construction industry towards adopting automation in the LPS implementation and guide future researchers to build a new generation of automated systems to implement the LPS better.

To this end, this research aims to address the following research question using a Systematic Literature Review method (Moher et al., 2009).

- *Research Question: How can automation of planning and control in the Last Planner System make construction projects Leaner?*

The specific objectives of this study are:

- Objective 1. To investigate the current status of automation of planning and control within the LPS framework and the key benefits provided by it.
- Objective 2. To understand how the benefits offered by automation of planning and control within the LPS framework can enable LC principles.
- Objective 3. To identify research gaps and recommend future research directions in the area of automation of planning and control within the LPS framework.

The rest of this paper is structured as follows. Firstly, a brief background about the LC and LPS is provided. Then, the methodology for conducting this review study is explained. The following section discusses the results of the systematic literature review. Further, a discussion regarding the potential of automation of planning and control within the LPS to support LC principles is presented. Finally, future research directions are proposed.

2. Background

2.1. *Lean Construction (LC)*

LC is a production management philosophy for construction projects whose roots originate from the Toyota Production System. The Toyota Production System refers to a set of principles and practices adopted by Toyota with the basic philosophy of eliminating all kinds of wastes (such as overproduction, inventory, and defects, etc.) from its vehicle production system and consequently developing the most efficient production methods (Ohno, 1982; Womack et al., 1990). The term 'Lean' was associated with this production management philosophy as it emphasized "using less of everything" (Womack et al., 1990, p. 13), for instance, fewer resources, lesser inventory, and minimum cost (Womack et al., 1990).

To improve the construction industry's productivity, Lauri Koskela (Koskela, 1992, 2000) started exploring the application of lean production in construction, also termed LC (Koskela, 2000). Similar to Lean Production, LC also aims to maximize value and minimize waste in construction (Sacks et al., 2010a). It conceptualizes construction projects as a production system comprising flows and transformations. While the transformation aspect focuses on converting a set of input resources into a modified form, the flow aspect centers on the activities that transpire between the transformations, such as inspection, transfers, and delays. Although both consume the resources, flow activities are not necessary from the perspective of adding value to the customer. Similarly, some parts of transformation activities might be unnecessary if they can be removed using alternate methods. Such unnecessary activities are termed non-value-adding or waste (Koskela, 2000). To improve the performance of construction projects, LC emphasizes eliminating the flow activities and making the transformation activities more efficient. The LC principles are based on the conceptual notions of lean production theory in construction and define the foundations over which LC tools and methodologies are built (Koskela, 2000). The LPS is a widely adopted LC methodology (Larsson and Ratnayake, 2021). It has proven its benefits in improving construction project performance across indicators such as time, cost (Formoso and Moura, 2009), and quality (Koskenvesa and Koskela, 2005).

2.2. *Last Planner System*

The traditional way of construction project management was transformation view dominant. The project planning and control mainly concentrated on the division of work through activities and monitoring the performance against the set targets. However, the flow activities of construction projects, such as the flow of resources, handoffs between the trade crews, and inspections of finished work, lacked adequate attention. Further, a reactive approach to schedule delays was adopted instead of continuously trying to keep the project within targets (Ballard, 2000). A production control system, which considers the flow aspects of construction and emphasizes making proactive efforts to achieve the plans, was lacking. To this end, the LPS of production control in construction was developed in the 1990s (Ballard, 1997; Ballard and Howell, 1994; Howell and Ballard, 1994).

Initially, the LPS had two components: production unit control and work flow control. The primary role of the production unit control is to progressively enhance the quality of assignments for the trade crews. This is done through the Weekly Work Planning (WWP) and Learning stage. In the WWP stage, quality assignments (appropriately sized, ordered, defined, and sound) for each week are committed by involving the field execution team in the planning process. In the learning stage, the performance against the plans is assessed, and actions are taken to avoid non-conformances in the future. The role of work flow control is to ensure the flow of work between the trade crews at an adequate pace and order. This is achieved through the lookahead planning stage. At this stage, activities from the higher schedule levels are broken down to the level of operations. The constraints associated with each operation are identified, and the operations are scheduled according to the status of their constraints (Ballard, 2000). Identifying, tracking, and removing constraints associated with the operations is called 'Constraint Management.' It plays a crucial role in setting up an adequate workflow on the site (Mao et al., 2022). The lookahead planning stage also involves designing operations and identifying a set of operations for which all the constraints have been removed (Ballard, 2000).

Although the LPS improved the cost and schedule performance of the projects, the production control was found to be insufficient to ensure that the work being made ready was correct to achieve the project objectives (Ballard and Howell, 2003b). To this end, the LPS was extended from the production control function to include the phase scheduling stage. At this stage, the milestone-level master schedules are broken into process-level handoffs between different specialists using collaborative pull planning. The target milestones are inherited from the master schedules, which define the targets for each project phase (Ballard and Tommelein, 2021). The project planning and control functions, such as setting project-level objectives, were still kept beyond the LPS. Later, it was realized that project schedules created using conventional methods inadequately handle construction risks and uncertainties, and fail to involve those executing and managing the work (Ballard et al., 2020). To address these issues, the LPS was further extended to project planning and control by incorporating the project execution planning stage and enhancing the master scheduling stage. At the project execution planning stage, the decision regarding the project's feasibility based on anticipated risk levels is taken. From the project execution plan, the master schedule is prepared using collaborative pull planning. The expected uncertainties are identified, and different master schedule options are prepared to cater to the uncertainties (Ballard et al., 2020). The LPS has undergone several other improvements since its initial version as well, such as the extension of the LPS to the design phase of projects (Hamzeh et al., 2009), integration with location based planning (Seppänen et al., 2010) and the addition of new metrics to measure the performance of planning (Hamzeh et al., 2012). These changes led to the latest version of the LPS discussed in the recent LPS process benchmark (Ballard and Tommelein, 2021), which is adopted in this study. It is depicted in Fig. 1.

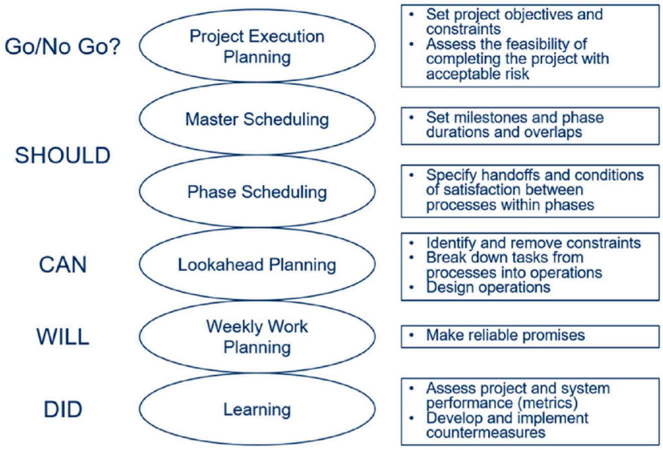


Fig. 1. Last planner system of project planning and control (Adapted from Ballard and Tommelein 2021).

3. Research method

3.1. Scope definition

This study exclusively examines the potential of automation to support project and production planning and control in the context of LPS. All six stages of the LPS, as depicted in Fig. 1, fall within the study's scope. However, certain aspects related to automation of planning and control in LPS were excluded from the scope. First, as this study intends to explore the impact of automation on the planning and control of field execution works, any efforts towards using automation for teaching LPS to students/practitioners are excluded. The focus of this study is limited to the construction phase of the projects due to two primary reasons: (1) the LPS is most frequently associated with the construction phase, and its implementation in other phases, such as the design is recent as compared to the construction phase (Chiu and Cousins, 2020) (2) an initial literature search regarding the implementation of automation of LPS in the design phase led to the identification of very few studies (also satisfying other inclusion and exclusion criteria of this study), indicating that the research in this domain is in a relatively nascent stage. Similarly, the scope does not include the implementation of LPS to plan factory-level production of offsite construction components, as the factory production is more of a manufacturing environment rather than construction. The scope does not include the application of LPS to industries other than construction, e.g., the shipbuilding industry. Next, as this study centers on LPS, studies related to any other lean-based planning and control technique, such as location-based planning, are considered in the scope only if they are applied in the context of LPS. In the control stage, this study does not include studies focused on the automation of progress monitoring or resource tracking, as several review articles in these areas have already been published elsewhere (Ekanayake et al., 2021; Reja et al., 2022).

3.2. Research design

The overall research design used in this study is depicted in Fig. 2. The research design is motivated by Aslam et al. (2021) for two reasons: (1) The nature of the two studies is similar (Aslam et al. (2021) reviewed the potential of Virtual Design and Construction to support Lean Project Delivery System), (2) The study was published in a reputed journal, proving the rigour of the adopted methodology. To understand the existing state of automation in the planning and control within the LPS framework and the benefits provided by it (Objective 1), a Systematic Literature Review (SLR) is adopted. SLR is a well-known scientific method to explore and understand the state-of-the-art in a particular knowledge domain (Zhao and Taib, 2022) in a reproducible and comprehensive manner (Abdelmegid et al., 2020). The SLR method used in this research fundamentally banks upon the preferred reporting items for systematic literature review and meta analysis (PRISMA) framework (Moher et al., 2009). To address Objective 2, the identified benefits in Objective 1 are mapped against LC principles suggested by Koskela (1992) based on the implication of the identified benefits on achieving the LC principles. Finally, based on the findings of Objectives 1 and 2, future research directions in the automation of planning and control within the LPS framework are suggested, which contribute towards accomplishing Objective 3.

