



An innovative integrated framework for multi-level production planning and control systems in construction

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ABSTRACT

The construction industry is plagued by chronic inefficiencies, such as low productivity, significant waste, cost overruns, and schedule delays. One of the most critical contributors to these issues is fragmented and ineffective planning and control methods. This research aims to address these challenges by developing an innovative integrated multi-level framework for production planning and control that harmonizes various planning methods and control metrics across different schedule levels. Employing the Design Science Research (DSR) methodology, this study systematically develops and evaluates an innovative framework that integrates internal and external project characteristics, utilizing the concept of "functionality" as a primary key for coherent integration. Furthermore, a multi-objective mathematical model is incorporated to clarify the framework's components and optimize the number of suggested planning methods and control metrics at each scheduling level, aiming to balance the functional requirements of project teams with the practicality of implementation.

The application of the framework to a renovation case study demonstrates its practicality and strategic value, effectively addressing real-world project management challenges. Moreover, industry and academic evaluations highlight its potential to significantly improve construction project management practices.

1. Introduction

The construction sector is the largest industry worldwide, constituting approximately 13 percent of the global Gross Domestic Product (GDP) (Ribeirinho et al., 2020) and 9.8% of the EU's GDP (Goulding and Rahimian 2012). Over the years, it has demonstrated its capability by completing increasingly ambitious projects, ranging from underground tunnels to towering skyscrapers. Despite these achievements, the industry faces significant challenges. Productivity in construction has exhibited sluggish growth, averaging merely 1 percent annually over the past twenty years (Ribeirinho et al., 2020). Additionally, construction activities contribute substantially to global waste generation (Akbari et al., 2024; Banihashemi et al., 2023), accounting for an estimated one-third of the world's total waste output, and are responsible for at least 40% of global CO₂ emissions (Rodriguez Trejo et al., 2024). Also,

McKinsey's research highlights that 98% of construction projects experience more than 30% cost overruns, and 77% are at least 40% behind schedule (Changali et al., 2015). Issues concerning planning and control processes, such as ineffective planning and control methods (Sheikhhoshkar et al., 2023b), poor constraint and data management (Elghaish et al., 2022; Ezzeddine et al., 2022), limited collaboration and communication among stakeholders (Asgari and Rahimian 2017; Viklund Tallgren et al., 2020), inefficient workflow (Hamzeh 2009), and inaccurate estimations (Hamzeh et al., 2019b), are among the key factors aggravating the aforementioned challenges.

The Critical Path Method (CPM), pioneered by Kelley and Walker in the 1950s, was among the earliest techniques devised for project planning and scheduling (Kelley Jr and Walker 1959). Although it remains a standard requirement in many countries, often mandated by project owners for scheduling purposes (Olivieri et al., 2016), the lean

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construction community has raised concerns about CPM's shortcomings. These criticisms include its limited focus on schedule workflow, prioritization of project control over production control, inadequate analysis of constraints, inadequate daily management of activities, and reliance on overly detailed schedules, even when project specifics are uncertain during the early stages (Olivieri et al., 2016). Over the past few decades, a wide array of planning and scheduling methodologies, techniques, and tools have been developed and utilized to confront the challenges inherent in construction projects' planning and control process. These encompass approaches such as critical chain project management (CCPM), line of balance (LOB), linear scheduling method (LSM), location-based management system (LBMS), last planner system (LPS), takt time planning (TTP), the fourth dimension of building information modelling (4DBIM), simulation-based methods (SM), advanced work packaging (AWP), workforce planning (WFP), Scrum and Kanban and tri-constraint method (TCM) (Arditi and Albulak 1986; Ballard 2000; Frandson and Tommelein 2014; Hall et al., 2022; Hamdi 2013; Saki-khales 2021; Seppänen et al., 2014).

Various scholars have attempted to integrate these planning methods and lean tools and principles to create a holistic approach that addresses their shortcomings. In this regard, research efforts have focused on merging LPS principles with BIM to optimize various aspects of project execution. These endeavors aimed to stabilize workflow, foster collaboration, implement efficient planning strategies like pull planning, improve visualization, resolve conflicts, and minimize cycle time (Sacks et al., 2010; Sbity et al., 2021). Integrating LBMS, LPS, and CPM has been explored to bridge gaps in traditional planning methods, with a focus on achieving lean objectives like waste reduction, enhanced productivity, aiding managers in analyzing delays, and minimizing variabilities (Olivieri et al., 2016). In the context of modular construction, efforts have been made to integrate LPS, CCPM, and LSM to address challenges such as the "student syndrome," ensuring task commitments, identifying reasons for non-completion, and monitoring task completion effectively (Salama et al., 2021). Automation of 4D BIM models integrated with location-based planning (LBP) methods and LPS has been proposed by Silveira and Costa (2023) to support project control cycles, aiming to increase the use of 4D BIM models and improve production planning and control reliability. Moreover, to further streamline workflows, it has been suggested to employ LPS combined with LBP methods to sequence work packages across locations (Ballard and Tommelein 2021). Heigermoser et al. (2019) introduced a prototype that partitions a construction project into zones, facilitating automated billing and providing a color-coded 4D simulation for the construction schedule in the short term within the LPS framework.

Furthermore, to maintain adherence to the project timeline and ensure the achievement of project objectives, efforts have been made to establish and employ a set of control metrics for the continuous monitoring and analysis of the project performance, efficiency, and other pivotal dynamic aspects. Within this context, Earned Value Management (EVM) serves as the prevailing control system, integrating three fundamental project management elements: scope, cost, and time (Hamzeh et al., 2019b). To address shortcomings of EVM, such as neglect of workflow consideration, inability to differentiate between critical and non-critical tasks, lack of alignment with lean construction principles, inaccuracies in assessing work completion and prediction, a diverse array of control metrics, infused with lean-oriented planning and scheduling methodologies, have been developed and put into practice over the past decades (Hamzeh et al. 2019a, 2019b; Sheikhhoshkar et al., 2024a). Furthermore, various academic papers have proposed a dynamic buffer monitoring approach to effectively manage and mitigate the complexities inherent in construction projects characterized by high levels of uncertainties (Zhang et al., 2018).

Despite the development of numerous individual and integrated planning and control methods, project managers still encounter challenges in achieving a fit-for-purpose planning and control system. Lack of understanding and knowledge regarding the effectiveness and

practical use of planning and scheduling techniques is cited as the main reason for this issue (AlNasseri and Aulin 2015; Sheikhhoshkar et al., 2023a). Additionally, there is a notable gap in the availability of an adaptable and well-suited system for project planning and control that addresses the diverse functional requirements of project teams and is applicable across a broad spectrum of project types. Hence, there's a need to identify appropriate mechanisms for gaining a deeper understanding of the underlying theories and concepts of different methods and tools. Furthermore, existing methods often remain fragmented, focusing either on strategy-pull or technology-push aspects without fully addressing the functional requirements of the project team (Sriprasert and Dawood 2003). As a result, the construction industry lacks a comprehensive planning and control system that meets the needs of project teams and enhances stakeholders' understanding. In this sense, Dallasega et al. (2021) also recommended that future research endeavors should be concentrated on developing a methodology for project planning and control that combines all the advantages of the methods that have been studied. Accordingly, this study seeks to develop a multi-level and integrated planning and control system for construction projects. This system will leverage existing planning methods and control metrics across various schedule levels while considering the functional requirements of project teams to ensure effectiveness. To achieve this, the objectives of this study are as follows.

- 1 Identify an appropriate mechanism to integrate various planning methods and control metrics across multiple schedule levels and improve understanding of the underlying theories and concepts of various planning and control approaches between project stakeholders
- 2 Provide a comprehensive framework for planning and control that operates across the functional requirements of the project team
- 3 Implement the proposed solution in a case study to show its practicality and applicability

This study contributes to the body of production planning and control knowledge by introducing and validating a novel, flexible, multi-level and integrated framework for planning, managing, and monitoring the dynamic and complex nature of the various construction projects more effectively.

The following sections outline the research methodology, describe the multi-level and integrated framework, and introduce a multi-objective mathematical model designed to clarify the framework and improve its results. They also detail a case study and the procedures for validation, followed by a discussion of the research findings and conclusions. Furthermore, the paper explores potential limitations and suggests avenues for future research and advancement in this particular field of study.

2. Methodology

This paper employs the design science research (DSR) methodology as an analytical and creative approach to develop a multi-level and integrated planning and control framework for construction site management. DSR primarily concentrates on understanding, explaining, and predicting the current natural or social environment by identifying issues, and crafting and assessing solutions to enhance performance (Van Aken 2005). By adopting this methodology, the intention was to contribute to the body of knowledge by developing a practical and effective framework for integrating planning methods and control metrics across various schedule levels. The inherent nature of DSR aligns to generate theoretically robust, applicable, and valuable solutions in addressing real-world challenges within the construction industry (Agrawal et al., 2022). The DSR methodology has previously demonstrated its utility in producing practical and technological artifacts within the construction industry. Agrawal et al. (2022) proposed a digitalization framework grounded in design science research to aid

practitioners in the strategic selection of an optimal level of sophistication in a Digital Twin (DT). Barkokebas et al. (2021) developed a framework, utilizing the DSR, to address the digitalization of remanufacturing phases in offsite construction through the integration of Building Information Modelling (BIM) and lean principles. Lerche et al. (2020) used a design science approach to provide a conceptual model for the last planner system (LPS) adapted to modular offshore wind construction.

Following the DSR approach proposed by Peffers et al. (2007), this research adopted a four-step process to develop the framework for construction planning and control systems, as depicted in Fig. 1. The steps encompassed: (1) find the problems and obtain understanding, (2) define research objectives, (3) develop a solution followed by its demonstration, data collection, and subsequent analysis, and (4) assess the solution's usefulness. Within the framework of DSR, as an umbrella for methodology, a mixed research method was employed, including a literature review, document analysis, site observation, semi-structured interviews with domain experts, survey, case study, and mathematical modelling and optimization. The following subsections delved into the DSR steps and the used methods.

2.1. Find the problems and obtain understanding

A thorough study was undertaken to figure out the key challenges and understanding of planning methods and control metrics. First, exhaustive literature reviews (Sheikhhoshkar et al. 2023a, 2023b, 2024a) were conducted addressing single and integrated planning and scheduling methods, control metrics, and their underlying concepts. This preliminary phase not only identified the prevailing gaps in current understanding but also paved the foundations for further studies in this domain.

Moreover, a document review and analysis were conducted on construction planning and control guidelines and recommended practices. This process involved a thorough review of the time management

guideline established by the Construction Management Association of America (CMAA), recommended procedures and guidelines associated with the last planner system, recommended practices outlined by the Association for the Advancement of Cost Engineering (AACE), guidelines for take time planning, and the guiding principles within the framework of location-based management systems and implementing 4DBIM.

Additionally, site visits enabled informal interviews and discussions with practitioners. Through direct observation of the implemented site planning and control approaches, as well as the documentation, pictures, quotes, and field notes analysis, hidden issues were brought to light, offering valuable practical insights. This step has revealed a lack in the construction project's planning and control system, which adequately meets the diverse requirements of the project team for planning, managing, and monitoring various project aspects. Furthermore, the deficiency of awareness and understanding of construction planning and control systems among project stakeholders is a concern that requires attention.

2.2. Define research objectives

In this step, the research objectives were defined based on the issues highlighted in step one, as well as the objectives outlined in the multi-level planning module of the IsoBIM project. The IsoBIM initiative outlines a collaborative approach for renovating buildings with external insulation based on lean and BIM paradigms. The primary objective is to facilitate the digital transformation of small and medium-sized enterprises (SMEs) in the wood construction sector to boost their efficiency and productivity. The IsoBIM framework, as shown in Fig. 2, aims to cover the entire process of renovation of buildings, beginning with identifying the optimal renovation solutions, progressing through the formulation of configuration and layout models, dynamic data management, and the development of a multi-level and collaborative planning and control framework and guideline for construction sites which is

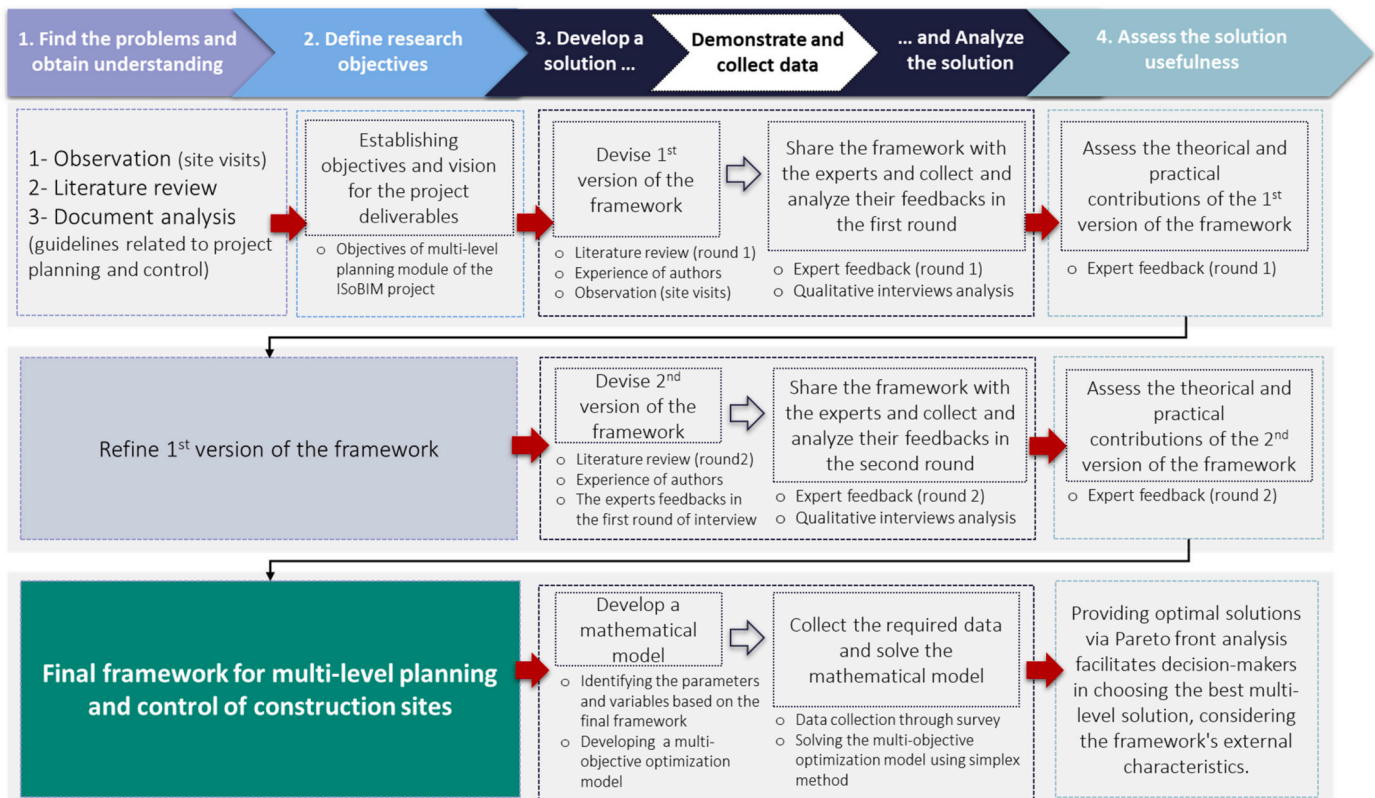


Fig. 1. Adopted methodological steps for applying DSR.

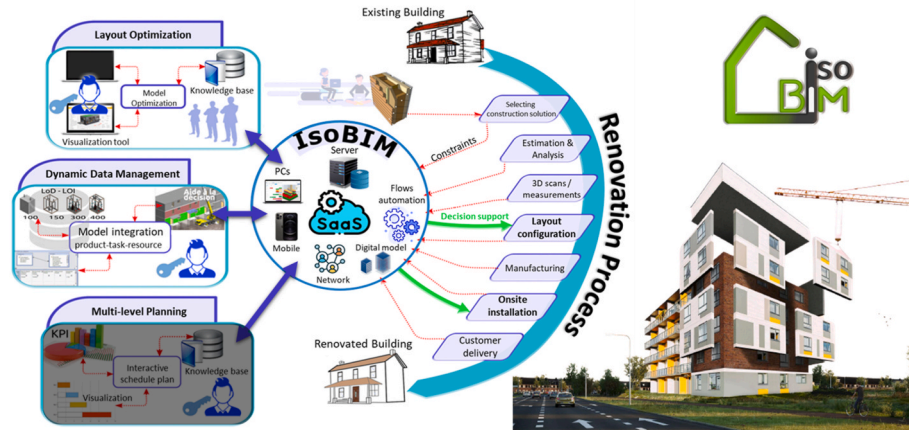


Fig. 2. IsoBIM project overview.

the related module of this research. As a result of this phase, one objective of this research is to develop a planning and control framework for construction projects that operates across multiple levels and integrates various planning methods and control metrics. Finding an appropriate mechanism to improve understanding of the underlying theories and concepts of various planning and control approaches on a deeper level and incorporate them into a comprehensive system as well as considering the knowledge and skills of stakeholders in construction projects are two further objectives.

2.3. Design and development

The framework's design and development followed a similar process to that outlined by Agrawal et al. (2023). To do this, stages 3 (framework design, demonstration, and analysis) and 4 (evaluation) were conducted iteratively. The first version of the framework was meticulously crafted, considering the conducted extensive literature review, the expertise and experiences of the authors gained over many years, and the observed production planning systems during a site visit.

Initially, the last planner system was intended to be regarded as a multi-level planning approach rooted in lean principles, while 4D BIM was to be perceived as the time management dimension of BIM to cover the research objectives. However, after a site visit, an endeavor was made to unveil the implemented production system utilized for project planning and control in real-world case studies. Fig. 3 illustrates the observed production system design for project planning and control at the visited project, which consists of multiple buildings within an

approximately 51-ha site in Paris. The responsible team for planning and control utilized an integrated production system, which combined various planning methods and control systems, including critical path method (CPM) and buffer control, location-based management system (LBMS), 4DBIM, last planner system (LPS) and takt planning to achieve more effective and practical approach. This on-site exploration resulted in a shift in perspective, leading away from the initial intention towards developing a multi-level planning framework based on the merits of diverse planning methods and control systems across distinct schedule levels. Consequently, a novel framework was devised, considering eight planning methods and two control systems: Earned Value Management (EVM) system, and lean-based control system. The primary objective of this framework was to integrate planning methods and control metrics across three schedule levels: long-term, mid-term, and short-term while considering the project characteristics.