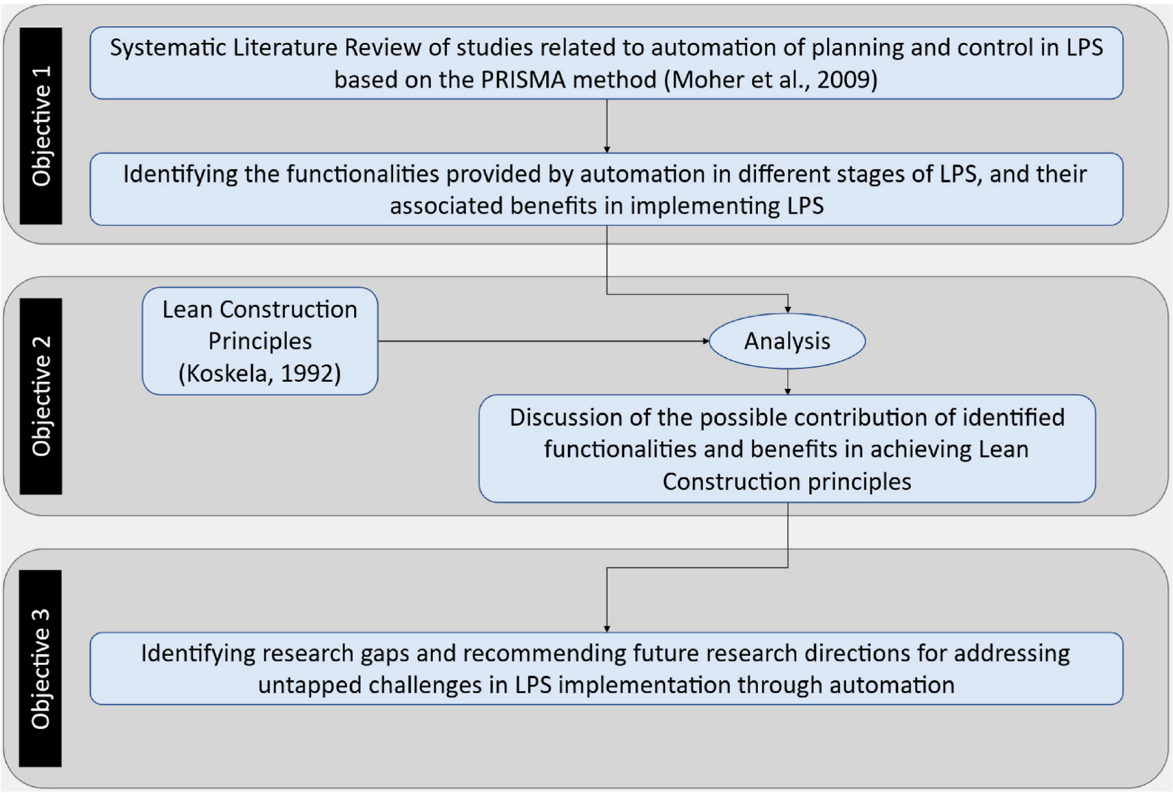


Fig. 2. Overall research design for the study.

3.3. Literature search

As a first step, a search protocol was developed, which included deciding the search field, keywords, databases, and criteria for selecting articles. Two extensive databases for literature search were utilized, i.e., Scopus and Web of Science. They were chosen as Scopus has a more comprehensive collection of recent literature, and Web of Science has a longer time horizon (Harzing and Alakangas, 2016). They have also been utilized by other review studies in the domain of construction engineering and management, such as Du et al. (2023).

Fig. 3 depicts the keywords utilized for the literature search. The term "automat*" and "optimiz*" were used to limit the search to articles focused on automation. The terms related to LPS were identified using the LPS process benchmarks (Ballard and Tommelein, 2016, 2021; Nutt III et al., 2020) and recent literature reviews on the interaction of technologies and LPS (Sbiti et al., 2021; Schimanski et al., 2020). Terms such as "master plan", "look ahead plan" and "weekly work plan" were used to indicate different stages of the LPS. Further, the terms such as "takt plan", "location based management system," and "line of balance" were added since the recent LPS process benchmark integrated these location based planning techniques with LPS (Ballard and Tommelein, 2021; Nutt III et al., 2020). Such methods explicitly incorporate the location of work and the flow of trades through these locations into the planning process. The keywords "constraint management" and "constraint analysis" were added to focus on the constraint management stage. As buffer computation is an essential part of LPS to manage workflow variability (Ballard and Tommelein, 2016), terms related to different types of buffers were added, e.g., "time buffer" and "space buffer." Finally, the term "construction" was used to limit the articles to the construction domain.

Fig. 4 depicts the process of selecting articles. The initial search on Scopus and Web of Science using the keyword string within TITLE-ABS-KEYWORD fields and ENGLISH language resulted in 811 and 521 articles, respectively. Removal of duplicates in the second stage led to 1036 results. In the third stage, articles were filtered based on the publication source, title, and abstract. Only the articles published in peer-reviewed

(“automat*” OR “optimiz*)
AND
(“lean” OR “last planner system” OR “LPS” OR “project execution plan” OR “master schedul*” OR "master plan" OR “phase schedul*” OR "phase plan" OR “look ahead plan” OR “look aheadschedul*” OR “look-ahead plan” OR “look-ahead schedul*” OR “lookahead plan” OR “lookaheadschedul*” OR “make-ready plan” OR “weekly plan” OR “weekly work plan” OR “collaborative plan” OR “commitment plan” OR “production plan” OR “pull plan” OR “takt plan” OR “takt schedul*” OR “location based management system” OR “line of balance” OR “short-interval planning system” OR “block scheduling” OR “even-flow production” OR “task breakdown” OR “design of operations” OR “constraint analysis” OR “constraint management” OR “workin-process buffer” OR “schedule buffer” OR “time buffer” OR “space buffer” OR “capacity buffer”)
AND
(“construction”)

Fig. 3. Keywords used for searching the articles.

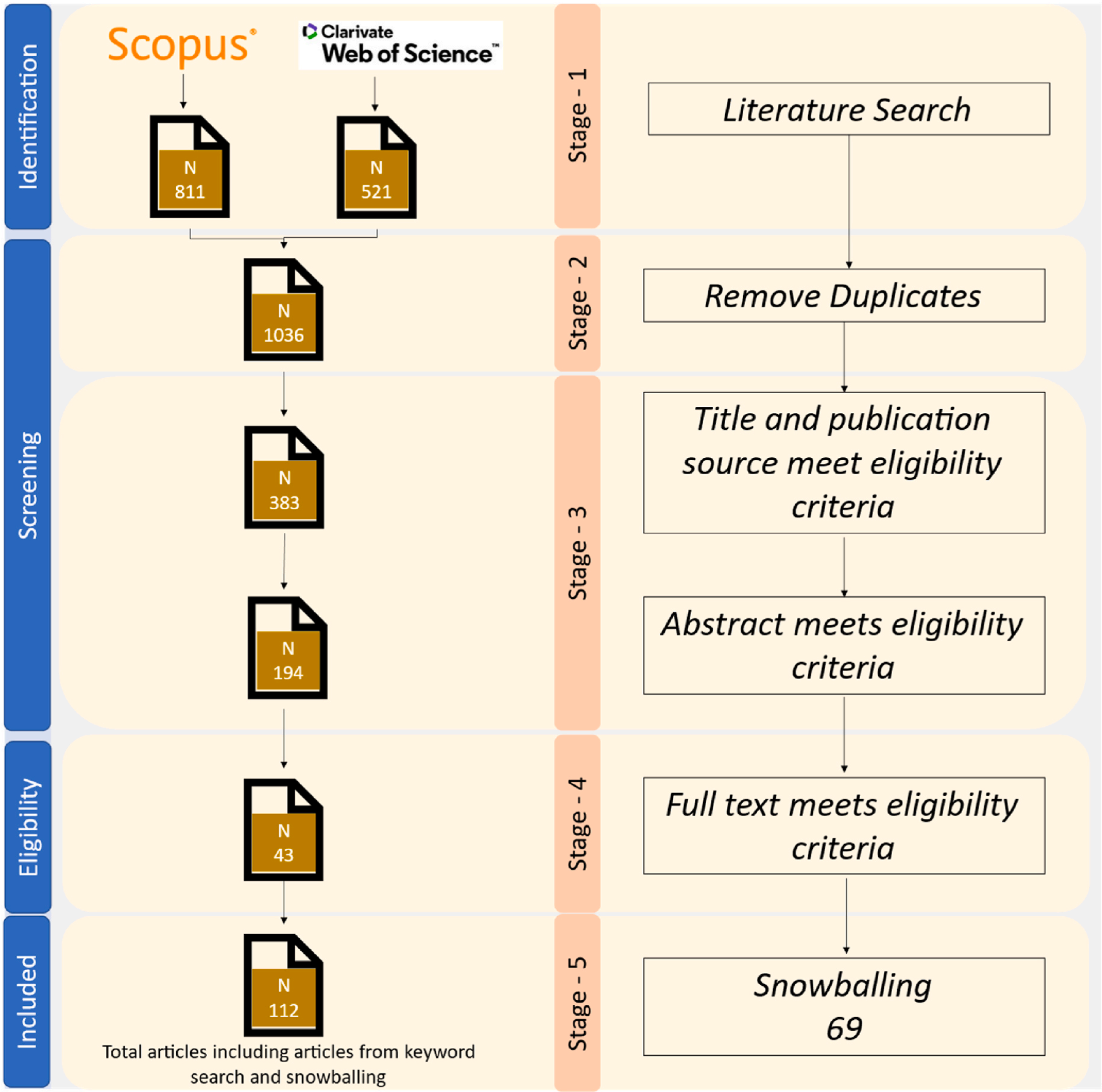


Fig. 4. Article selection procedure based on PRISMA workflow (Moher et al., 2009).

journals and the International Group for Lean Construction (IGLC) proceedings were selected. Several researchers suggested excluding conference articles from reviews as they are published in large volumes but have little contribution compared to peer-reviewed journal papers (Butler and Visser, 2006; Jin et al., 2018). However, the inclusion of IGLC proceedings was for three reasons: (1) it is one of the apex conferences in the domain of LC, (2) the selection of papers in IGLC follows a peer review method (Sarhan et al., 2019), and (3) IGLC papers have been considered within the scope of other LC related literature reviews (Aslam et al., 2021; Sarhan et al., 2019). The inclusion and exclusion criteria in Table 1 were used to select articles based on their titles and abstracts. These criteria were defined based on the scope of the study, as discussed in section 3.1. Any inconclusive literature at this stage was also moved for further analysis in stage 4.

In the fourth stage, a full text-based screening of 194 studies led to the selection of 43 articles for review. An initial analysis of these studies indicated that several articles did not appear in keyword search as they did not explicitly mention automation-related terms, e.g., ‘automate’ in their Title, Abstract, and Keywords; however, they contained automation functionalities related to LPS. To identify such missing articles, forward and backward snowballing was done from the articles selected in stage 4. Backward snowballing refers to checking each document’s reference list to search for further relevant articles. Forward snowballing refers to checking the citation list of each selected article to identify other relevant articles (Wohlin, 2014). In total, 112 articles (43 from the databases and 69 from snowballing) were selected for further analysis, consisting of 63 journal articles and 49 conference papers. To cross-validate the selected literature, the third co-author of this study also performed the literature search using the same steps. Fig. 5 depicts a distribution of finally selected articles based on the year of publication.

3.4. Literature analysis

The selected articles were summarized qualitatively using template analysis. Template analysis is a technique to produce an understanding of textual data (Brooks et al., 2015). It establishes a balance between the degree of structure in textual data analysis and the requirements of the study at hand. The development of a coding template is central to template analysis. It allows the development of flexible templates, which can be modified when new details appear in the analyzed data, making it a suitable approach for summarizing the evidence (King, 2012). Template analysis has been adopted by other researchers as well for

Table 1
Exclusion criteria for selection of articles.