The first framework version was presented to the experts, as detailed in Table 1, and multiple rounds of design and development were carried out. The demonstration and feedback processes were structured as periodic check-ins with the experts, totalling over 20 meetings spanning six months. These sessions involved ten experts from industry and academia, collectively amounting to approximately 28 h. Experts were asked to share their thoughts on four main aspects: 1) what parts of the framework made sense, 2) areas that needed improvement, 3) how useful the framework seemed in real-world projects, and 4) any perceived complexity in using it in practice.

Multiple meetings were held with the same expert to ensure comprehensive incorporation of feedback. This iterative design process

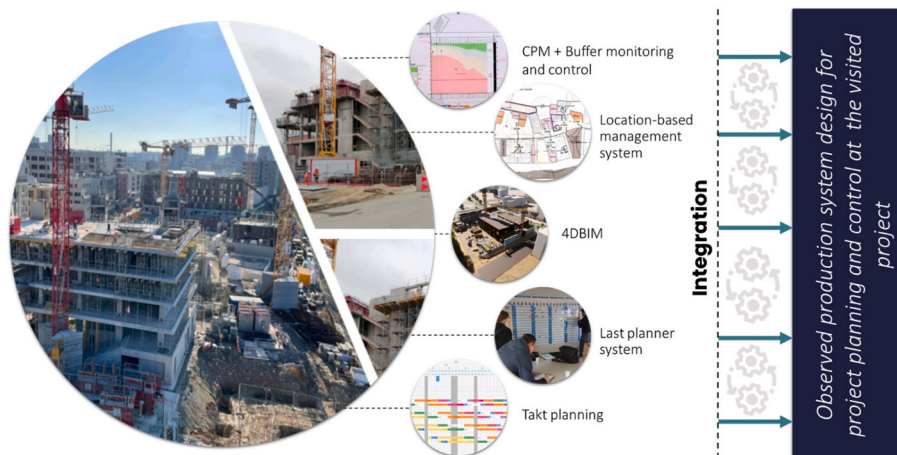


Fig. 3. Observed production system for planning and control in the visited projects.

Table 1

Profile of experts.

Type of experts	Experts code	Background/role	Experience (years)	Number of meetings	Total hours of interaction
Industry experts	IE1	Senior program scheduler	20–25	2	3
	IE2	Senior project manager	15–20	2	3
	IE3	Consultant lean management	10–15	1	1.5
	IE4	Senior project construction manager	15–20	2	3
	IE5	CEO of a lean construction software company	20–25	1	1.5
Academic experts	AE1	Senior lecturer in the built environment	15–20	2	3
	AE2	Full professor in construction management	25–30	3	3
	AE3	Assistant professor in construction management	5–10	2	2
	AE4	Associate professor in production planning and control	15–20	4	4
	AE5	Full professor in production management and control	15–20	4	4

persisted until theoretical saturation was achieved, denoting a point where no novel or pertinent feedback emerged during the demonstrations. Some pivotal comments from experts that significantly influenced the framework's development are summarized in Table 2.

Upon unveiling the initial iteration of the framework to experts and acknowledging challenges identified in the literature concerning the insufficient comprehension and knowledge about diverse planning methods and control metrics between project stakeholders in construction (AlNasseri and Aulin 2015; Salling et al., 2023; Sheikhhoshkar et al., 2023a), it became evident that the initial version was complex and impractical for implementation. Subsequently, guided by the insights provided by experts, the first version underwent a comprehensive revision. Following another round of literature review and feedback from experts, the second version of the framework was developed and evaluated.

It should be noted that experts were selected based on three key factors: 1) their practical experience and theoretical comprehension of the study's topics, including traditional and lean-based planning and scheduling methods, control systems, and collaborative planning methods, 2) diversity in their professional roles, incorporating both academic and industry experts with different relevant roles to ensure various skills and perspectives, and 3) their openness to actively engage in several feedback sessions.

2.4. Assess the Solution's usefulness

The assessment of artifacts within the Design Science Research (DSR) methodology holds significant importance as it serves to verify their utility, quality, and effectiveness in addressing the identified problem.

Table 2

Some of the quotes from experts that caused important changes in the framework.

Sample statements from the Experts	Derived insights for the framework
"In the initial iteration of the conceptual framework, a key difficulty lies in connecting the three layers of diverse characteristics." "Given the constant changes in methods and techniques within the domain, it is advisable to shift focus towards employing planning, scheduling, and control principles instead of specific methods in a multi-level framework. This approach is crucial to adapt to the evolving nature of the domain and provide a more flexible and comprehensive strategy." "What specific planning and control principles should be put into action and applied at each level of schedule?"	Played an important role in defining and incorporating functionality as a key concept within the framework for effectively integrating the three layers. Aided to formulate the functionality concept as a common concept for planning methods, control metrics and schedule levels. This additionally encouraged study into the essential functionalities inherent in planning methods across various schedule levels. This led to a more thorough examination and exploration of the required external characteristics to develop a production planning and control system.
"While delving into solutions for SMEs is interesting, there's a lack of information about organizational characteristics. To make the implementation more practical, it's essential to consider another layer focusing on the specific traits of the company or organization." "Review the project schedule specifications provided by the client for various projects and include the relevant items in the framework."	Involved in collecting and analyzing project schedule specifications, followed by including essential components into the framework to enhance its practicality.

To do so, two approaches were considered for the framework's validation, including a renovation project case study targeting the campuses of the University of Lorraine and the utilization of quantitative performance metrics derived from satisfaction surveys (Peffer et al., 2007). Regarding the satisfaction surveys, the framework was evaluated through demonstrations to selected experts over an iterative six-month process encompassing design, development, and evaluation stages. This phase involved considering five evaluation facets based on the study that was conducted by Barkokebas et al. (2021) and taking into account expert feedback. These aspects included 1) applicability, 2) flexibility and adaptability, 3) ease of understanding, 4) integration, and 5) completeness. Table 3 provides the details of the assessment criteria.

2.5. Develop a multi-objective mathematical model

A multi-objective mathematical model was formulated to clarify and

Table 3

Framework evaluation criteria details.

Framework evaluation criteria	Definition
Applicability	The framework is applicable to implement in real-world construction projects of varying scales and complexities.
Flexibility and Adaptability	The framework easily adapts to changes in project requirements, scope, or industry regulations.
Ease of Understanding	The framework is easy to understand by individuals with limited project planning and control knowledge and notably enhances project stakeholders' understanding of their planning and control requirements.
Integration	The framework seamlessly and effectively integrates commonly used project planning methods and control metrics across different levels of the schedule.
Completeness	The approach followed in the framework to develop multi-level planning and control is sufficient, making the framework exhaustive and complete

define the framework's components. The initial phase explicitly defined requisite sets, indices, parameters, variables, objective functions, and constraints, all contingent upon the framework's integral components. Not only does this model contribute to the tangibility of the framework's components and demonstrate its practical functioning, but it also serves a primary goal of minimizing the number of planning methods and control metrics while concurrently maximizing functionalities at each scheduling level. Following this, data required for the mathematical model was gathered based on the knowledge and experience of domain experts. Due to the linear nature of the defined optimization problem, the simplex method in the Gurobi solver (utilizing an academic license) was employed to solve the problem.

Additionally, the mathematical model offers users flexibility by providing a Pareto front. This approach empowers users to select a feasible solution tailored to the specific characteristics of their organization, project, environment, and stakeholders. Essentially, the model furnishes a comprehensive and adaptable solution that aligns with the unique requirements of diverse project contexts.

3. Proposed multi-level and integrated framework for project planning and control

The initial step involved thoroughly exploring the required attributes to design a system for project planning and control. This process entailed an in-depth analysis of literature and guidelines as well as interviews with domain experts. Then, moving forward with the development of the framework, efforts were directed towards crafting a solution that aimed to consider the different functional requirements of the project team. In this process, internal and external characteristics were strategically incorporated and integrated. The proposed framework, presented in Fig. 4, focuses on these two main components required for designing a production system for project planning and control through integrating different planning methods and control metrics at three schedule levels. The following subsections delved into the components of the framework.

3.1. External characteristics

In the design of a production system for project planning and control, it is crucial to consider various project characteristics such as project type, size, location, resources and form of contract. In the first phase of this study, emphasis was placed on identifying and extracting these pertinent project characteristics. However, after receiving expert feedback and engaging in extensive discussions, it became evident that more than solely considering project characteristics is required for selecting a system for project planning and control. Therefore, it was necessary to broaden the scope for a more comprehensive and practical approach. Consequently, external characteristics were incorporated to provide a broader context, including environmental factors, organizational structure, stakeholder specifications, and project-specific demands. These components play a crucial role in selecting a system for project planning and control.