Articles included if the focus on	Articles excluded if they focus on
• Automation of planning and control in different stages of the LPS in construction projects	• Automated progress monitoring, activity, material, workforce, or resource tracking • Design, Contracting, or Operation and maintenance phase of the project • Production planning and control of offsite production of prefabricated components • Any other lean-based planning and control methods, such as location based planning, buffer management methods, and constraint management, if not used in the context of LPS • Review Papers, if they do not propose any new model, method, or framework related to automation in the LPS • Developing systems for teaching the LPS or LC rather than focusing on actual field implementation • Utilizing tools and technologies to support planning and control in LPS without any automation

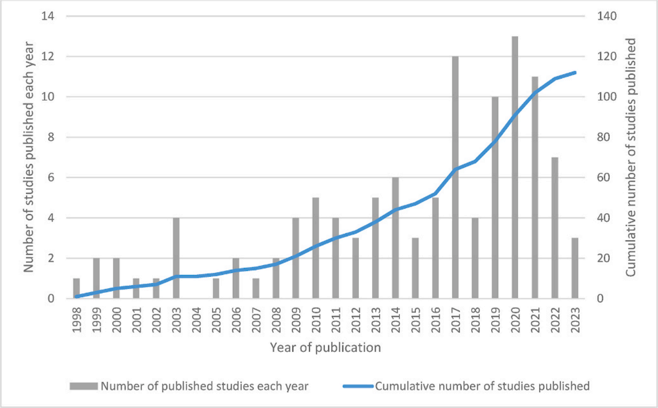


Fig. 5. Distribution of selected studies based on year of publication.

systematic literature review (Naghshbandi et al., 2021; Zhang et al., 2022). An initial examination of the selected articles was done to develop the templates. Afterward, all the articles were coded according to the designed template for in-depth analysis of the evidence. The themes used for summarizing the data in the templates are described in Table 2.

Table 2
Themes used for developing the template.

Theme	Description
Meta-data	Record the article title, authors, university of the primary author, country, year of publication, and source of publication
Problem Addressed	Describe the problem and research gap addressed by the article
Approach	Summarize the approach used by the article to solve the problem
Technology Used	The key technology/algorithm used by the study for automation
Type of project	Mention the kind of construction projects to which the approach is applicable
Capabilities of automation	Describe the parts of project planning and control that are automated in the article
Summary of findings	Summarize the key findings of the study and the benefits provided by automation
LC Principle impacted by automation	Mention the LC principles (if mentioned) enabled by the automation functionalities
Limitations	Summarize the limitations of the study
Additional Notes	Record any other relevant information

4. Results

Addressing Objective 1, this section summarizes the findings regarding state-of-the-art of automation in each stage of LPS (as depicted in Fig. 1) and the benefits related to such automation.

4.1. *Project execution planning, master scheduling, and phase scheduling*

The project execution planning, master scheduling, and phase scheduling stage focus on a relatively longer planning time horizon dedicated to making decisions at the entire project or phase level (Ballard et al., 2007; Ballard and Tommelein, 2021). Considering their similar nature, they are analyzed together in this section. A summary of the existing efforts towards their automation, key tools/technologies used for automation (if any), and the benefits realized or anticipated in the literature due to such automation is provided in Table 3.

Our literature search revealed no article related to the project execution planning stage. This might be attributed to the recent addition of this stage in the LPS. In the master scheduling stage, researchers assessed project completion risks (Gerber et al., 2010) and safety risks (Rozenfeld et al., 2009) in the schedules using tools such as Monte Carlo Simulation and 4D BIM. Bortolini et al. (2019) proposed using 4D BIM's automated time-based conflict detection feature to improve logistic planning at the master schedule level. However, the study was focused only on logistic planning from the perspective of steel fabrication works. Other researchers focused on computing optimum buffers (González et al., 2013; Poshdar et al., 2018). However, they lacked extensive field testing in complex construction projects (Poshdar et al., 2018) and focused only on repetitive projects (González et al., 2013).

In phase scheduling, researchers utilized automated quantity takeoff from BIM to compute accurate process durations automatically (Sbiti et al., 2021; von Heyl and Teizer, 2017). Schimanski et al. (2021c) developed the BeaM!-tool to generate the Gantt chart representation of the phase plans based on the user-entered process duration and dependency information. The process sequencing knowledge base and project information database have recently been utilized to develop the preliminary phase schedules for mechanical and electrical works (Sbiti et al., 2022). A few studies explored the utilization of optimization approaches in the phase scheduling stage (Ponz-Tienda et al., 2015). However, most of the efforts in this stage failed to consider location based methods in the LPS context and the deadline constraint satisfaction for each phase.

4.2. *Lookahead planning*

The lookahead planning (LAP) process consists of three steps: (1) task breakdown, (2) constraint identification and removal, and (3) design of operations (Ballard and Tommelein, 2021). A summary of existing automation efforts in these three steps is provided in Table 4. A comparatively higher number of findings in the LAP stage can be attributed to the fact that LAP is a comprehensive stage incorporating multiple planning tasks.

4.2.1. *Task breakdown*

At this stage, processes from phase schedules are broken down into lower levels of details to be assigned to trade crews. The initial efforts towards its automation utilized expert knowledge-based templates to break down the schedules hierarchically (Breit et al., 2008; Haiati et al., 2016). However, the knowledge bases were limited in scope and capability to handle dynamic situations on construction sites. Amer et al. (2021a) utilized transformer machine learning to develop a model to predict the operations corresponding to master schedule activity

Table 3
Summary of existing automation capabilities in project execution planning, master scheduling, and phase scheduling.

S. No.	Automation Functionalities	Tool/ Technology Used	Realized/ Anticipated Benefits due to the functionalities	References
Master Scheduling				
1	Risk analysis of the master schedule through the development of probability distribution curves of the duration of activities, milestones, and the whole schedule	Monte-Carlo Simulation	Enable selection of risk-optimum schedules	Gerber et al. (2010)
2	Prediction and quantification of safety risk levels in the developed schedules	BIM; Detailed knowledge base of construction activities and associated unsafe events	Support creation of safer schedules; Enable computation of safety risk with less effort and greater accuracy	(Rozenfeld et al., 2009; Sacks et al., 2009)
3	Detection of potential conflicts between the moving objects on-site during long-term logistic plan preparation	BIM	Less spontaneity in transportation on-site; Reduction in potential conflicts and NVA activities	Bortolini et al. (2019)
4	Computation of optimum time buffer for activities considering multiple objectives	Goal-seeking multi-objective optimization with project time, cost, plan reliability, and schedule stability as project objectives	Reduction in errors in computing buffers; Providing flexibility to the user to choose the final buffer allocation	Poshdar et al. (2018)
5	Computation of optimum Work-In-Process (WIP) buffer	Discrete event simulation-based optimization, Multi-objective Analytical Model with minimizing time and maximizing productivity as optimization objectives	Identification of buffer sizes for multiple objectives, such as minimizing cycle time and maximizing productivity	(González et al., 2013; González and Alarcón, 2009)
Phase Scheduling				
1	Calculation of the duration of processes in the phase schedules using automated quantity takeoff and productivity databases	BIM	Improving the accuracy of schedules	(Fosse et al., 2017; Sbiti et al., 2021; Schimanski et al., 2019; Schimanski et al., 2021c; von Heyl and Teizer, 2017)
2	Development of Gantt Chart representations of the phase plans	NA	Enable quick generation of visual representation of the plans	(Schimanski et al., 2021b; Schimanski et al., 2021c)
3	Development of phase schedules for Mechanical and Electrical construction	BIM; Information Database (MySQL); Knowledge base of activities and their sequencing	Reduction in time and effort required for the generation of schedules	Sbiti et al. (2022)
4	Development of optimum phase schedule for structural works phase	Resource-constrained optimization of project duration	Reduction in time required for completing the phase	Ponz-Tienda et al. (2015)

*NA indicates no specific tool/technology was used except programming to perform automation.

description based on data from past projects. However, it focused on only finding the probabilistically best matches to the textual description of the master schedule activity rather than predicting all the required operations.

4.2.2. *Constraint identification and removal*

The initial efforts in the direction of constraint identification focused on developing suggestive systems, which suggest different categories of constraints to the users. For instance, Zaeri et al. (2017) utilized a semi-automated Excel spreadsheet to suggest pre-coded categories of constraints. Such suggestive categories can enable structured, accurate, and comprehensive constraint identification. However, identifying specific details related to constraints, such as their particular attributes, remained manual. Other researchers focused on identifying critical constraints from pre-identified constraints. The critical constraints have maximum influence on the constraints of the other trades and overall project performance (Chua and Shen, 2005). However, they focused only on resource and information availability constraints.

Other studies were focused on facilitating constraint removal by providing real-time data related to constraint. Chua et al. (1999) and Sriprasert and Dawood (2003) utilized Web-based centralized information databases, which could be updated by different stakeholders. All stakeholders could access the updated information from the databases in real-time through query languages such as Structured Query Language (SQL) (Sriprasert and Dawood, 2003). Such systems could facilitate the development of reliable plans by better stakeholder collaboration through quick information communication. Similarly, Thorstensen et al. (2013) developed a system to automatically visualize the constraint status in the form of traffic lights. However, such studies required the concerned data to be manually entered into the databases. Further, data conversion from native to database-specific formats, such as XML, was needed (Chua et al., 1999). To this end, (Soman et al., 2020) developed an approach to automatically check the constraint violations in look-ahead schedules from heterogeneous datasets using linked data. However, they fell short in exploring geometry-based constraint checks such as safety and site layout constraints.

4.2.3. *Design of operations*

At this stage, the steps required to perform operations, their sequence, and the responsible parties are determined are determined (Ballard and Tommelein, 2021). For sequencing, researchers have utilized Natural Language Processing (NLP) to develop models to learn sequencing knowledge from past project schedules (Amer and Golparvar-Fard, 2021). Such systems could be used to predict the upcoming tasks given a set of input tasks (Amer and Golparvar-Fard, 2021) and automatically sequence a given set of unordered tasks (Amer et al.,

Table 4
Summary of existing automation capabilities in Lookahead scheduling.