The subitems of each category of external characteristics were extracted and defined by combining literature analysis and experts' opinions. In this regard, the initial effort to identify these factors included analyzing project characteristics and project complexity factors affecting project performance proposed in the studies of [Cho et al. \(2009\)](#), [Bakhshi et al. \(2016\)](#), and ([Favié and Maas 2008](#)). Subsequently, an initial list of the identified factors from the literature was shared with experts involved in an iterative six-month process of framework development and validation. Through their feedback, the factors were revised and categorized into the broader context depicted in Fig. 5.

Without considering these external factors, the solution may not align effectively with the project specifications. Nevertheless, incorporating all these external factors into developing a project planning and control system made the system more complex. Therefore, this research proposed multiple feasible solutions through a mathematical model and Pareto front chart to deal with this challenge and streamline the decision-making process. Leveraging this approach gives project teams the capability and flexibility to select the best combinations and integrations of planning methods and control metrics across various schedule levels, considering the external factors unique to their project and specific circumstances.

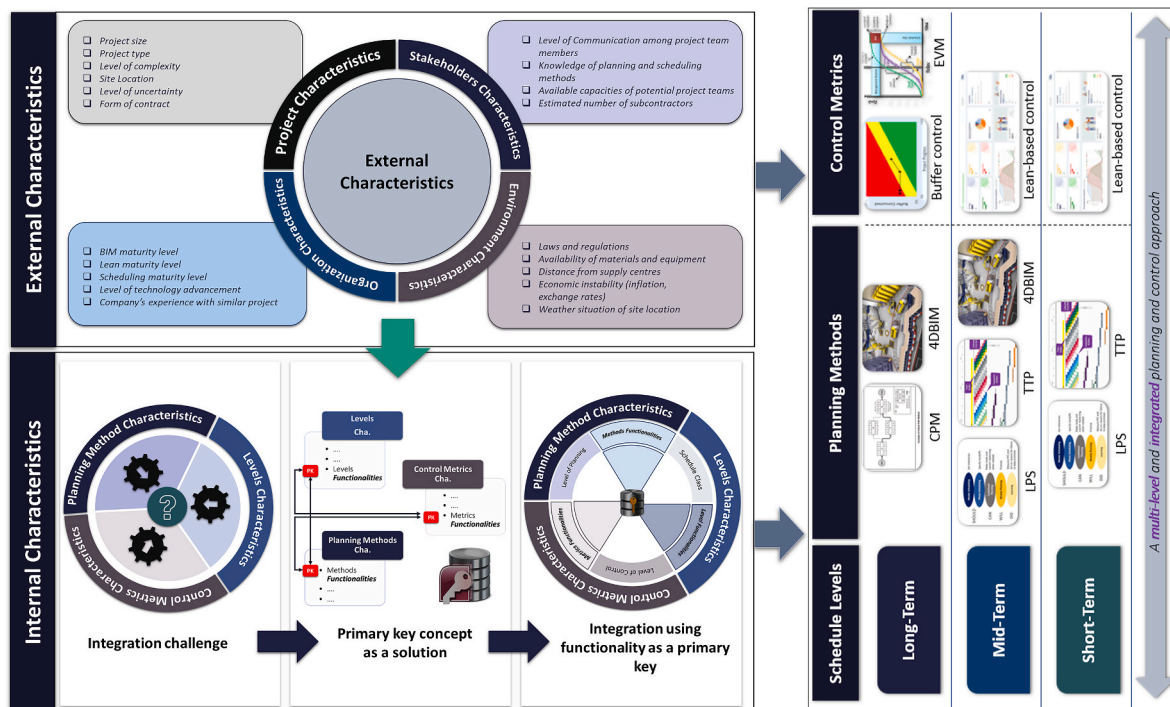


Fig. 4. Proposed multi-level and integrated framework for project planning and control.

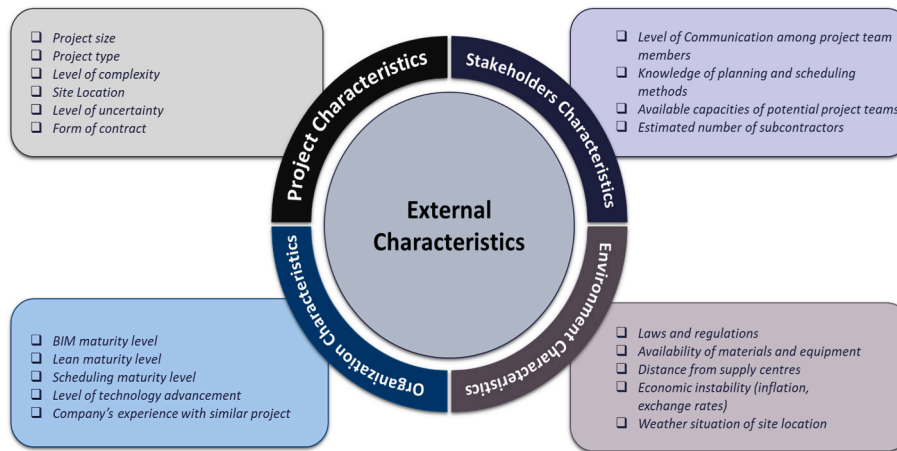


Fig. 5. Suggested external characteristics for the multi-level planning and control system.

3.2. Internal characteristics

An essential function of this study concerning internal characteristics lies in identifying essential internal features necessary for designing a production system for project planning and control. Reviewing literature and guidelines as well as expert feedback led to planning methods, control metrics, and schedule levels being identified as the main components. It was, however, a challenge to integrate all three components smoothly and seamlessly. To address the integration challenge of the framework, a concept known as the primary key in relational database management was identified, drawing upon the experience and knowledge of the authors. Within a relational database, the primary key functions as a unique identifier for each table row, ensuring the uniqueness of values and facilitating effective data retrieval and integrity (Connolly and Begg 2005). Consequently, in this research, the main goals and objectives of each planning method, control metric, and schedule level were considered as their functionality, serving as the primary key for integrating these three components.

The concept of functionality is commonly shared among various planning methods, control metrics, and schedule levels in this framework. It helps project stakeholders better understand the production planning and control system requirements for construction projects. Examples of the functionalities contained within control metrics are managing constraint removal, controlling uncertainty, monitoring project progress and performance, and measuring the make-ready process. Similarly, the functionalities associated with planning methods include improving the reliability of the planning, decreasing workflow variability, considering contractual requirements, and managing work density. For further details on functionalities, refer to the studies conducted by Sheikhhoshkar et al. (2023a, 2024a), where they extracted and analyzed the functionalities related to planning methods and control metrics. Fig. 6 depicts the components constituting the internal characteristics of the framework.

Following establishing and defining the functionality concept as a solution for integrating three components within the framework's internal characteristics, the objective was to implement the framework and choose the most appropriate planning methods and control metrics for each scheduling level. To do this, two types of data needed to be gathered. Firstly, since the aim was to combine planning methods and control metrics across various schedule levels, the following understanding was required.

- 1 How well did each planning method match each schedule level?
- 2 Which schedule level is each control metric suited to?
- 3 Which planning method is each control metric aligned with?

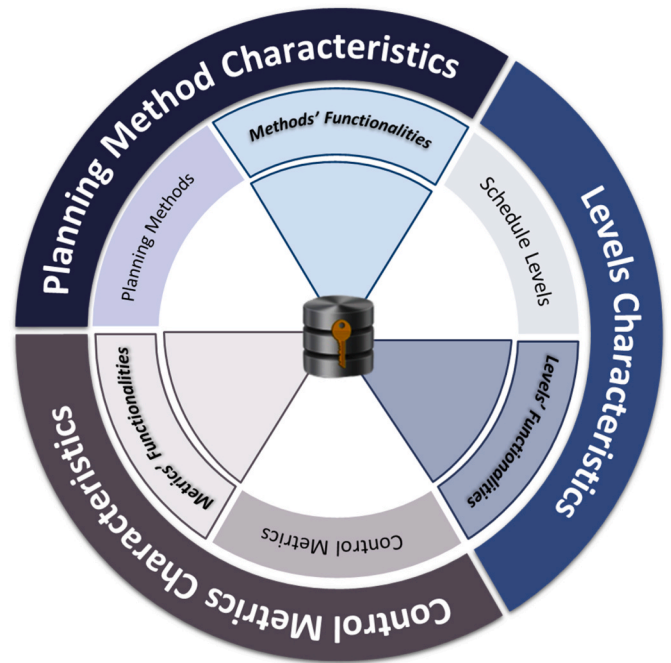


Fig. 6. Internal characteristics for the multi-level planning and control system.

Secondly, considering the integration of three components using the functionality concept, it was necessary also to determine.

- 1 The extent to which each planning method supported a specific functionality.
- 2 The extent to which each control metric supported a specific functionality.
- 3 The contribution of each schedule level to supporting the functionality.

To illustrate the dynamics of the proposed framework, this study considers eight planning methods, namely advance work packaging (AWP), 4D building information modelling (4DBIM), critical chain project management (CCPM), critical path method (CPM), last planner system (LPS), location-based management system (LBMS), linear scheduling method (LSM), and takt time planning (TTP). Additionally, the examination incorporates nine control metrics, widely advocated in scholarly literature and practical guidelines to track various aspects of project progress (Hamzeh et al., 2019b; Lin and Golparvar-Fard 2021;

Sheikhhoshkar et al., 2024a), including cost performance index (CPI), schedule performance index (SPI), milestone variance (MV), percent planned complete (PPC), required level (RL), tasks made ready (TMR), capacity to load ratio (CLR), location risk index (LRI), and task anticipated (TA). Moreover, the schedule structure is broken down into three levels: long-term, mid-term, and short-term. In terms of functionalities, 19 groups of functionalities were selected from Sheikhhoshkar et al. (2023a, 2024a), and Sheikhhoshkar et al. (2024c) studies and considered (Table 4).

The relationship between the principal components is distinctly illustrated in Fig. 7. The first step involved collecting the necessary data to operationalize the mathematical model, guided by the connections shown in Fig. 7. Questionnaires, semi-structured interviews with domain experts, and analysis of relevant documents such as published papers and project planning and control guidelines were employed to collect a sample of data to illustrate how the suggested framework works. The primary set of necessary data involves identifying potential links between planning methods and control metrics, as well as assessing how well planning methods align with different schedule levels and how control metrics relate to these levels. This information is obtained through a literature analysis (Sheikhhoshkar et al., 2024a) and guidelines review. The data are binary, representing 1 for a connection or 0 for no connection.

The second set of data focuses on how much support each planning method, control metric, and schedule level provides for different functionalities. This information was gathered by conducting surveys and semi-structured interviews with experts in the field. They were asked to rate the level of support for each functionality on a Likert scale ranging from 0 (no support) to 4 (very high support).

By leveraging the framework and aligning it with the project team's specified functional requirements, the framework is capable of suggesting the most suitable planning methods and control metrics for each level of schedule. However, integrating different planning methods and control metrics across different levels of schedule can be complex for project teams to implement and manage. To deal with complexity, this research suggests a multi-objective mathematical model to simplify this process and better understand the framework components. The

following section delves into the proposed mathematical model.

4. Multi-objective mathematical model

This section presents a multi-objective optimization model for an integrated multi-level framework for production planning and control systems in construction. The aim is to minimize the number of planning methods and control metrics at each level of the schedule while supporting maximum project team requirements in terms of functionalities. The relevant sets, indicators, parameters, decision variables, objective functions, and constraints utilized in the proposed mathematical model are outlined as follows.

4.1. Sets and indices

- j : index for the planning method, $j \in [1..J]$.
- k : index for the control metric, $k \in [1..K]$.
- l : index for the schedule level, $l \in [1..L]$.
- i : index for the functionalities, $i \in [1..I]$.

4.2. Input parameters

$J = 8$: number of planning methods

$K = 9$: number of control metric

$L = 3$: number of schedule levels

$I = 19$: number of functionalities

R_i : level of user requirement for functionality i , $R_i = [0, 1, 2, 3, 4]$.

P_{ij} : level of support for functionality i in planning method j , $P_{ij} = [0, 1, 2, 3, 4]$.

M_{ik} : level of support for functionality i in control metric k , $M_{ik} = [0, 1, 2, 3, 4]$.

S_{il} : level of support for functionality i in schedule level l , $S_{il} = [0, 1, 2, 3, 4]$.

A_{jk} : connects planning method j to control metric k . $A_{jk} = 1$ means that planning method j is mapped by control metric k .

B_{jl} : connects planning method j to schedule level l . $B_{jl} = 1$ means that planning method j is matched with schedule level l .

C_{kl} : connects control metrics k to schedule level l . $C_{kl} = 1$ means that control metric k is matched with schedule level l .

W_j : A weight to evaluate the coverage of the planning methods in terms of functionalities

$$W_j = \sum_{i=1}^I P_{ij} \quad (1)$$

V_k : A weight to evaluate the coverage of the control metrics in terms of functionalities

$$V_k = \sum_{i=1}^I M_{ik} \quad (2)$$

U_l : A weight to evaluate the coverage of the schedule levels in terms of functionalities

$$U_l = \sum_{i=1}^I S_{il} \quad (3)$$

4.3. Output variables

Binary decision variable X_j :

$X_j = 1$ If planning method j is decided to be deployed

$X_j = 0$ Otherwise

Binary decision variable Y_k :

$Y_k = 1$ If control metric k is decided to be deployed

$Y_k = 0$ Otherwise

Table 4
Functionalities considered in project planning and control systems.

ID	Functionality concepts	References
F1	Collaboration management	
F2	Commitment planning	Sheikhhoshkar et al. (2023a, 2023b), Sheikhhoshkar et al. (2024a, 2024c), and Sheikhhoshkar et al. (2024b)
F3	Communication management	
F4	Conflict management	
F5	Constraint management	
F6	Contract and delay management	
F7	Integration management	
F8	Learning and knowledge sharing	
F9	Risk management	
F10	Process and flow management	
F11	Project performance management	
F12	Reliability management	
F13	Resource management	
F14	Root cause analysis	
F15	Safety and logistics management	
F16	Supply chain management	
F17	Visualization	
F18	Waste management	
F19	Real-time site monitoring	

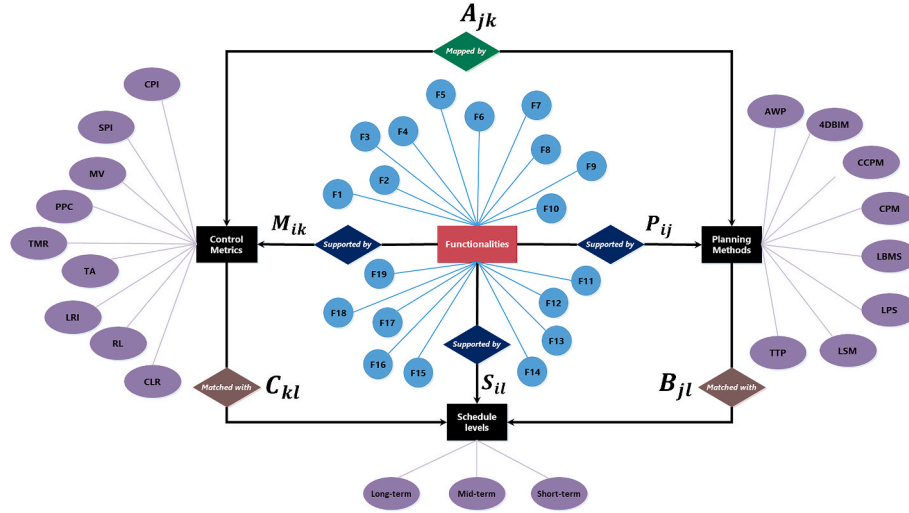


Fig. 7. Relational diagram of the main components of the multi-level framework for a case study.

4.4. Objective functions

$$Z_1 = \max \left(\sum_j W_j \cdot X_j + \sum_k V_k \cdot Y_k \right) \quad (4)$$

$$Z_2 = \min \left(\sum_j X_j \right) \quad (5)$$

$$Z_3 = \min \left(\sum_k Y_k \right) \quad (6)$$

Equations (4)–(6) aim to maximize project team requirements in terms of functionalities while minimizing the number of planning methods and control metrics at each level of schedule.

Subject to:

$$\forall k \in [1..K], \sum_{j=1}^J (A_{jk} \times X_j) - Y_k \geq 0 \quad (7)$$

Equation (7) ensures that if a control metric is selected, then at least one planning method that supports this control metric must also be selected.

$$\forall l \in [1..L], \sum_{j=1}^J (B_{jl} \times X_j) \geq U_l \quad (8)$$

Equation (8) demonstrates that deploying a particular schedule level requires the simultaneous deployment of at least one planning method corresponding to that level.

$$\forall l \in [1..L], \sum_{k=1}^K (C_{kl} \times Y_k) \geq U_l \quad (9)$$

Equation (9) specifies that once a particular level of schedule has been designated for deployment, at least one corresponding control metric for that level must be deployed.

$$\forall j \in [1..J], \sum_{l=1}^L (B_{jl} \times U_l) \geq X_j \quad (10)$$

Equation (10) enforces that if a scheduling level is active, at least one applicable planning method for that level must be chosen.

$$\forall k \in [1..K], \sum_{l=1}^L (C_{kl} \times U_l) \geq Y_k \quad (11)$$

Equation (11) enforces that if a scheduling level is active, at least one applicable control metric for that level must be chosen.

$$\forall i \in [1..I], \sum_{j=1}^J (P_{ij} \times X_j) \geq R_i \quad (12)$$

Equation (12) ensures that the selected planning methods meet the user requirements in terms of functionalities

$$\forall i \in [1..I], \sum_{k=1}^K (M_{ik} \times Y_k) \geq R_i \quad (13)$$

Equation (13) guarantees that the selected control metrics cover the user requirements in terms of functionalities.

5. Case study

A case study involving a renovation endeavor targeting the campuses of the University of Lorraine was conducted to indicate the applicability of the proposed framework and mathematical model. IUT Nancy-Brabois, part of the University of Lorraine, is undertaking a significant energy renovation project funded by the France Relance plan. Over two years, the project will renovate four departments and two workshops, aiming to improve energy efficiency and create a better learning environment. This initiative aligns with governmental efforts to reduce carbon footprints and enhance public building infrastructure. The project highlights a commitment to sustainability and the well-being of students and staff while promoting academic excellence. Fig. 8 illustrates the layout and an overview of this case study.