S. No.	Automation Functionalities	Tool/Technology Used	Realized/Anticipated Benefits due to the functionalities	References
Task Breakdown				
1	Prediction of lookahead operations, given an activity or process description	Transformer architecture-based Natural Language Processing	Assisting planners in the quick generation of plans	Amer et al. (2021a)
Constraint identification and removal				
1	Semi-automated constraint identification by suggesting categories of constraints	Database of constraints, implemented through Excel spreadsheets or web-based information containers	Structured and exhaustive constraint identification; Reduction in manual errors of typing	(Alarcón and Calderón, 2003; Choo et al., 1999; Choo and Tommelein, 2000; Jeong Choo et al., 1998; Kanai et al., 2021; Sriprasert and Dawood, 2003; Wang et al., 2016; Zaeri et al., 2017).
2	Identification of critical constraints having maximum impact on overall project delays	Integrated Production Scheduler (An internet-based tool developed by Chua et al. (2003))	Simplifying the process of identifying critical constraints	Chua and Shen (2005)
3	Information sharing regarding the constraints among the project stakeholders	Javabeans, XML, Web-based databases, IoT Standards	Improving information flow; Increasing transparency; Support enhancing plan reliability	(Chua et al., 1999, 2003; Conte et al., 2022; Dave et al., 2010, 2016; David and Shen, 2001; Faloughi et al., 2014; Iordanova et al., 2020; Li Jun et al., 2000; Sriprasert and Dawood, 2002, 2003)
4	Visualization of constraint status based on inputs from stakeholders	NA	Reducing time and effort required for visualization	Thorstensen et al. (2013)
5	Constraint checking in LAP	BIM, Linked Data	Improving the speed of constraint checking; Reducing chances of errors; Enabling stakeholders to assess the impact of change in constraint status dynamically	Soman et al. (2020)
Design of Operations				
1	Based on sequencing knowledge: • Prediction of upcoming tasks based on a set of input tasks, • Identification of precedence relationships between a set of unordered tasks	Natural Language Processing (utilized Deep Neural Networks and Recurrent Neural Networks with Long Short-Term Memory)	Enabling the quick generation of correct work sequences even in previously unseen scenarios on construction projects	(Amer et al., 2022; Amer and Golparvar-Fard, 2021)
2	Updating operation logic and input models of a simulation model for LAP	Knowledge base of operation details (e.g., constituents of the operations, their precedence relationships) and simulation input modeling; BestFit (a distribution-fitting program)	Saving time for planners by automatically updating operation logic as and when project conditions change	Song and Eldin (2012)
3	Probabilistic prediction of the parameters related to the future state of the operations. For instance, forecasting operation duration based on as-built performance data and the impact of uncertainty-causing factors such as weather.	Discrete event simulation; Hybrid discrete event and continuous simulation	Improving plan reliability; Enabling informed decision-making	(Mohamed et al., 2021; Song and Eldin, 2012)
4	Prediction of operation parameters, e.g., durations (non-probabilistically) in different situations, such as different numbers of crews and material quantities	Discrete event simulation	Improving plan reliability; Enabling informed decision-making	(Abdelmegid et al., 2019, 2023)
5	Prediction of productivity of operations based on as-built data using the linear regression method	Linear regression based on as-built data from past projects	Improving plan reliability; Eliminating the need for dedicated simulation professionals to develop simulation models	Salama et al. (2021)
6	Development of: • multiple near-optimum lookahead schedules, • most time and cost-optimal lookahead schedule	Genetic Algorithm, Simulation, Reinforcement Learning, Constraint Logic Programming	Generating error-free lookahead schedules quickly; Creating schedules with shorter durations and lower cost implications under specified constraints as compared to those made by humans	(Chua and Yeoh, 2009; Dawood and Sriprasert, 2006; Dong et al., 2012, 2013; Soman and Molina-Solana, 2022)
7	Quantity takeoff and geometric data extraction from BIM	BIM	Minimizing the time needed for planning and reducing errors in the planning process	(Chen et al., 2020, 2021; Heigermoser et al., 2019; Raol et al., 2020; Schimanski et al., 2019; Schimanski et al., 2021a; Tavakolan et al., 2021; Zeng et al., 2023b)
8	Clash detection	BIM	Reducing change orders, rework, and Requests for Information (RFI)	(Andújar-Montoya et al., 2020; Bhatla and Leite, 2012; Raol et al., 2020; Wickramasekara et al., 2020; Zhang et al., 2018)
9	Optimum allocation of two tower cranes to tasks in their overlapping work zone	Discrete event simulation-based optimization with the optimization objective of reducing the total duration of crane activities	Reducing the total duration of tasks and idle time of cranes	(Al Hattab et al., 2017; Hattab et al., 2014)
10	Optimum concrete order planning based on demand fluctuations on site	Heuristic evolutionary optimization with the objective function of minimizing total cost to fulfill the site	Enabling handling of concrete demand fluctuation with minimum cost; Reducing uncertainties based on data-driven decisions	Chen et al. (2021)

(*continued on next page*)

Table 4 (*continued*)

S. No.	Automation Functionalities	Tool/Technology Used	Realized/Anticipated Benefits due to the functionalities	References
		concrete demand for a given lookahead time		
11	Automated assignment of offsite production process patterns to building elements in BIM	BIM; Rule base containing rules to identify the production process patterns	Aiding in the identification of potential on-site delays due to offsite disruptions	Zeng et al. (2023a)
12	Automated connection between BIM models and lookahead schedules to develop 4D BIM	BIM, Visual programming (using Dynamo)	Reducing the time and effort required for generating 4D BIM models	(Lin and Golparvar-Fard, 2021; Silveira and Costa, 2023)
13	Computation of optimum WIP buffer	Discrete event simulation-based optimization with minimizing cost and time or maximizing productivity as objectives	Determining buffer sizes to minimize cost and time or maximize productivity	(González et al., 2013; González and Alarcón, 2009)

*NA indicates no specific tool/technology was used except programming to perform automation.

2022). However, being dependent upon the past data, the models inherently learn the mistakes from the past. Also, the accuracy of the models had scope for improvement.

Simulation techniques have played a pivotal role in automating LAP. Researchers have utilized as-built data with simulation systems to predict future operation durations (Mohamed et al., 2021) and anticipated delays (Song and Eldin, 2012). In addition, as the static simulation model may not correctly reflect the ever-changing site conditions, Song and Eldin (2012) utilized real-time site data and operation logic knowledge base to update the operational logic and input model of simulation automatically. Considering the uncertainties in construction projects, such simulation systems could support decision-making by generating probabilistic activity and project completion time (Mohamed et al., 2021). However, the lack of consideration of constraints limits their benefits from the perspective of lookahead scheduling.

Earlier efforts to incorporate constraint status in LAP focused on automatically allocating the activities to four types of buffers (pulling buffer, working buffer, screening buffer, and shielding buffer) based on the estimated time of satisfaction of constraints (Chua et al., 2003). However, the system worked as a 'rescheduler,' taking an existing schedule as input for making changes. Dong et al. (2012) utilized the genetic algorithm (GA) to develop time or cost optimum schedules considering several constraints such as information, resources, space, etc. Dong et al. (2013) utilized simulations to create multiple error-free lookahead schedule options. However, these approaches had two limitations: (1) the constraints, such as equipment availability, materials, approvals, and safety requirements, were overlooked, and (2) the user had to update the status of constraints within the system manually. Addressing some of these limitations, Soman and Molina-Solana (2022) utilized Reinforcement Learning (RL) for the automated generation of lookahead plans, with the reward function of RL depending upon constraint violations. This study failed to consider geometric constraints and required significant manual data input, such as the operations, durations, and precedence relationships. To this end, automated quantity takeoff from BIM was utilized for planning functions such as duration calculation (Heigermoser et al., 2019) and material order placing (Chen et al., 2021). Similarly, BIM's automated clash detection feature has been utilized to identify clashes among different scopes of work (Bhatla and Leite, 2012). Using the geometric and spatial information from BIM and scheduling decision-making rules expressed as Semantic Web Rule Language (SWRL), Tavakolan et al. (2021) developed a decision support system for developing feasible construction and resource plan alternatives. However, they failed to consider spatial constraints. Additionally, due to varying detail levels between lookahead plans and BIM models, creating 4D BIM models demanded significant manual work. Semi-automated methods for developing 4D BIM models in LAP have been developed (Lin and Golparvar-Fard, 2021); however, full-scale automation is still lacking.

Lately, efforts have aimed at improving the lookahead supply chain and logistics management through automation. Automated systems have been found to enhance coordination between offsite (e.g., material suppliers) and on-site stakeholders (e.g., subcontractors) via precise material demand calculation, geometric information extraction, and cost-effective order planning (Bataglin et al., 2020; Chen et al., 2021). Zeng et al. (2023a) developed a rule-based system to automatically assign production process patterns to prefabricated elements, which could be linked to site installation lookahead schedules. Using this linked information, the planners could anticipate the impact of delays in offsite production and transportation processes on the on-site schedule. However, the delay calculation process and data input regarding the status of offsite processes remained manual.

4.3. Weekly work planning (WWP)

At this stage, reliable commitment plans for a week are collaboratively developed based on the readiness of work for execution (Ballard and Tommelein, 2021). A summary of existing automation efforts in this direction is provided in Table 5.

Early efforts in this direction focused on utilizing manually created project information databases to perform automated resource overallocation checking and cost calculation in weekly work plans (Choo et al., 1999). Other studies focused on the automatic computation of measures to quantify the task readiness for execution without flow interruption (Lin and Golparvar-Fard, 2021; Sacks et al., 2012). Similarly, crew productivity data from past projects was utilized to generate reliable productivity forecasts using simulations (Shehab et al., 2020). The capabilities of simulations to replicate the actual field situations were utilized by researchers to predict the workflow behavior of trade crews on construction sites (Brodetskaia et al., 2011). However, the model was based on site-specific observations, limiting its generalizability. To incorporate safety as a factor for assessing task readiness, Rozenfeld et al. (2009) developed a safety knowledge-based model to quantify the risk level in scheduled construction tasks. However, the approach needed extensive manual effort to create the knowledge base. Data-driven methods were developed to compute WIP buffers (González et al., 2006, 2011); however, they focused majorly on repetitive construction projects only.

BIM has been extensively utilized for automation in WWP. Its features, such as automated quantity takeoff (Naticchia et al., 2019) and clash detection (Toledo et al., 2016), have been utilized to develop accurate and reliable weekly plans. Dallasega et al. (2018) proposed the concept of 'pitch' (quantity of work needed to be completed by a particular crew size in a defined location and time interval) to assign the work in weekly plans. They also proposed a tool for automated computation of pitch based on manually defined task sequence, duration, and manpower required. Pitch enabled better control by providing location based plans for tracking. However, the generated quantities were suboptimal and needed manual adjustment based on budget.

Table 5
Summary of existing automation capabilities in weekly work planning.