Given the diverse array of buildings within this project necessitating both internal and external refurbishment, it assumes the form of a comprehensive program. Thus, it becomes imperative for the project team to adopt a systematic approach containing the planning, managing, and monitoring of various facets, such as trade and resource allocation, flow of work, logistical considerations, management of uncertainties, as well as fostering collaboration and coordination among subcontractors, among other pertinent aspects. To implement the framework, the renovation project team was asked to outline their functional requirements (based on 19 functionalities) using a Likert scale ranging from 0 (no importance) to 4 (very high importance) to develop a planning and control system. Following the data collection process, all necessary data for the framework and mathematical model parameters has been acquired, facilitating the initiation of model execution.

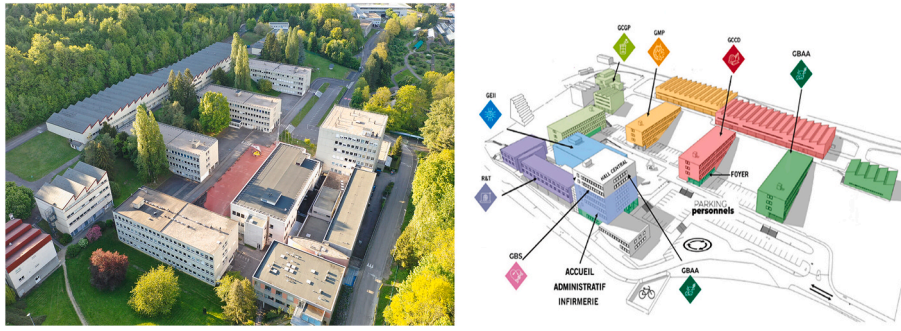


Fig. 8. An overview and layout of the renovation case study.

6. Results and analysis

The mathematical model was implemented using Python 3.11, with the Gurobi linear solver employed to address the optimization problem through the simplex method. The Pareto front chart was utilized to visualize the results. Given three objective functions within the mathematical formulation, the Pareto front graph facilitates an understanding of how solutions are distributed across all objectives. In multi-objective optimization problems, multiple potentially optimal solutions are common, as each solution may optimize one objective function while compromising others. The Pareto frontier identifies solutions that embody the optimal trade-off between all objective functions. A solution not dominated by any other solution within the feasible solution space is deemed to reside on the Pareto frontier (Tušar and Filipić 2014). In the present study, the Pareto front chart gives users and project teams the flexibility to select the most feasible solution that satisfies the particular needs of various project circumstances.

Fig. 9 illustrates the Pareto front plots, showing the outcomes based on the project team's functional requirements. At each level of the schedule, the solutions are represented by a point on the surface, and moving along the surface alters the balance between the objectives. The project team can trade-offs between the three objectives, including the number of planning methods and control metrics, and the required functionalities. Obviously, achieving maximum functionality requires team and organization knowledge of various planning methods and control metrics suggested in the results. However, due to limited knowledge of project planning and control methods among stakeholders (AlNasseri and Aulin 2015), there is a tendency to choose solutions with fewer planning methods and control metrics, potentially sacrificing some functionalities.

In addition, Table 5 displays several iterations of the findings for

each objective function, as well as selected planning methods and control metrics at various schedule levels. These iterations adhere to the functional requirements of the considered renovation case study, with a strong emphasis placed on collaboration management, commitment planning, resource management, constraint management and reliability management. Visualization, supply chain management, and waste management are also valued, but to a lesser extent. Contract management, in contrast, is regarded as less important for this case study.

The project team should decide to sacrifice certain functionalities due to the organization's maturity level and the knowledge of the stakeholders. Thus, a trade-off solution was selected, entailing fewer planning methods and control metrics to align with the project's constraints.

As shown in Fig. 9 and Table 5, according to the project team's requirements for the selected case study, a more complex surface with varying gradients and more iterations is observed at the mid-term level, suggesting a more varied relationship exists between the number of planning methods and control metrics on the objective of maximizing functionalities. A greater variety of planning methods and control metrics have been suggested by the model for this level compared to the others. This highlights the importance of the mid-term level in the planning process, where a thorough approach to planning and control is generally required. It is interpreted that the mid-term level is a crucial phase within the renovation case study, where significant emphasis is placed on collaborative and commitment planning as well as constraint management. Also, robust resource and reliability management are necessitated to adapt to project dynamics and sustain progress. The recommendation for a higher variety of planning methods reflects the necessity for diverse strategies to tackle various tasks and challenges that arise during this phase.

Moreover, an increase in control metrics indicates an emphasis on

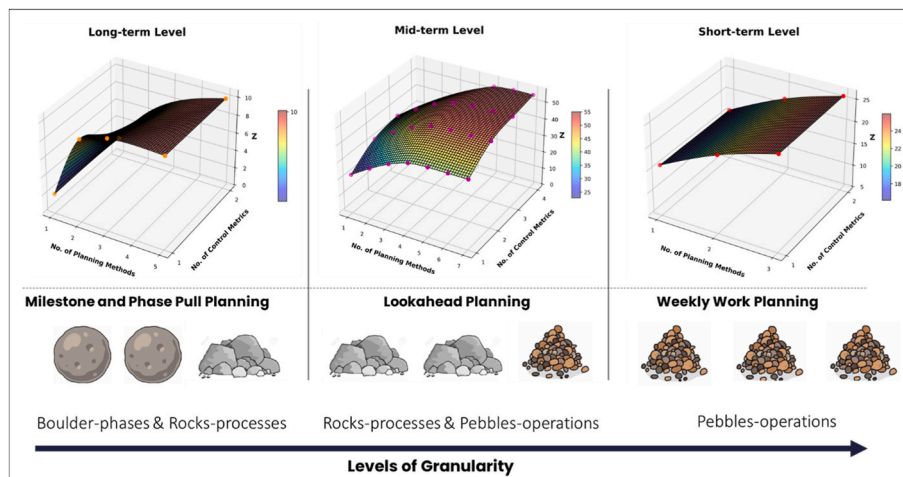


Fig. 9. Pareto front graphs for the results.

Table 5

Iterations of the findings for each objective function at each level of the schedule.

Z1	No.PM (Z2)	No.CM (Z3)	Planning Methods (PM)									Control Metrics (CM)								
			4DBIM	AWP	CPM	CCPM	LBMS	LSM	LPS	TTP	CLR	CPI	LRI	MV	PPC	RL	SPI	TA	TMR	
Long-term level																				
2	1	2	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	
9	2	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	
10	3	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	
10	5	1	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	0	0	
10	5	2	1	1	1	1	1	0	1	0	0	0	1	0	0	0	1	0	0	
Mid-term level																				
22	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	
29	2	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	
32	1	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	
35	1	3	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	
39	2	2	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	
42	2	3	1	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	
45	3	2	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	
48	3	3	1	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	1	
50	5	2	1	1	0	0	1	0	1	1	1	0	0	0	0	0	0	0	1	
52	4	3	1	0	0	0	1	0	1	1	1	0	0	1	0	0	0	0	1	
53	5	3	1	1	0	0	1	0	1	1	1	0	0	1	0	0	0	0	1	
54	5	4	1	0	0	1	1	0	1	1	1	0	0	1	0	0	0	1	1	
Short-term level																				
16	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	
16	1	2	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	
22	2	1	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0	
22	2	2	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0	
26	3	1	0	0	0	0	1	0	1	1	1	0	0	0	0	1	0	0	0	
26	3	2	0	0	0	0	1	0	1	1	1	1	0	0	0	1	0	0	0	

the thorough monitoring and management of different project aspects. Thus, the model seeks to create a balance among a wide variety of components to avoid delays and resource waste.

Table 5 highlights the selected options, including planning methods and control metrics, at each level of the schedule for the case study. 4DBIM and CPM were chosen for long-term schedule alongside SPI as a control metric to track the project performance at a high level. The rationale behind selecting these methods is grounded in their efficacy and applicability for this schedule level as well as meeting the project team's requirements at master and phase scheduling to fulfill contract obligations regarding the schedule plan. CPM scheduling is recognized for its utility in traditional project management contexts, facilitating tasks such as delay analysis and compliance with contractual obligations (Olivieri et al., 2016). Moreover, the integration of 4DBIM into the long-term level offers multifaceted benefits. It empowers project stakeholders by providing a visual representation of the schedule plan, thereby enhancing comprehension and enabling the identification of potential time-space conflicts. Furthermore, the utilization of 4DBIM contributes to bolstering project safety protocols, constructability evaluation and overall project understanding (Sheikhhoshkar et al., 2023a).