S. No.	Automation Functionalities	Tool/ Technology Used	Realized/ Anticipated Benefits due to the functionalities	References
1	Computing cost of allocated works; Identifying instances of resource overallocation in the weekly plans	MS Access database programmed through Visual Basic for Applications	Enabling quick comparison of different alternatives; Detecting resource conflicts before they happen on site	(Choo et al., 1999; Choo and Tommelein, 2000; Jeong Choo et al., 1998)
2	Quantity takeoff and geometric data extraction from BIM	BIM	Reduction in time required and errors in planning	(Dallasega et al., 2019; Heigermoser et al., 2019; Naticchia et al., 2019)
3	Computation of indexes to measure workflow reliability	Custom-made LPS implementation software such as KanBIM	Enabling the assignment of tasks such that they can be reliably completed without workflow disruptions	(Gurevich and Sacks, 2014; Lin and Golparvar-Fard, 2021; Sacks et al., 2011, 2012; Sacks et al., 2010b)
4	Generation of assignment-level work plans based on standard productivity values for piling works	Holonic management system, Multi-objective Ant Colony Optimization to minimize the number of piling equipment and their travel time	Enabling the quick generation of near-optimum work plans through automated collaboration between resources	Naticchia et al. (2019)
5	Prediction of the on-site flow pattern of trade crews (for interior finishing and MEP activities)	Discrete Event Simulation	Enabling quick evaluation of different resource assignment strategies in terms of time, workflow, work-in-progress buffer, and productivity	(Brodetskaia et al., 2011, 2013)
6	Prediction of crew productivity for WWP based on crew performance data from past projects	Discrete event simulation and Agent-based simulation	Generating reliable production rates for crews	Shehab et al. (2020)
7	Clash Detection in WWP meetings	BIM	Enabling reduced number of RFIs; Shortening of WWP meetings	Toledo et al. (2016)
8	Prediction and quantification of safety risk levels of planned tasks in the weekly work plans	BIM; Detailed knowledge base of construction activities and associated unsafe events	Enabling the creation of safer weekly work plans	Rozenfeld et al. (2009)
9	Generation of Building Information Model breakdown structure	BIM	Enable rapid retrieval of model contents; Reduction in meeting durations; Reduction in latency in resolving issues in meetings	(Rischmoller et al., 2017a, 2017b)
10	Generation of color-coded space inclusive representation of a day-level schedule	MS Excel VBA	Simplify workforce planning; Identification of mistakes and time-space conflicts in schedules	(Bascoul et al., 2020; Bascoul and Tommelein, 2017; Frandson and Tommelein, 2014)
11	Prediction of commitment plans based on production variables such as workers, buffers, planned and actual progress	Multiple Linear Regression	Increasing reliability of commitment plans; Improving labor productivity; Simplifying data collection and analysis process	(González et al., 2010, 2011)
12	Computation of work in process buffers	Multiple Linear Regression	Minimizing cycle time; Ensuring continuous flow of work; Improving plan reliability	(Gonzalez et al., 2008; González et al., 2006, 2011, 2013; González and Alarcón, 2009)

*NA indicates no specific tool/technology was used except programming to perform automation.

4.4. Learning

The learning phase focuses on measuring the progress, analyzing the plan failures, learning from them, and preparing better plans to avoid their failure in the future (Ballard and Tommelein, 2021). Existing literature on automation in this phase can be divided into three primary focus areas: sharing progress information, computing control metrics, and learning from as-built data. A summary of existing automation efforts in this phase is provided in Table 6.

In the direction of automated information flow, researchers utilized web-based information storage systems to enable real-time access to updated progress information for all the stakeholders. For instance, Cho and Fischer (2010) developed a web-based system to update the supply status of building elements, which was automatically converted into BIM-based visualizations and sent to all the stakeholders. Dave et al. (2016) proposed the integration of Internet of Things (IoT) frameworks with VisiLean (Dave et al., 2011) to ensure automated and real-time transfer of information from field data collection systems (such as RFIDs, Magnetic Boards, etc.) to VisiLean database. Other researchers focused on automatically sending notifications to stakeholders responsible for constraint removal (Carneiro et al., 2017) and quality checking (Liu and Shi, 2017). Similarly, Kim & Kim (2014) developed a system to alert field engineers with the quantity of engineered-to-order materials required in a lookahead period, and send material orders to suppliers as soon as material request gets approved. The KanBIM used 3D BIM models and status signals to make such information easy to understand. For instance, traffic light signals were displayed on a 3D model to

Table 6
Summary of existing automation capabilities in the learning phase.

S. No.	Automation Functionalities	Tool/ Technology Used	Realized/ Anticipated Benefits due to the functionalities	References
1	Sharing of progress information among stakeholders in real-time	Web-based/ Cloud-based services, IoT Standards	Enabling better coordination and communication among stakeholders, and early detection of problems; Reducing time required for collecting and communicating the information	(Abbaszadegan et al., 2022; Cho and Fischer, 2010; Dave et al., 2016; Ghossaini et al., 2018; Nakagawa, 2006; von Heyl and Demir, 2019)
2	Notifying the concerned stakeholders about progress, emergent tasks, and constraints through alert signals or messages	Custom-made LPS implementation software and mobile applications such as KanBIM and SyncLean	Enhancing coordination between the stakeholders; Enabling pull flow control; Reducing material and work-in-progress inventories; Enabling smooth handovers on site; Saving time required for collecting and communicating the information	(Daou et al., 2015; Ghossaini et al., 2018; Gurevich and Sacks, 2014; Kim and Kim, 2014; Liu and Shi, 2017; McHugh et al., 2019; Sacks et al., 2011, 2012; Sacks et al., 2010b)
3	Visual representation of progress or constraints on 3D models	BIM	Enabling a better understanding of information	(Dallasega et al., 2019; Gurevich and Sacks, 2014; Sacks et al., 2011, 2012; Sacks et al., 2010b)
4	Quantity takeoff of the work progress from BIM	BIM	Accuracy of progress measurement	(Abbaszadegan et al., 2022; Cho and Fischer, 2010)
5	Computing control metrics such as Planned Percentage Complete, Task Anticipated, Task Made Ready, etc.	Custom-made or Commercialized LPS implementation software and mobile applications such as KanBIM, SyncLean, and VisiLean	Reducing the time required and human errors in data compiling and generating the metrics; Enabling quick identification of mismatch between the as-planned and as-built progress; Enabling faster decision-making for updating the plans	(Alarcón and Calderón, 2003; Carneiro et al., 2017; Cho and Fischer, 2010; Dave et al., 2011; Ghossaini et al., 2018; Kanai et al., 2021; Schimanski et al., 2019; Schimanski et al., 2021b; Schimanski et al., 2021c)
6	Partially automating the recording of reasons for plan failure by providing suggestive categories	Database of reasons for plan failure, implemented using Excel spreadsheets or commercialized	Reducing human errors and inconsistencies in data recording	(Dave et al., 2011; Kanai et al., 2021; Zaeri et al., 2017)
		LPS software (e.g., VisiLean)		
7	Dynamically developing near-optimum work plans based on site conditions	Holonic management system, Multi-objective Ant Colony Optimization, BIM, IoT, Rule-based system	Saving computational effort and time as the optimization approach could generate near-optimal solutions without the need to run completely; Saving manual effort; Enabling just-in-time supply chain management	(Dave et al., 2015a; Naticchia et al., 2019)
8	Prediction of planned percentage complete for the week based on progress during the week	Singularity Functions	Enabling quick and timely detection of potential deviations from the plans	(Ezzeddine et al., 2019; Shehab et al., 2019)
9	Generation of reports such as as-planned vs. as-built progress, productivity, and manpower reports; Location based delay risk reports; Various reports related to emergent tasks such as their type (e.g., structural, MEP), location, parent tasks, and time taken to resolve them	Custom-made or commercialized LPS implementation software and mobile applications such as Instantask, and VisiLean	Preventing stakeholders' time in finding what and where problems are; Improving planning reliability; Assisting in prioritization of plan failures	(Daou et al., 2015; Emdanat et al., 2016; Heigermoser et al., 2019; Kanai et al., 2021; Keskiniva et al., 2021; Lin and Golparvar-Fard, 2021)
10	Updating the information in higher-level plans based on updates in the lower-level plan	Object-oriented modeling of tasks	Avoiding re-typing of data	Brondsted et al. (2003)

* NA indicates no specific tool/technology was used except programming to perform automation.

demonstrate the readiness of work based on information updated by trade crews (Sacks et al., 2010b). Limited attempts have been made to address information flow between different levels of plans (Brondsted et al., 2003); however, such attempts lacked field-level implementation and testing.

Researchers automated the computation of several control metrics based on the progress data. Such metrics include Percentage Plan Complete (ratio of weekly completed to planned work assignments) (Dave et al., 2011), Constraint Removal Index (signifying the constraints removed against the constraints planned to be removed) (Carneiro et al., 2017), Earned Value Management metrics (Schimanski et al., 2019), Task Anticipated (fraction of tasks in commitment plan to those which were anticipated in lookahead plan) and Task Made Ready (fraction of tasks whose constraints were removed to those which were anticipated in lookahead plan) (Schimanski et al., 2019).

Research on automating the learning from as-built data in the learning phase can be divided into two groups: recording reasons for failure and utilizing algorithms on as-built project data to create better plans. Zaeri et al. (2017) developed a semi-automated Excel spreadsheet to record reasons for plan failure, enabling users to eliminate typing mistakes. However, only broad categories of reasons were provided, and detailed descriptions had to be mentioned by the user. Looking at the other group, Dallasega et al. (2018) and Schimanski et al. (2018) developed tools to increase/decrease work pitches based on progress data. Other researchers automatically developed visual reports of as-planned vs. as-built workforce and productivity data (Heigermoser et al., 2019). However, these approaches were reactive, as the user had to wait a week to make changes to the plan. To this end, Andújar-Montoya et al. (2017) utilized real-time project contextual data, such as temperature and humidity, to automatically guide workers to start/stop work based on quality requirements. Shehab et al. (2019) developed an approach to predict the planned percentage complete for the week based on the progress achieved up to a particular time in a week. However, these studies could not automatically adjust the plans based on site conditions. To this end, Dave et al. (2015a) proposed the concept of intelligent products, where each product in a construction project is incorporated with the intelligence about its product and process information to react to site conditions dynamically. The holonic management system developed by Naticchia et al. (2019) could adjust the piling work plans based on site progress and human-machine collaboration through its ability to involve human decision-makers when required. However, the approach needed to be expanded to projects beyond piling works. Similarly, Sacks et al. (2020) proposed a digital twin-enabled workflow for real-time control but lacked field implementation and validation.