Given external variables affecting the project's dynamics, a strategy that integrates three planning methods and three control metrics was considered at the mid-term level. This includes 4DBIM, LPS, and TTP as planning methods and LRI, TA, and TMR as control metrics. The lookahead planning process involves identifying work that is to be done shortly (typically over the next 6–8 weeks) and ensuring that it is 'made ready' to be executed without interruption. This process helps in identifying potential constraints or bottlenecks in advance and resolving them before they can impact the project schedule. Therefore, integrating various planning methods and control metrics at this level offers a comprehensive system for production planning and control, ensuring compliance with project schedules and budget constraints. This integration enhances spatial and temporal project visibility, streamlines workflows through predictable scheduling, and improves communication and coordination among trades. By leveraging the strengths of each

method—TTP's emphasis on workflow continuity (Lehtovaara et al., 2021), LPS's flexibility, adaptability and collaboration (Ezzeddine et al., 2022), and 4DBIM's dynamic visualization capabilities (Sheikhhoshkar et al., 2019)—project teams can achieve superior resource utilization, proactive risk mitigation, and enhanced communication. This multifaceted approach not only increases the project's ability to adapt to changes but also improves overall quality and safety on-site, making it a robust strategy for managing complex construction and renovation projects. Also, regarding the control metrics, applying control metrics such as location risk index (LRI), task anticipated (TR), and task made ready (TMR) play a crucial role in monitoring and managing the readiness and risk levels of upcoming tasks, enabling targeted risk mitigation and minimizing delays as well as measuring the successful performance of the lookahead planning process (Hamzeh et al., 2015). Together, these approaches enhance project performance, quality, and safety, making them essential strategies for managing this complex renovation project effectively.

At the short-term level, considering the functional requirements of the project team, which entail the integration of last planners into the process for commitment planning, resource management, fostering collaboration, and ensuring continuity of resources and workflows, alongside external factors, the LPS and TTP were selected the planning methods. Concurrently, PPC and CLR were identified as relevant control metrics for effectively monitoring and managing the aforementioned processes. Applying PPC and CLR as control metrics is crucial for effectively tracking and managing weekly work planning. PPC provides a direct indicator of planning reliability, reflecting the percentage of tasks completed as planned. This offers immediate insights into the effectiveness of weekly planning efforts and enables timely adjustments to enhance predictability and performance (Hamzeh et al., 2019a). On the other hand, CLR evaluates the balance between available capacity and the work scheduled, serving as a key indicator of resource utilization efficiency (Hamzeh et al., 2019a). Together, these metrics empower project teams to spot differences between planned and actual progress, optimize resource allocation, and mitigate potential bottlenecks, ensuring that the project stays on track and aligns with the overarching

project objectives.

By advocating the integration of both lagging and leading control metrics at mid-term and short-term levels of the schedule, the project team gains a comprehensive understanding of project performance. This approach not only facilitates retrospective analysis and learning from past occurrences but also enables predictive analytics, facilitating the anticipation and identification of future schedule delays and potential issues before they occur.

As a result, Fig. 10 illustrates the proposed production planning and control system for the case study, incorporating four planning methods and six control metrics across three schedule levels to address the functional requirements of the project team. This case study depicts the practical application of the proposed framework and mathematical model in formulating a production planning and control system for construction projects.

The proposed framework serves as a foundational basis for a decision support system (DSS). To effectively implement the framework, developing a DSS that can elicit the functional requirements of the project team and recommend suitable planning and control systems would be highly beneficial and efficient. One significant challenge in implementing such a system is sourcing experts with diverse knowledge and experience in various planning and control systems to build a comprehensive knowledge repository for the DSS. Additionally, integrating multiple planning methods and control metrics poses implementation challenges. To address this, it is crucial not only to present the framework's results but also to develop a detailed methodological guideline. This guideline should outline the necessary steps, activities, processes, roles, responsibilities, and information required for successful implementation.

By developing a comprehensive guideline, the result of this study can provide a tangible and impactful outcome for the industry, facilitating the practical application of the framework. This approach ensures that the integration of planning methods and control metrics becomes feasible and enhances the overall efficiency and effectiveness of project management practices across different project types. It should be noted that developing the guideline falls outside the scope of this study. Subsequent research endeavors will focus on formulating a methodological guideline for the effective implementation of the proposed system.

7. Framework evaluation and assessment

Although the application of the proposed framework to the case study has demonstrated its effectiveness, for a more comprehensive assessment, a survey was distributed among academic and industrial experts who participated in the six-month endeavor of conceptualizing, developing, and evaluating the framework. The survey used a five-point

Likert scale from 'strongly disagree' (1) to 'strongly agree' (5). This data collection step resulted in ten responses for assessing the framework. Fig. 11 presents the survey questions, respondents' answers, and the average response for each question.

The survey analysis reveals strong support for the framework's utility in real-world applications, with an average rating of 4.1 for applicability, signalling its relevance across various scales and complexities of construction projects. The framework's flexibility and adaptability are valued, with an average rating of 4.2, indicating its robustness in dealing with changes in external and internal characteristics. Most noteworthy is the ease of understanding, which stands out with a striking average of 4.8, illustrating that the framework is well-received for its clarity and its ability to enhance stakeholders' comprehension of planning and control requirements by defining and considering the functionality concept. Integration of the framework with existing planning and control methods is acknowledged positively, reflected by an average rating of 4.2. Lastly, a strong average rating of 4.1 confirms the framework's completeness and indicates that it provides a thorough system for production planning and control. Collectively, these ratings underscore the framework's robustness and its potential to streamline project management practices in the construction industry.

8. Discussion and summary

This discussion synthesizes the core elements and contributions of the study, emphasizing its significance, innovations, and implications for both theory and practice within the construction management domain. This study contributes to the body of production planning and control knowledge by introducing a novel framework proposing a multi-level and integrated approach. Initially, the authors endeavored to identify the challenges and issues related to planning and control by actively engaging in real-world construction projects. Through site visits, document analysis, literature review, and informal interviews and discussions with industry professionals, it became evident that the dynamic and complex nature of construction projects has led to a lack of comprehensive methods, tools, and systems for effective planning and control.

Throughout the decades, a vast range of planning methods and control metrics have been developed to address the planning, monitoring, and management challenges inherent in construction projects. However, there remains a significant gap in both academic literature and industry practice regarding a system that seamlessly integrates the advantages of various planning methods and control metrics while also considering the knowledge and decision-making capabilities of project stakeholders (Dallasega et al., 2021). Additionally, it was noted that stakeholders often lack a comprehensive understanding of these

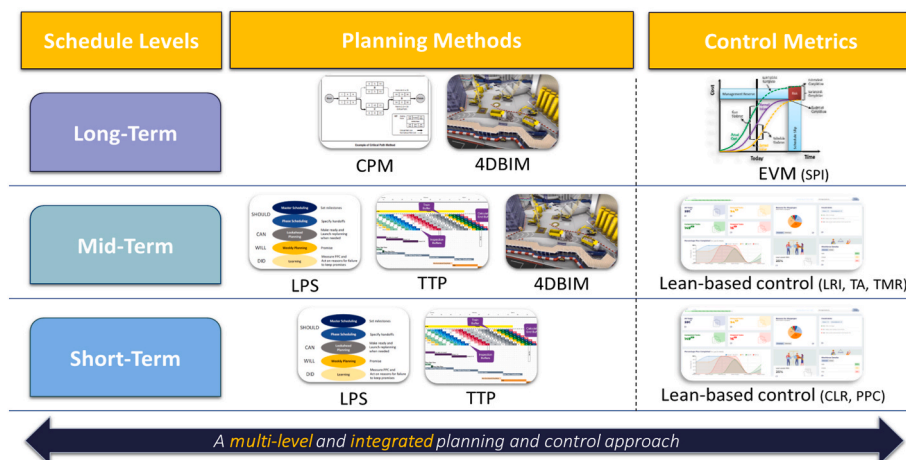


Fig. 10. Proposed production planning and control system for the renovation case study.

Framework Evaluation Aspects	Likert scale					
	1 Strongly Disagree	2 Disagree	3 Neutral	4 Agree	5 Strongly Agree	
Applicability:						
The framework is applicable to implement in real-world construction projects of varying scales and complexities.	0%	0%	20%	50%	30%	4.1
Flexibility and Adaptability:						
The framework easily adapts to change in project requirements, scope, or industry regulations.	0%	0%	20%	40%	40%	4.2
Ease of Understanding:						
The framework is easily to understand by individuals with limited project planning and control knowledge and notably enhances project stakeholders' understanding of their planning and control requirements.	0%	0%	0%	20%	80%	4.8
Integration:						
The framework seamlessly and effectively integrates commonly used project planning methods and control metrics across different levels of the schedule.	0%	0%	10%	60%	30%	4.2
Completeness:						
The approach followed in the framework to develop multi-level planning and control is sufficient, making the framework exhaustive and complete	0%	0%	30%	30%	40%	4.1

Fig. 11. The survey inquiries and outcomes derived from the assessment of the proposed framework.

planning methods and control metrics, further complicating effective project planning and control. Design science research (DSR) was employed in this study to design, develop, and evaluate a novel solution in multiple steps. The authors were assisted by ten experts from both industry and academia for six months to develop a comprehensive and practical framework. The proposed framework is centred around an extensive process that effectively integrates internal and external characteristics necessary for construction project planning and control. This ensures a thorough understanding tailored to the specific requirements of each project. This approach not only recognizes the diversity of construction projects in terms of type, size, and complexity, but also acknowledges the dynamic interplay between environmental factors, organizational structures, and stakeholder demands. As a result, the framework offers a flexible and adaptable tool that can be utilized in various project environments, expanding its applicability and enhancing its usefulness in the field.

To deal with the lack of project stakeholder's knowledge regarding various planning methods and control metrics, a strategic approach was taken by applying the concept of the "primary key" inspired by database management systems, into the framework. To do so, the aims and objectives of planning methods, control metrics and schedule levels were extracted and defined as their functionalities. This concept played the primary key role in integrating the main components in the proposed framework. This integration was pivotal in creating a coherent system that seamlessly aligns planning methods and control metrics across different schedule levels, thereby fostering efficiency, simplifying complexities, and improving the understanding and decision-making capabilities of project stakeholders.

Integrating a multi-objective mathematical model into the framework not only clarifies its components and operational mechanisms but also marks a notable methodological advancement in optimization. This model provides a structured approach to navigating the inherent complexities of selecting and integrating various planning methods and control metrics at three schedule levels. The optimization objectives encompass maximizing the functional requirements of the project team while minimizing the number of planning methods and control metrics for more effective and practical implementation.

The application of the framework to a renovation case study serves as a practical validation of its effectiveness and relevance. The case study illustrates how the framework can be operationalized to address real-

world project management challenges, offering insights into its adaptability and the strategic value of its recommendations for planning and control practices. The results of the case study incorporate four planning methods and six control metrics across three schedule levels as a production planning and control system to address the functional requirements of the project team. The proposed system not only ensures the project stays on schedule and effectively manages time and cost, which are crucial factors for project success, but it also addresses various essential aspects such as supply chain management, workflow and resource allocation, uncertainties, collaboration, coordination, and communication within the project team, as well as daily task management.

To further emphasize the scalability of the framework to large, complex projects, it's essential to recognize that each project type, including residential and commercial building projects, infrastructure projects, and industrial projects, presents unique challenges and requirements. While the case study demonstrates adaptability, it's crucial to acknowledge practical constraints that may arise in diverse project settings. For instance, large-scale infrastructure projects often involve intricate logistics, extensive stakeholder coordination, and stringent regulatory compliance, which could impact the implementation of the framework. Similarly, in industrial projects characterized by high precision and operational efficiency demands, practical considerations such as technological integration and workforce skillsets play pivotal roles in framework applicability.

By addressing these diverse practical constraints explicitly, the framework's scalability and applicability to large, complex projects are underscored. This systematic approach not only enhances strategic planning capabilities but also optimizes resource allocation and minimizes inefficiencies across sectors. For instance, in infrastructure projects, where timely completion and budget adherence are critical, the framework can facilitate comprehensive project oversight and risk management. Likewise, in industrial projects, the framework's integration of planning and control systems can foster continuous process improvement and operational excellence, thereby enhancing overall project outcomes. This adaptability highlights the framework's potential as a universal tool in project management, capable of accommodating the distinctive challenges and demands of various project types while driving sustainable project success.

Eventually, the positive evaluation of the framework by academic

and industry experts, as reflected in satisfaction survey metrics, underscores its strengths in terms of applicability, flexibility and adaptability, ease of understanding, integration and completeness. This endorsement highlights the framework's potential to significantly contribute to the field of construction management, offering a robust, innovative, and user-friendly tool for enhancing production planning and control practices.

9. Comparative context

This section compares the proposed framework with the integrated planning methods and control systems discussed in previous studies. In earlier works, the integration of planning methods and control systems aimed to cover each other's shortcomings without addressing a wide range of the project's functional requirements regarding a planning and control system. In contrast, the proposed framework in this study is designed to first cover a wide variety of functional requirements (19 groups of functionalities) and then integrate planning methods and control systems based on the functional requirements of the project team. This framework acts as an umbrella that can utilize all planning methods and control metrics, offering more generality than solutions suggested in the literature. Additionally, it simplifies stakeholder understanding by employing the functionality concept, making it easier for stakeholders to grasp the relevance and utility of different planning methods and control metrics. Table 6 presents a more detailed comparative analysis.

10. The implications of the findings

The integrated multi-level framework developed in this study offers significant implications for future construction management practices. By harmonizing various planning methods and control metrics across different schedule levels, this framework tackles the industry's pressing challenges, such as ineffective planning and control systems, inefficient workflow, insufficient address the functional needs of a project team concerning a planning and control system, and frequent delays and cost overruns. The framework's innovative approach, which incorporates

internal and external characteristics and utilizes a multi-objective mathematical model to optimize the integration process, has the potential to enhance the efficiency and effectiveness of construction project management substantially.

Practically, the application of this framework in real-world applications, as demonstrated in a renovation case study, highlights its strategic value and practicality, making a compelling case for its broader adoption. The positive evaluations from industry and academic experts further underscore its potential to transform production planning and control in construction. Adopting this framework can lead to a transformative shift in construction practices, and better-informed decision-making, promoting a more systematic, transparent, and proactive approach to project planning and control, which is crucial for the industry known for its complexity and variability.

11. Conclusion, limitations and future directions

This research develops an integrated multi-level framework for production planning and control in the construction industry, employing a design science research (DSR) methodology. This approach emphasizes the creation of practical and effective solutions for integrating planning methods and control metrics across various schedule levels, addressing the dynamic and complex nature of construction projects. The framework is designed to enhance the efficiency and effectiveness of construction project management by leveraging a combination of planning methods and control metrics, tailored to the specific requirements of each project. It acknowledges the diversity of construction projects and the need for a system that can adapt to varying project requirements, environmental factors, organizational structures, and stakeholder demands. A significant aspect of this study is its focus on addressing the knowledge gap among project stakeholders regarding various planning methods and control metrics. Employing the concept of "functionality" as a primary key for integration of the main components of the framework, facilitates a better understanding and decision-making process among stakeholders, ensuring a coherent system that aligns planning methods and control metrics across different schedule levels.

The application of a multi-objective mathematical model within the framework represents a methodological advancement in optimization, providing a structured approach to selecting and integrating various planning methods and control metrics. This model aims to maximize the functional requirements of the project team while minimizing the number of planning methods and control metrics, thereby simplifying implementation and enhancing practicality. The validation of the framework through a renovation case study demonstrates its applicability and strategic value in real-world project management scenarios. Specifically, the framework and mathematical model recommend integrating CPM, LPS, TTP, and 4DBIM as a production planning and control system for the case study. Additionally, a combination of EVM and lean-based control metrics was proposed to effectively monitor and control various project aspects.

In addition, the positive evaluation of the framework by experts, as evidenced by satisfaction survey metrics, highlights its potential to significantly contribute to the field of construction management by offering a robust and innovative tool for improving production planning and control practices.

Overall, the study presents a comprehensive and practical solution to the challenges faced in construction project management, with the potential for widespread application across various types of construction projects. However, a limitation of this study is that only a renovation case study was considered to demonstrate the practicality and validity of the approach. While this provides valuable insights, broader validation across different types of construction projects would strengthen evidence for the framework's generalizability and applicability in diverse contexts.

Looking forward, future research could expand on integrating

Table 6
Comparative analysis of previous studies and proposed framework.

Comparison aspect	Previous Studies (Integrated planning methods)	Proposed Framework
<i>Reason for integration</i>	Covering each other's shortcomings.	The functional requirements of the project team.
<i>Coverage of functional requirements</i>	Limited coverage.	Covers a wide variety of functional requirements (19 groups of functionalities).
<i>Adaptability</i>	Not Flexible in changing the project requirements.	Adapts to changes in project requirements, scope, and regulations.
<i>Generality</i>	Focused on specific integrations without broad applicability.	Provides a general and encompassing solution applicable across various projects.
<i>Simplification mechanism</i>	None, assumed stakeholders understand all methods and metrics.	Employs the functionality concept to simplify understanding for stakeholders.
<i>Stakeholder understanding</i>	Complex for stakeholders with limited knowledge of planning methods and control metrics.	Simplifies decision-making by relating to tangible functional requirements, making it easier for stakeholders to engage.
<i>Example scenario</i>	Asking stakeholders if they think LPS would be helpful, which many might not understand.	Asking stakeholders if they want to improve collaboration and communication, a concept they can easily relate to.
<i>Decision basis</i>	Integration decisions were not clearly driven by project-specific functional requirements.	Every suggested system is driven by the functional needs of the project team.

additional planning methods such as agile techniques and scrum, as well as exploring further control metrics. Moreover, developing detailed implementation guidelines would facilitate the practical application of the integrated approach in various real-world scenarios. Subsequent research endeavors could concentrate on formulating a methodological guideline for implementing the suggested system.

Data availability Statement

All data, models, or code generated or used during the study are available from the corresponding author by request.

CRediT authorship contribution statement

Moslem Sheikhhoshkar: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hind Bril El-Haouzi:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Alexis Aubry:** Writing – review & editing, Validation, Supervision, Methodology, Investigation, Conceptualization. **Farook Hamzeh:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Mohammad Sakikhales:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

In the course of preparing this manuscript, the authors utilized the ChatGPT/Scholar AI tool to enhance the language and readability of the paper. Following the use of this tool, the authors thoroughly reviewed and edited the content as necessary, and take full responsibility for the final content of the publication.

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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