5. Enabling LC principles through automation of planning and control in LPS framework

Building upon the benefits of automation in LPS identified through the systematic literature review presented in the above sections, this section moves towards achieving objective 2 of the study. To this end, the prospect of automation of planning and control in LPS to facilitate achieving LC principles in construction projects is presented. The LC principles discussed in this study have been adopted from Koskela (1992) and have been utilized in other studies as well (Benachio et al., 2021; Sacks et al., 2010a). A summary of the benefits of automated planning and control in LPS and their linkages with LC principles is provided in Fig. 6.

5.1. *Reduce the share of non-value-adding activities*

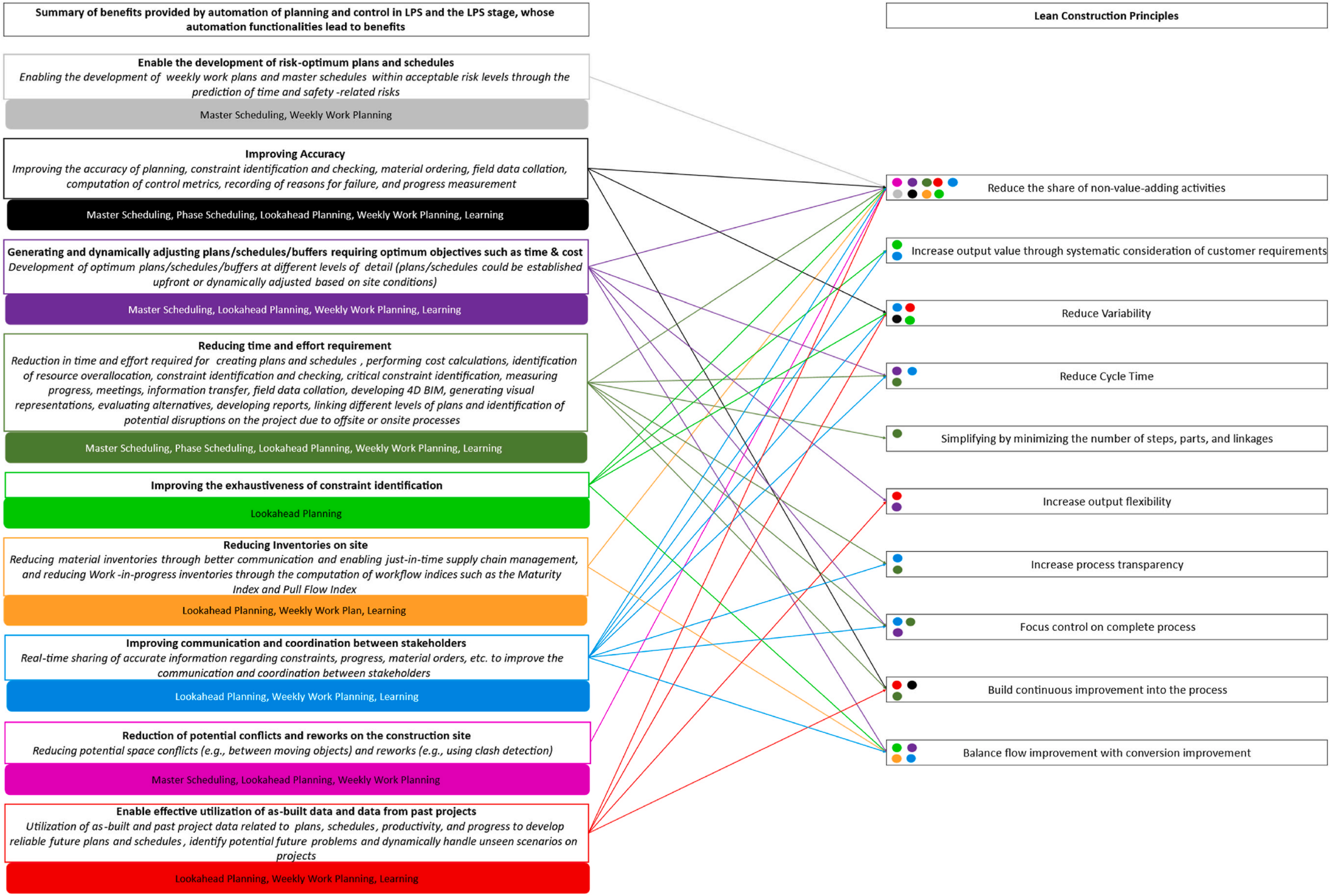
Non-value-adding activities or 'waste' consume resources and time but do not yield value (Koskela, 1992). LC considers seven types of waste such as overproduction, correction, inventory, waiting, and transportation (Koskela, 2000). Significant challenges in LPS implementation can be linked to 'waste' in the planning process, such as the need for extra resources (Porwal et al., 2010), possibility of errors (Hamzeh et al., 2016), and the lack of safety considerations (Hamzeh et al., 2016). For instance, incorrect plans may necessitate revisions (Hamzeh et al., 2016), space conflicts, and rework on site (Dong et al., 2013). Our literature review reveals that the automation of planning and control in the LPS can solve these challenges and reduce waste on construction sites in several ways. Firstly, automation can reduce the time and effort required in the planning and control process through functionalities such as quantity take-off (Cho and Fischer, 2010), clash detection (Bhatla and Leite, 2012), schedule generation (Dong et al., 2012), real-time communication (Sacks et al., 2012), control metrics computation (Carneiro et al., 2017), and constraint checking (Soman et al., 2020). Further, the possibility of manual errors in the planning and control process is also eliminated through automation (Dong et al., 2013; Zaeri et al., 2017). Automation in LPS improves constraint management through holistic constraint identification and accurate constraint checking. Better constraint management improves the plan reliability (Lagos and Alarcón, 2021) and reduces the waste time on site due to issues such as resource and space conflicts (Dong et al., 2012; Hamzeh et al., 2012). The computation of indexes reflecting workflow and improvement of information flow allows the reduction in work-in-progress inventories (Sacks et al., 2010b), which is considered waste (Sacks et al., 2009). Considering the high level of uncertainty at the master scheduling level, risk analysis tools such as the Monte-Carlo simulation can assist the stakeholders in making informed decisions and more reliably selecting plans within acceptable risk levels. In the learning stage of the LPS, automation supports effectively utilizing as-built data and data from past projects to predict plans more reliably (Shehab et al., 2020). Higher plan reliability leads to improved productivity, reduced rework (Ballard, 2000), and ameliorates overall project performance (Olano et al., 2009). Through safety risk level prediction and visualization at master and weekly planning levels (Sacks et al., 2009), automation can enable the development of safer plans. This reduces the possibility of unsafe work conditions on site, which may lead to a waste of resources (Lindhard and Wandahl, 2013). According to Sacks et al. (2010a), 'automated generation of construction tasks' in planning from BIM can cause waste due to an increased inventory of plan alternatives; however, our literature review did not reveal any such reported findings in the context of LPS. We perceive that further research is needed to explore the possibility of this negative impact of automation. Further, the utilization of optimization approaches to develop the most optimum plans can tackle this negative interaction partially.

5.2. *Increase output value through systematic consideration of customer requirements*

This principle emphasizes improving the value through each activity by considering the requirements for the next activity and the final customer (Koskela, 1992). This is done through flow design by adequately identifying customers and analyzing their needs. The LPS involves actively identifying the prerequisites (or constraints) for upcoming activities and removing them through lookahead planning and make-ready process before execution. Based on our findings, automation assists in achieving this LC principle in two ways. First, constraint identification can be done exhaustively through suggestive constraint categories (Wang et al., 2016). Second, real-time information transfers and alerting systems can quickly send the progress and constraints status to relevant stakeholders. Through such information accessibility, planners can accurately identify the requirements at different work fronts and plan the work in a more informed way (Dave et al., 2016).

5.3. *Reduce variability*

This principle emphasizes reducing the variability of production processes and flows to ensure consistent outputs (Koskela, 1992, 2000). Our literature review revealed that the automation of planning and control reduces the possibility of human errors in LPS implementation. Reduction in mistakes through automated systems alleviates plan variability (Aslam et al., 2021; Sacks et al., 2010a). In addition, the availability of information about the progress status enables reducing the variability of flows. For instance, Bataglin et al. (2020) found that the availability of updated progress information in lookahead planning helped the development of better load plans for engineered-to-order components and reduced the variability of their onsite delivery. Thus,



Summary of benefits provided by automation of planning and control in LPS and the LPS stage, whose automation functionalities lead to benefits

Enable the development of risk-optimum plans and schedules
Enabling the development of weekly work plans and master schedules within acceptable risk levels through the prediction of time and safety-related risks
Master Scheduling, Weekly Work Planning

Improving Accuracy
Improving the accuracy of planning, constraint identification and checking, material ordering, field data collation, computation of control metrics, recording of reasons for failure, and progress measurement
Master Scheduling, Phase Scheduling, Lookahead Planning, Weekly Work Planning, Learning

Generating and dynamically adjusting plans/schedules/buffers requiring optimum objectives such as time & cost
Development of optimum plans/schedules/buffers at different levels of detail (plans/schedules could be established upfront or dynamically adjusted based on site conditions)
Master Scheduling, Lookahead Planning, Weekly Work Planning, Learning

Reducing time and effort requirement
Reduction in time and effort required for creating plans and schedules, performing cost calculations, identification of resource overallocation, constraint identification and checking, critical constraint identification, measuring progress, meetings, information transfer, field data collation, developing 4D BIM, generating visual representations, evaluating alternatives, developing reports, linking different levels of plans and identification of potential disruptions on the project due to offsite or onsite processes
Master Scheduling, Phase Scheduling, Lookahead Planning, Weekly Work Planning, Learning

Improving the exhaustiveness of constraint identification
Lookahead Planning

Reducing Inventories on site
Reducing material inventories through better communication and enabling just-in-time supply chain management, and reducing Work-in-progress inventories through the computation of workflow indices such as the Maturity Index and Pull Flow Index
Lookahead Planning, Weekly Work Plan, Learning

Improving communication and coordination between stakeholders
Real-time sharing of accurate information regarding constraints, progress, material orders, etc. to improve the communication and coordination between stakeholders
Lookahead Planning, Weekly Work Planning, Learning

Reduction of potential conflicts and reworks on the construction site
Reducing potential space conflicts (e.g., between moving objects) and reworks (e.g., using clash detection)
Master Scheduling, Lookahead Planning, Weekly Work Planning

Enable effective utilization of as-built data and data from past projects
Utilization of as-built and past project data related to plans, schedules, productivity, and progress to develop reliable future plans and schedules, identify potential future problems and dynamically handle unseen scenarios on projects
Lookahead Planning, Weekly Work Planning, Learning

Lean Construction Principles

Reduce the share of non-value-adding activities

Increase output value through systematic consideration of customer requirements

Reduce Variability

Reduce Cycle Time

Simplifying by minimizing the number of steps, parts, and linkages

Increase output flexibility

Increase process transparency

Focus control on complete process

Build continuous improvement into the process

Balance flow improvement with conversion improvement

Fig. 6. The interactions between the benefits provided by automation of planning and control in LPS and LC principles (The blocks on the left represent the major categories of benefits identified in section 4. The solid filled blocks below each of these blocks mention the stages of LPS, whose automation functionalities led to these benefits. The blocks on the right represent the LC principles. The arrows from the automation benefit categories to the LC principles indicate the linkage between the two. To improve the clarity of understanding, each benefit category block and originating arrows are coded with different color. Further, circular shapes, whose color matches the outline of benefit category blocks, are added to LC principles blocks to indicate the linkage.)

the use of real-time information transfer systems in the LPS implementation contributes toward reducing variability in flows. Based on the process knowledge and as-built data, the simulation systems can assist in assessing the impact of uncertainty-causing factors on the schedules, thus reducing the uncertainties in field execution (Song and Eldin, 2012). Likewise, automation improves constraint management, which is crucial for lowering project uncertainties (Wang et al., 2016). Reduction in uncertainties can also be linked to variability reduction (Koskela, 1992).

5.4. Reduce cycle time

Cycle time is the total of processing time and durations for non-value-adding activities like inspection and waiting. It also encompasses planning, continuous improvement, and communication cycles (Koskela, 1992). The LPS implementation faces hurdles such as long planning meetings (Dave et al., 2015b), time-consuming data collation, and extended information flow cycles (Dave and Koskela, 2014). Our review revealed that automation addresses such challenges and enables achieving this LC principle in three ways. First, using optimization algorithms such as GA, schedules of shorter duration requirements can be generated (Dong et al., 2012). Second, automated systems can reduce planning cycle time by quickly creating plans. For instance, Soman (2020) reported that their algorithm could generate a constraint-free lookahead schedule within 11 s, while manual scheduling by practitioners took a few hours. Third, the communication and continuous improvement cycle times can also be reduced through automation. Automated information transfer and alerting systems cut communication delays, aiding early issue spotting (Abbaszadegan et al., 2022). Rapid computation of control metrics and generation of visual reports enable timely reactive measures, minimizing control cycle time (Lin and Golparvar-Fard, 2021).

5.5. Simplify by minimizing the number of steps, parts, and linkages

This principle focuses on reducing the complexity of a product or process (Koskela, 1992). Existing literature has reported complexity in implementing the LPS through several effort-intensive steps. For instance, the need to update each plan level separately (Perez and Ghosh, 2018), manually collecting plans from all subcontractors separately and collating them (Dave et al., 2015b). Automated information transfer and alerting systems can eliminate multiple steps in collating and communicating the information to the relevant stakeholders (Dave et al., 2016). The steps required for generating reports, such as color-coded BIM-based progress and safety visualizations (Sacks et al., 2009), get reduced through automated data analysis and visualization. Such visual depictions can also enable an easy understanding of the information (Sacks et al., 2009). Automatically linking different levels of plans in LPS can simplify updating them (Amer et al., 2021a). Existing review studies in the LC domain hint towards increased complexity due to the generation of multiple plan options through automated systems (Aslam et al., 2021; Sacks et al., 2010a). This study did not reveal any such issue reported in the LPS context implementation. Hence, further research is needed to explore this interaction. In addition, using technology requires additional staff training and technology-related management efforts (Boton et al., 2021), which can increase complexity.

5.6. Increase output flexibility

This principle emphasizes ease of adapting to changes and new conditions in production (Koskela, 1992). The situations on construction projects are ever-changing, necessitating plans in LPS to be adjusted accordingly (McHugh et al., 2022). Recent developments such as adaptive simulation systems (Song and Eldin, 2012), lookahead planning based on linked data enabled constraint checking (Soman and Molina-Solana, 2022), and holonic management system for dynamically adjusting work plans (Naticchia et al., 2019) can contribute towards achieving this principle. These systems adapt to actual field situations and make decisions to tackle them optimally, thus improving the flexibility of the planning process.

5.7. Increase process transparency

This principle focuses on improving process transparency through several means, such as visual display of flow and process attributes, and improving information accessibility (Koskela, 1992). Researchers have reported different transparency-related challenges in LPS implementation, such as inadequate information during planning sessions (Hamzeh, 2011) and poor communication (Gao and Low, 2014). Automated information transfer and alerting systems can enhance process transparency in LPS implementation (Li Jun et al., 2000). In addition, automated visual representations such as progress visualization in BIM models (Dallasega et al., 2019) contribute to ease of visual management and improve transparency. However, the transparency of the planning and control process can also be compromised due to automation. Algorithms like GA and Machine Learning, used in automated systems, may function as black boxes for construction practitioners, as they generally lack familiarity with such algorithms. Thus, they might struggle to comprehend the decision basis, lowering transparency.

5.8. Focus control on the complete process

According to this principle, the overall process optimization should be the focus instead of optimizing each subprocess in isolation. Based on our literature review, the existing automated planning and control efforts can contribute to achieving this principle in three ways. First, the dynamic replanning systems that generate global optimum plans rather than only individual resource-level optimization (Naticchia et al., 2019) can steer the plans toward achieving project targets. Second, systems aiding on-site and offsite production coordination through information sharing (Chen et al., 2022) and identification of offsite production patterns (Zeng et al., 2023a) facilitate a pull flow between them. Thus, offsite factories can produce according to on-site demand instead of always having to reach their maximum capacity. Finally, the automated identification of critical constraints (Chua and Shen, 2005) enables the stakeholders to focus on the most important constraints for the project's overall time performance instead of concentrating only on an individual activity level. However, stakeholders must not devalue the removal of constraints other than critical ones, as this can have a negative implication for this principle.

5.9. Build continuous improvement into the process

Learning from failure and continuously improving the process is an important LC principle (Koskela, 1992). LPS incorporates this by measuring metrics such as Planned Percentage Complete, analyzing reasons for failure, and identifying countermeasures (Ballard and Tommelein, 2021). However, this is found to be one of the least and inadequately implemented steps in LPS (Dave et al., 2015b; Perez and Ghosh, 2018). Automation in LPS implementation assists in achieving this LC principle. Tools such as regression and simulation enable effective utilization of the as-built data from the same/past projects to improve future plans (Shehab et al., 2019). Suggestive categories enhance the accuracy and comprehensiveness of identifying reasons for the failure of plans (Zaeri et al., 2017). Automated computation of control metrics, generating graphs related to the frequency of reasons for failure and as-planned vs. as-built progress support stakeholders in quickly identifying the issues and thus making informed decisions (Heigermoser et al., 2019). Dynamically adjusting the plans based on site conditions enables the plans to be adapted to actual field conditions (Naticchia et al., 2019), thus contributing to continuous improvement.

5.10. *Balance flow improvement with conversion improvement*

This principle emphasizes that in addition to improving value-adding activities, non-value-adding activities, such as supporting flows, should also be improved. The evidence from automation in planning and control in LPS indicates that automation can help improve both flow and conversion. Several studies have utilized optimization algorithms to develop time and cost-optimum schedules at different levels of detail (Dawood and Sriprasert, 2006; Soman and Molina-Solana, 2022), thus contributing towards conversion improvement. In addition, other researchers utilized automation to address challenges related to the information flow (Dave and Koskela, 2014), thus contributing to flow improvement. Similarly, the computation of workflow indices enables the development of weekly plans to maintain workflow continuity on site (Sacks et al., 2012), thus contributing towards flow improvement.

5.11. *Benchmark*

This principle focuses on identifying the best processes from the industry, benchmarking them, and steering toward achieving them (Koskela, 1992). Based on the literature review in this study, existing efforts to automate planning and control in LPS do not contribute towards achieving this principle.

6. Future research

The findings in sections 4 and 5 indicate that automation of different aspects within the LPS framework supports achieving LC principles on construction projects. However, the full potential of such automation is yet to be realized, which can be attributed to two major reasons. First, prior research has automated some LPS components; much implementation still remains manual. Second, as the LPS is a collaborative planning approach requiring the active involvement of different construction stakeholders (Ballard, 2000), automation approaches should consider this social aspect of LPS. The research on automation in LPS suggests that inadequate knowledge of the workforce about technology, the additional workload caused by it, and the industry's resistance to change hinder its adoption (Boton et al., 2021; Dave et al., 2011; Thorstensen et al., 2013). Thus, we perceive that leveraging automated planning and control for improved LPS implementation and achieving LC principles requires future research on the People and Technology related aspects, termed as the 'People layer' and 'Technology layer' in this study (depicted in Fig. 7). Both layers should collaborate for optimal results. This aligns with the recent LC 4.0 paradigm, which emphasizes balancing people (culture and actors), processes (production philosophy), and technology triad for effective technology-driven transformation in construction (González et al., 2022).

6.1. *People layer*

We envision the following research directions in the People layer:

1. Production planners should be trained in technologies such as AI, simulation modeling, Digital Twins, and Linked Data. Construction workers and site personnel should receive training to effectively operate the interfaces of automated systems designed for their use. Construction management and technology researchers should collaborate with construction practitioners to develop optimum curriculums for training construction workers and professionals and educating upcoming graduates.
2. Lean emphasizes 'automation with a human touch,' i.e., automation should support decision-making rather than taking complete control (González et al., 2022). Therefore, future research is needed to develop frameworks to guide organizations in effectively establishing a balance between the collaborative aspects of LPS and the benefits of incorporating automation into it.

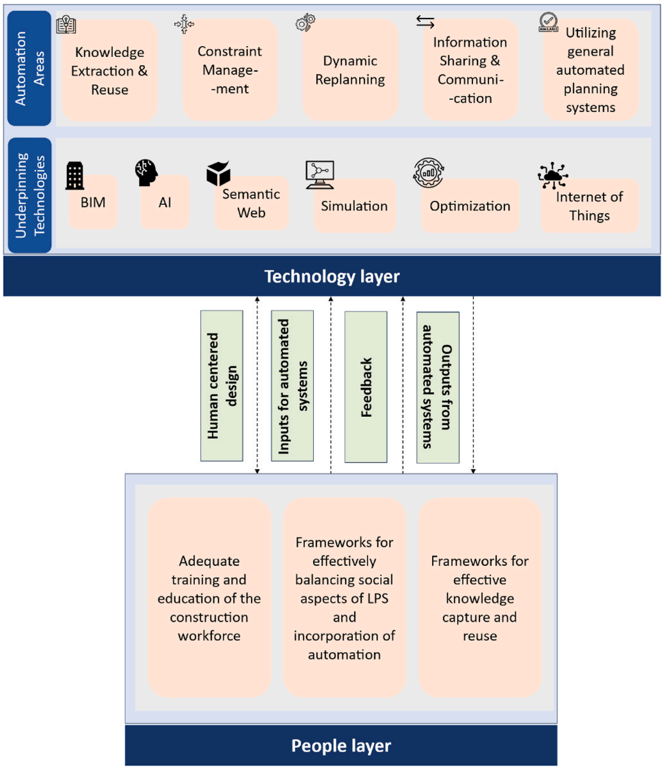


Fig. 7. Vision for future research in automation of planning and control in the LPS.

3. Being data-driven and collaborative, the LPS implementation can generate significant knowledge, potentially improving planning and control in future projects. However, knowledge capture remains challenging due to the fragmented construction industry and construction projects being ad-hoc (Dave and Koskela, 2009). To this end, guidelines and frameworks should be developed to enable effective knowledge capture and reuse, which automated systems can utilize in the future.

6.2. *Technology layer*

We envision the following research directions in the Technology layer:

6.2.1. *Knowledge extraction and reuse*

The LPS implementation can generate knowledge in various forms, such as collaborative plans, minutes of meetings, identified constraints, reasons for failures, and 5 Why analysis documents. However, reusing this knowledge becomes strenuous as these documents are stored in unstructured text documents, requiring manual review by decision-makers. To this end, automated knowledge extraction and reuse can provide unparalleled benefits for implementing LPS. Existing research in this direction has focused only on predicting task sequence in LAS operations and structuring reasons for failure recording through suggestive categories. Therefore, further research is needed to develop automated systems to accurately extract comprehensive knowledge from different levels of schedules in LPS, maintain the interlinking between these different schedules, and use these knowledge bases to predict accurate schedules for new situations. Knowledge from other documents, such as reasons for failure analysis, should be extracted and integrated with the scheduling knowledge bases so that the automated planning systems do not repeat the planning mistakes in the earlier schedules. To this end, knowledge modeling techniques such as Ontologies and Knowledge Graphs, and AI techniques such as NLP and deep learning can play a pivotal role. Such systems can be pivotal in addressing the LPS implementation challenges of repeating failures and slow learning from the past (Hamzeh et al., 2016). Also, they can contribute towards achieving the LC principles of continuous improvement, reducing non-value-adding activities and cycle time, and simplification.

6.2.2. Constraint management

The existing suggestive constraint identification systems give stakeholders an idea about the categories of constraints (Zaeri et al., 2017); however, identifying exact details about the constraints and their attributes for each operation remains manual. Off-late, researchers have started utilizing AI to automatically identify constraints and their attributes from text documents (Wu et al., 2021a,b) for Advanced Work Packaging. Future research should focus on developing such systems within the LPS context. AI techniques such as NLP, deep learning, and knowledge management techniques such as ontologies can play a vital role.

Next, existing automated constraint-checking approaches in LPS fell short of checking geometric constraints such as safety and site layout. To this end, future research should extend the Linked Data-based approach to check geometric constraints. Existing studies for automated constraint checking utilized ifcOWL ontology for data representation (Soman et al., 2020), which lacks the semantic expressivity to handle geometric constraints (Guo et al., 2021; Pauwels et al., 2017). To this end, future research can focus on utilizing other existing ontologies or developing new ones to represent the geometrical data and perform automated constraint checking adequately. Further, efforts should be made to create modular constraint definitions in concerned languages, such as Shapes Constraint Language (SHACL), which Construction professionals can easily reuse without the need to learn constraint definition languages. Through such improvements, automation in the LPS can contribute towards achieving LC principles of reducing non-value-adding activities, simplifying, reducing cycle time, increasing value, and increasing flexibility.

6.2.3. Dynamic replanning systems

Existing studies on dynamically adjusting plans based on as-built data and site conditions suffer from four limitations. First, they have mostly been at a prototypical stage, lacking field-level implementation and validation (Sacks et al., 2020). Second, such studies have been limited to specific projects, e.g., piling (Naticchia et al., 2019). Third, they focus only on a particular level of planning in LPS, lacking integration between different levels. Fourth, the existing systems consider time or cost-based optimization, neglecting flow optimization. The measurement of flow on construction projects is still a problem open for research (Kenley, 2019). To this end, future research should focus on developing scalable, dynamic replanning systems for different construction projects through extensive field-level testing. Attention should also be given to establishing the connection between different levels of plans, such that changes made at one level of the plan get automatically reflected at other levels. The replanning should be done to achieve optimization from the perspective of all the levels of planning in the LPS stages rather than focusing only on a particular level. Methodologies should be developed to measure the flow and consider it an optimization objective with replanning systems. In addition, such automated planning systems should be equipped with the intelligence to involve human decision-makers whenever necessary. Technologies such as BIM (as a data source), Semantic Web (to access distributed databases), AI (to learn from past data and establish links between different levels of plans), Simulation and Optimization (to simulate possible future events and find out optimized solutions) can play a critical role to this end. Such systems can help achieve several LC principles, such as reducing non-value-adding activities, simplifying, reducing cycle time, continuous improvement, focusing on the complete process, balancing flow improvement with value improvement, and increasing flexibility.

6.2.4. Application of general automated planning and control systems in the context of LPS

Various tools and techniques have been developed to automate construction project planning based on methods other than the LPS (Amer et al., 2021b; Faghihi et al., 2015). Future research should focus on utilizing such existing systems in the LPS context. For instance, researchers have automated generating and optimizing line-of-balance plans satisfying the milestone and deadline constraints (Zolfaghar Dolabi et al., 2014; Zou et al., 2018). At the same time, the phase scheduling stage of LPS focuses on utilizing location based planning methods and developing process-level plans that satisfy milestone constraints inherited from the master schedules. Even though similarities exist between the two, the application of such optimized planning methods is not explored in phase scheduling. Therefore, future research should assess the applicability of such existing automated planning and control systems in the context of LPS and utilize them in the LPS after making the required changes.

6.2.5. Information sharing and communication

The literature review in this study depicted that real-time information transfer between stakeholders plays a critical role in successfully implementing LPS by enabling informed decision-making, and enhancing coordination. However, research addressing the difficulties faced in such communication at a technological level has not gained much attention. Dave et al. (2016) utilized IoT standards for communication (Open-Messaging Interface and Open-Data Format); however, the system had challenges in sharing the targeted information efficiently and integrating with existing information containers in construction. To this end, future research is needed to develop better communication interfaces that can interact with the siloed information without interoperability issues and disseminate relevant information to the construction stakeholders promptly and efficiently. Semantic web technologies combined with IoT can provide potential solutions to such challenges (Rhayem et al., 2020).

6.3. Interactions between the people and technology layers

As shown in Fig. 7, the People and the Technology layers are expected to mutually support each other to maximize benefits from the automation of planning and control within the LPS framework. González et al. (2022) suggested designing technological systems in the LC context through a human-centered design approach, which focuses on system development from the users' perspective through their active participation (Giacomin, 2014). The frameworks for effective involvement of construction stakeholders developed in the People layer can govern the requirements of the automated LPS implementation tools from the user's perspective. Further, using the human-centered design, the user interfaces of the automation tools can be developed through multiple rounds of user feedback. Therefore, the human-centered design carries a two-way link between two layers in Fig. 7. The automation areas, such as knowledge management and dynamic replanning, require continuous user input. For instance, AI-based knowledge management systems provide better results if the training databases are created adequately (Eken et al., 2020). Organizational frameworks and workforce training can facilitate a structured knowledge base creation, causing the 'Inputs for automated systems' arrow in Fig. 7. The outputs from automated systems can support decision-making in the LPS implementation, causing the 'Outputs from automated systems' arrow in Fig. 7. Continuous user feedback can help to refine the developed automation systems, exemplified by the 'Feedback' arrow in Fig. 7. For instance, if a system-predicted plan fails to achieve the anticipated time/cost levels on site, the algorithms/knowledge bases must be adapted to actual field situations based on the inputs from different construction stakeholders. Thus, future research in the directions mentioned in Fig. 7 will initiate a continuous improvement cycle between the two layers.

7. Conclusion

This study investigated the potential benefits of automation of planning and control in LPS to achieve LC principles on construction projects through better implementation of LPS. To this end, three objectives were set for this study (Section 1). To address the first objective of identifying state-of-the-art of benefits provided by the automation of planning and control within the LPS framework, a systematic literature review of 112 studies was conducted. The review led to the identification of 50 functionalities provided by automation in six stages of LPS (Section 4) and their associated benefits, which can be categorized into nine major categories (Fig. 6). To address the second objective of understanding the implications of the benefits of such automation in achieving LC principles, LC principles suggested by Koskela (1992) were mapped against the identified benefits of automation (Fig. 6). Linking identified benefits and LC principles revealed that the automation of planning and control within the LPS framework mostly positively impacts the achievement of 10 out of 11 LC principles (Section 5 and Fig. 6). Based on the findings, it can be concluded that adopting automated planning and control supports the LPS implementation in several aspects and enables achieving LC principles on construction sites, thus making the projects leaner. Finally, to address the third objective of identifying future research areas in the domain of automation of planning and control within the LPS framework, research concerning the People and Technology related aspects is suggested. The People layer addresses human and organizational challenges in adopting automated LPS. The Technology layer concentrates on further utilization of technological developments to address untapped challenges in LPS implementation. The interactions between the two layers to mutually support each other for maximizing the benefits realized by automation are demonstrated.

This study contributes to the body of knowledge in LPS research by identifying the existing state of automation of planning and control and its benefits. Thus, it extends the domain knowledge about the implications of technology integration with LPS from technologies such as BIM (Sbiti et al., 2021; Schimanski et al., 2020) to automation of planning and control through other technologies such as simulations, semantic web, and artificial intelligence. It also contributes to the state of research about understanding the synergies between technology and lean (Aslam et al., 2021; Sacks et al., 2010a) by demonstrating the implications of automated planning and control within the LPS framework toward achieving LC principles. The results of this study are expected to provide LPS and construction automation researchers with a way forward toward developing socio-technical systems for project planning and control. For practitioners, the findings of this study are expected to help achieve lean objectives on their construction projects by systematically applying automated systems in different phases of LPS. Building on this study, empirical studies can be undertaken to validate this research's findings and explore any new interactions between LC principles and automation of planning and control within the LPS framework.

CRediT authorship contribution statement

Ajay Kumar Agrawal: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft. **Yang Zou:** Conceptualization, Supervision, Writing – review & editing. **Long Chen:** Supervision, Writing – review & editing. **Mohammed Adel Abdelmegid:** Writing – review & editing. **Vicente A. González:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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